Original Research

Association Between Pitch Break on the 4-Seam Fastball and Slider and Shoulder Injury in Major League Baseball Pitchers

A Case-Control Study

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Background: Few specific risk factors are known for shoulder injury in professional pitchers. New pitch-tracking data allow for risk stratification based on advanced metrics.

Purpose/Hypothesis: The purpose of this study was to determine the association between shoulder injury, pitch frequency, and pitch metrics (velocity, total break, break angle, and spin rate) for the 4-seam fastball, curveball, and slider. We hypothesized that more frequent use of the 4-seam fastball would be associated with shoulder injury.

Study Design: Case-control study; Level of evidence, 3.

Methods: The Major League Baseball (MLB) database was queried for pitchers who had been placed on the injury list (IL) with a shoulder injury between 2015 and 2019. Injured pitchers were matched 1:1 with controls (pitchers not on the IL with a shoulder injury during the study period), based on age (±1 year), history of ulnar collateral ligament reconstruction, position (starter vs reliever), and pitches thrown during the injury season (±500). Pitch frequency, velocity, horizontal break, vertical break, total break, and spin rate for the season were collected from the Baseball Savant website for the 4-seam fastball, curveball, and slider. Univariate analysis was used to determine group differences for individual variables. Multiple logistic regression was performed to determine odds ratios (ORs) for shoulder injury associated with pitch frequency, velocity, total break, break angle, and spin rate. Covariates included age, position, ulnar collateral ligament reconstruction status, expected weighted on-base average, and total pitches thrown.

Results: Overall, 233 injured pitchers were evaluated. The most common reason for IL placement was inflammation (78/233; 33.5%) followed by strain or sprain (61/233; 26.2%). Increased total pitch break was associated with an increased risk of shoulder injury for the 4-seam fastball (OR, 1.340 [95% confidence interval (CI), 1.199-1.509]; $P < .001$) and slider (OR, 1.360 [95% CI, 1.206-1.554]; $P < .001$). For the slider, a decreased spin rate (OR = 0.998 [95% CI, 0.997-0.999]; $P = .026$) and a more vertical break angle (OR = 1.170 [95% CI: 1.073-1.278]; $P = .004$) were associated with increased risk of injury.

Conclusion: Increased pitch break of the 4-seam fastball and slider was associated positively with shoulder injury in MLB pitchers. These findings add to the understanding of throwing injury and ability to detect risk using ball-tracking technology.

Keywords: shoulder; overhead throwing; baseball; injury prevention

Despite a plethora of advanced analytics and risk stratification, injury rates remain high among professional pitchers. Given their high volume of maximal effort throws, pitchers sustain almost 40% of all Major League Baseball (MLB) injuries.[4] Two recent epidemiologic studies of injuries in MLB identified the shoulder as the most commonly injured upper extremity joint,[4,14] comprising 17% of all injuries between 2011 and 2016, with 78% of those injuries occurring in pitchers.[14]

Multiple risk factors have been identified for ulnar collateral ligament (UCL) injury in pitchers,[9] and several studies have used the PITCHf/x database (www.pitchinfo.com) to identify factors associated with UCL reconstruction (UCLR) pertaining to frequency of pitch types, velocity, and

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release point.[5,7,11,19,29] For example, UCL injury is associated with greater 4-seam fastball pitch frequency and velocity.[6,31] This finding is attributed to a greater elbow valgus stress when throwing a fastball.[12] Although risk factors for UCL injury are frequently reported, similar risk factors for shoulder injury are unknown.[7]

Escamilla et al[13] demonstrated that shoulder torque and angular velocity was significantly greater when throwing a fastball, slider, or curveball compared with a change-up. Each of these pitches is differentiated by the typical velocity, spin rate, and spin axis with which it is thrown. These findings suggest that forces acting on the shoulder differ significantly based on the axis of spin and amount of spin being exerted. In addition, individual pitchers throw each pitch type with a unique spin axis and rate.[26] Therefore, biomechanics may significantly differ as pitchers exert higher spins or more movement within the same pitch type. Pitch break and spin rate have gained greater attention as critical metrics to pitching performance. Spin rate has been correlated with pitch movement, which has, in turn, been correlated with the rate of swings and misses on a pitch.[2] Although field data cannot directly measure pitch biomechanics, measures of spin rate, pitch break, and break angle to assess injury risk would be invaluable for players and coaches.

The 4-seam fastball, slider, and curveball are particularly useful for study because of their unique spins and movement patterns. The 4-seam fastball moves with backspin and resists gravity while breaking to the arm side of the pitcher.[27] The curveball contains front spin, resulting in movement that falls more than the isolated effect of gravity and away from the pitcher's arm.[27] By contrast, the slider has a radial spin (perpendicular to the direction of movement), which results in movement that resists gravity and moves away from the pitcher's hand.[27] The purpose of this study was to identify pitching metric risk factors for shoulder injury in MLB pitchers. We hypothesized that more frequent use of the 4-seam fastball, with its greater velocity and spin rate, would be associated with shoulder injury.

METHODS

Shoulder injuries were first identified using transaction reports from the MLB website (www.mlb.com),[21] and related pitching data were collected from Baseball Savant (www.baseballsavant.mlb.com).[35] Baseball Savant uses information from Statcast, which employs multiple high-speed cameras and radar systems to report ball-tracking metrics.[35] The system, implemented by the MLB through Washington State University, has been shown to have a spatial resolution of 0.03 inches per pixel, exposure times of 50 μs with motion blur <0.080 inches.[25]

Study Population

Included in the study were all pitchers from the MLB website who were placed on the injured list (IL) with a chief concern including the word "shoulder" on his throwing side with at least 1 pitch recorded during the index year. Players are placed on the IL for 10 to 60 days after a physician's determination that they are unable to play.[20] The index year was defined as the year in which IL placement was made. A control group was assembled using pitchers who did not have a reported shoulder injury for at least 5 years prior to the season collected according to transaction reports; 5 years was chosen as the injury-free period to be consistent with the amount of Statcast data available. Players in the control group were matched 1:1 on the basis of age (±1 year), pitches thrown in the season of interest (±500), history of UCLR as noted on MLB reports,[22] and whether they were a starting pitcher or relief pitcher. Doing so focused the analysis on the variables of interest (ie, pitch velocity, pitch movement, movement angle, and spin rate). After being identified as control candidates by matching for these variables, the controls were picked using an algorithm in Microsoft Excel (Microsoft Corp) that identified uninjured pitchers who matched injured pitchers in all pertinent variables within the defined parameters. A single uninjured match was selected via a simple randomization strategy using a random-number generator to assign a control from potential matches for each injured pitcher.[33] In addition, the reason for being placed on the IL was collected from MLB transaction reports for each pitcher in the injured group.

A total of 233 pitchers were placed on the IL between 2015 and 2019 because of throwing arm shoulder injury. These players were matched to 233 control pitchers. When broken down by pitch type, there were 441 pitchers in the 4-seam fastball group, 359 in the slider group, and 301 in the curveball group (Figure 1).

Data Collection

Age, total pitches, and expected weighted on-base average (xwOBA) in the season of injury were collected from Baseball Savant for each pitcher. We used xwOBA as a performance metric because it calculates the expected value of opponent hitters against a given pitcher given the exit velocity and launch angle of batted balls. In addition, the

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Ethical approval was not sought for the present study.

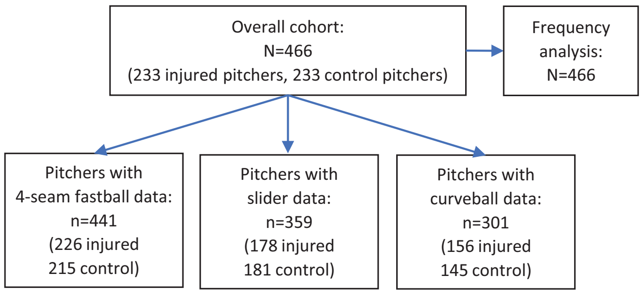

Figure 1. Study inclusion flowchart for frequency, 4-seam fastball, slider, and curveball analyses.

data for 4-seam fastballs, sliders, and curveballs for the season of injury according to the following variables: frequency of use $\left(\left[\frac{\text{Pitches of one type}}{\text{Total pitches}}\right] \times 100\right)$, mean velocity, mean total pitch break, mean horizontal break (number of inches the ball moves on the x-axis from release to crossing the plate; Hbreak), mean vertical break (number of inches the ball moves on the y-axis from release to crossing the plate; Vbreak), and spin rate. A positive Hbreak is defined as moving away from a right-handed batter, whereas a more positive Vbreak is defined as less drop than would be expected due to gravity (Figure 2). Hbreak was collected and normalized for pitcher handedness, in which left-handed Hbreak values were flipped on the x-axis.

Hbreak and Vbreak were used to calculate break angle, defined as the angle, in degrees, from vertical to the straight-line path from the release point to where the pitch crossed the front of home plate,[3] using the following equation: Break angle $= \arctan\left(\frac{\text{Vbreak}}{\text{Hbreak}}\right)$ (Figure 2). Each pitch type was then placed on a 4-quadrant 360° axis on the basis of its Hbreak and Vbreak values (quadrant 1: –Hbreak and +Vbreak, quadrant 2: +Hbreak and +Vbreak, quadrant 3: +Hbreak and –Vbreak, quadrant 4: –Hbreak and –Vbreak) to display the average placement for each type as viewed from the pitcher's perspective.

Statistical Analysis

For the collected continuous variables, means and standard deviations were used in a t test to determine significant differences between groups (injured and control). Normality for these variables were assessed visually using Q-Q plots and density plots, which revealed each variable distribution to be approximately normal.[15] For the collected binary variables (position and UCLR status), the z test for proportions was used. Multiple logistic regression was performed to determine the odds ratio (OR) for risk of shoulder injury due to frequency of pitches for the 4-seam fastball, curveball, and slider. This analysis included pitchers included in both the injured and control groups. Those pitchers who had no data recorded for a particular pitch type were analyzed using a pitch frequency of 0% for that pitch type. Covariates included age, total pitches, position (starting pitcher vs relief pitcher), xwOBA, and UCLR status. Separate multiple logistic regression models were then made for the 4-seam fastball, slider, and curveball to determine the log OR of shoulder injury related to pitch velocity, pitch break, break angle, and spin rate for each pitch with the same covariates included.

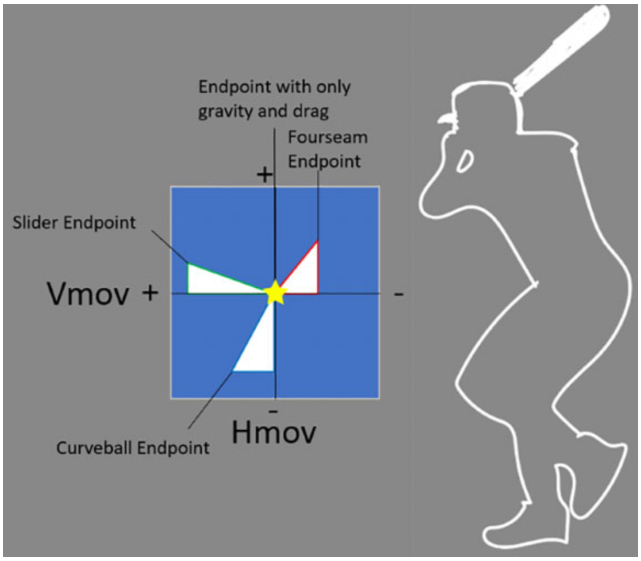

Figure 2. Pitch type movement pattern illustration for a right-handed pitcher facing a right-handed batter. Hmov, horizontal movement; Vmov, vertical movement.

Unconditional logistic regression analysis was selected instead of matched analysis because of the lack of a sparse data problem.[28,32] While matches were selected for each case individually, each control matched for multiple cases, as the matched variable parameters suited many available control pitchers. In other words, a single control was appropriately matched for multiple cases because of the homogeneity of these variables in the professional pitching population, thus eliminating the need for conditional analysis. This method allowed for greater precision without sacrificing validity.[28] Multicollinearity was assessed using variance inflation factors. The highest variance inflation factors were seen with slider break (3.7) and slider break angle (3.7) variables. These were included based on a cutoff value of 5.[10,17,34] Bonferroni correction was used to adjust for multiple comparisons in each individual model using the *p.adjust* function in R. R software, Version 4.0.2 (R Foundation for Statistical Computing), was used for data analysis.

RESULTS

Descriptive Data

The descriptive data for the injured and control groups are listed in Table 1. There were no significant differences between the groups in terms of age, xwOBA, total pitches in the study season, UCLR status, or position. The most common reason for being placed on the IL in the injured group was inflammation (78/233; 33.5%), followed by

TABLE 1
Overall Pitcher Characteristics[a]

Overall	Injured (n = 233)	Control (n = 233)	*P* Value, Bonferroni Adjusted
Age, y	28.8 ± 3.7	28.8 ± 3.6	>.999
xwOBA	0.332 ± 0.041	0.335 ± 0.049	>.999
Pitches thrown in season	1027 ± 750	973 ± 800	>.999
Underwent UCLR, n	72	72	>.999
Starting pitcher, n	119	119	>.999
Mean no. pitches, (%) thrown			
4-seam fastball	36.4 (21.4)	38.1 (22.1)	>.999
Slider	18.0 (14.9)	19.8 (16.6)	>.999
Curveball	9.3 (10.4)	9.2 (11.3)	>.999

[a]Data are reported as mean ± SD unless otherwise indicated. UCLR, ulnar collateral ligament reconstruction; xwOBA, expected weighted on-base average.

TABLE 2
Shoulder Injuries (n = 233 Injured Pitchers)

Injury	n (%)
Shoulder inflammation	78 (33.5)
Shoulder strain/sprain	61 (26.2)
Shoulder impingement	22 (9.4)
Tendinitis	21 (9.0)
Soreness	14 (6.0)
Fatigue	8 (3.4)
Shoulder surgery	6 (2.6)
Tightness	6 (2.6)
Shoulder discomfort	4 (1.7)
Bursitis	4 (1.7)
Torn labrum	1 (0.4)
Scapular stress injury	1 (0.4)
Thoracic outlet syndrome	1 (0.4)
Contusion	1 (0.4)
Subluxation	1 (0.4)
Not reported	4 (1.7)

strain/sprain (61/233; 26.2%), impingement (22/233; 9.4%), and tendinitis (21/233; 9.0%). Additional reasons for IL status included soreness, fatigue, surgery, tightness, discomfort, bursitis, torn labrum, scapular stress injury, thoracic outlet syndrome, contusion, and subluxation. Four players (1.7%) did not have a stated reason for being placed on the IL more specific than shoulder injury (Table 2).

Univariate Analysis

4-Seam Fastball. A similar proportion of injured and control pitchers threw the 4-seam fastball (226/233 vs 215/233). The groups that threw the 4-seam fastball were also similar with respect to age, xwOBA, total pitches, UCLR, position, velocity, and spin rate. The injured group exhibited significantly more total break (18.7 vs 17.2 inches; $P < .001$) and with relatively more horizontal movement compared with vertical according to break angle (296° vs 293°; $P = .015$) (Table 3 and Figure 3).

Slider. A similar proportion of injured and control pitchers threw the slider (178/233 vs 181/233). The 2 groups that threw the slider were also similar with respect to age, xwOBA, total pitches, UCLR, position, velocity, break, and break angle (Table 3 and Figure 3). The injured group displayed a significantly lower spin rate (2324 rpm) compared with the control group (2420 rpm; $P = .003$).

Curveball. A similar proportion of injured and control pitchers threw the curveball (156/233 vs 145/233). The 2 groups were also similar with respect to age, xwOBA, total pitches, UCLR, position, velocity, and break angle (Table 3 and Figure 3). The injured group displayed significantly lower values than the control group in spin rate (2377 vs 2516 rpm; $P < .001$) and break (11.8 vs 13.4 inches; $P = .008$).

Multivariate Analysis

Pitch Frequency. According to a multiple logistic regression model, there was no significant increase in shoulder injury associated with 4-seam fastball, slider, or curveball frequency (Table 4).

4-Seam Fastball. The multiple logistic regression model determined that there was a significantly increased risk of shoulder injury with increased total break of the 4-seam fastball (OR, 1.340 [95% confidence interval (CI), 1.199-1.509]; $P < .001$) and no increased risk with change in 4-seam fastball break angle ($P > .999$) (Table 5 and Figure 3).

Slider. The multiple logistic regression model determined that there was a small yet significant decrease in shoulder injury associated with increased spin rate (OR, 0.998 [95% CI, 0.997-0.999]; $P = .026$). In addition, shoulder injury was significantly associated with increased break (OR, 1.360 [95% CI, 1.206-1.554]; $P < .001$) and more downward break angle (OR, 1.170 [95% CI, 1.073-1.278]; $P = .004$) (Table 5 and Figure 3).

Curveball. The multiple logistic regression model determined that there were no curveball variables that were significantly associated with shoulder injury (Table 5).

DISCUSSION

The principal finding of this study is that shoulder injury in professional pitchers was associated with the movement of some of their pitches. Increased break in the 4-seam fastball and slider was associated significantly with shoulder injury. In addition, lower spin rate of the slider was associated with increased shoulder injury. Although univariate analysis showed differences between injured and uninjured groups with regard to pitch break and spin rate of the curveball, the multivariate model did not show these variables to be associated significantly with injury when controlling for all covariates, suggesting that, independently, they are not useful predictors of shoulder injury risk. The difference in the 4-seam fastball pitch break between the injured and uninjured groups was notable in the context of MLB pitching. According to Baseball Savant, the uninjured group average of 17.2 inches was in the 46th

TABLE 3
Pitcher Characteristics by Pitch Type[a]

	Injured	Control	P Value, Bonferroni Adjusted
4-seam fastball group	(n = 226)	(n = 215)	
Age, y	28.8 ± 3.7	28.9 ± 3.5	>.999
xwOBA	0.332 ± 0.041	0.332 ± 0.049	>.999
Total pitches in season	1029 ± 752	995 ± 807	>.999
Underwent UCLR	70	67	>.999
Starting pitcher	116	112	>.999
4-seam fastballs in season	362 ± 327	391 ± 364	>.999
Velocity, mph	92.8 ± 2.6	92.9 ± 2.7	>.999
Spin rate, rpm	2242 ± 155	2271 ± 162	.554
Total break, in	18.7 ± 2.8	17.2 ± 2.5	**<.001**
Break angle, deg	296 ± 10	293 ± 10	**.015**
Slider group	(n = 178)	(n = 181)	
Age, y	29.1 ± 3.7	28.5 ± 3.4	>.999
xwOBA	0.338 ± 0.039	0.337 ± 0.052	>.999
Total pitches in season	1141 ± 806	1113 ± 889	>.999
Underwent UCLR	55	46	>.999
Starting pitcher	96	92	>.999
Sliders in season	227 ± 195	217 ± 202	>.999
Velocity, mph	84.4 ± 3.1	84.2 ± 3.1	>.999
Spin rate, rpm	2324 ± 249	2420 ± 244	**.003**
Total break, in	8.2 ± 3.2	7.7 ± 3.5	>.999
Break angle, deg	263 ± 5	261 ± 5	>.999
Curveball group	(n = 156)	(n = 145)	
Age, y	29.1 ± 3.7	28.5 ± 3.4	>.999
xwOBA	0.338 ± 0.039	0.337 ± 0.052	>.999
Total pitches in season	1141 ± 806	1113 ± 889	>.999
Underwent UCLR	55	46	>.999
Starting pitcher	96	92	>.999
Curveballs in season	155 ± 153	154 ± 172	>.999
Velocity, mph	78.4 ± 3.7	78.5 ± 3.4	>.999
Spin rate, rpm	2377 ± 294	2516 ± 285	**<.001**
Total break, in	11.8 ± 4.2	13.4 ± 4.6	**.018**
Break angle, deg	262 ± 4	261 ± 4	.089

[a]Data are reported as mean ± SD or No. of pitchers. Bold P values indicate statistically significant difference between groups ($P < .05$). UCLR, ulnar collateral ligament reconstruction; xwOBA, expected weighted on-base average.

percentile of movement in 2019, whereas the injured group average of 18.7 inches was in the 77th percentile in 2019.[35] In contrast to our hypothesis, 4-seam fastball velocity was not associated with increased shoulder injury.

Despite the slider break's not showing a significant difference between groups, the regression model showed increased break to be associated with injury. We evaluated for the potential of a suppressor effect, as the model showed higher spin rate being a negative predictor of injury whereas angle and movement were positive predictors. However, this was not the case, as the spin rate variable individually was lower in the injury group instead of being positively correlated independently but negatively correlated in the multivariate model. Furthermore, in a model with spin rate removed as a predictor, break and break angle remained significantly associated with injury (Appendix Table A1). Therefore, we determined that the lack of significant difference in slider break between injured and uninjured groups was likely due to the strict standard we set for significance using the Bonferroni corrections. The unconditional multivariate logistic regression applied allowed for greater precision given there was no issue of sparse data,[28] which led to significance being found in the regression models but not in univariate analysis.

Spin rate and pitch break are typically positively correlated[26]; however, the difference in injury association seen between these 2 variables may highlight the concept of gyroscopic spin or gyrospin. Spin rate is composed of 2 types of spin: transverse spin, perpendicular to the direction of motion, and gyrospin, parallel to the direction of motion. The spin rate reported by the Statcast system is the calculated Pythagorean sum of transverse spin and gyrospin.[23] The proportion of transverse spin to gyrospin a ball has is dependent on the ball's spin axis, or the angle of the ball's rotation relative to the ground. The observed movement of the ball is proportional to the magnitude and direction of transverse spin but is not related to gyrospin. A ball with perfect gyrospin is similar to a football thrown with a perfect spiral in that it will not move at all other than via the forces exerted upon it by gravity and drag. The gyroscopic spin of a spiral football pass has been found to cause what has been descripted as a gyroscopic precession: a torque

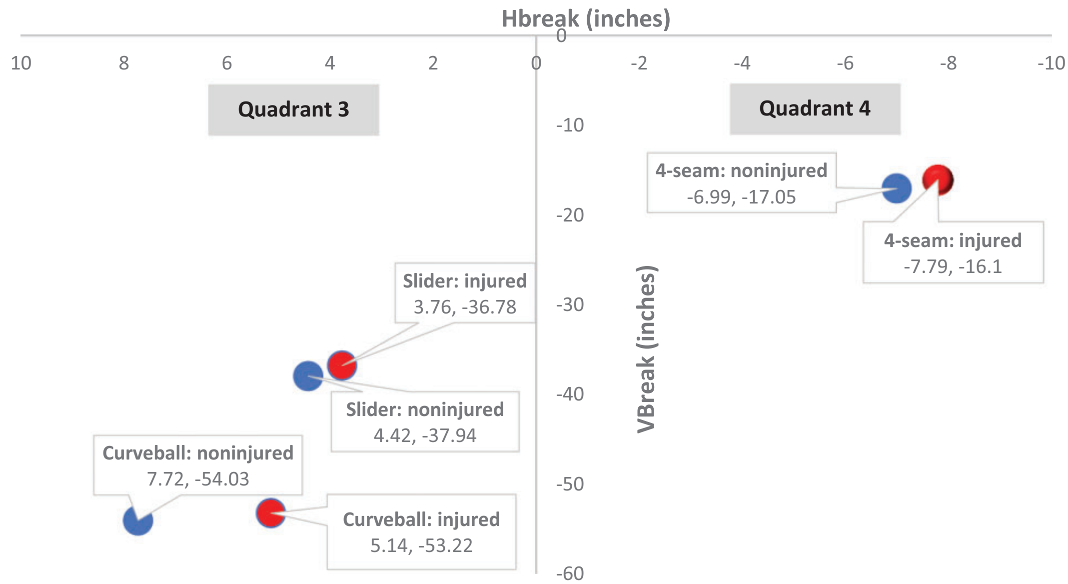

Figure 3. Pitch break plotted as reported horizontal break (HBreak) and vertical break (Vbreak). Visual interpretations of pitch break measured using Statcast differ, as overall break measured is not the Pythagorean sum of Hbreak and Vbreak but rather an analysis of how much the ball path differs from the expected path due to gravity resistance.

TABLE 4
Multiple Logistic Regression Pitch Frequency as Risk Factors for Shoulder Injury[a]

Factor	Coefficient	SE	OR (95% CI)	*P* Value, Bonferroni Adjusted
4-seam fastball frequency	–0.004	0.004	0.996 (0.987-1.004)	>.999
Slider frequency	–0.010	0.007	0.990 (0.976-1.004)	>.999
Curveball frequency	–0.006	0.010	0.994 (0.974-1.014)	>.999

[a]Descriptive variables such as age, total pitches, ulnar collateral ligament reconstruction history, expected weighted on-base average, and position were not significantly associated with shoulder injury ($P > .999$) in our model and were not reported for the purpose of clarity. OR, odds ratio.

TABLE 5
Multiple Logistic Regression Pitch Type Metrics as Risk Factors for Shoulder Injury[a]

Factor	Coefficient	SE	OR (95% CI)	*P* Value, Bonferroni Adjusted
4-seam fastball				
Velocity	–0.007	0.049	0.993 (0.902-1.093)	>.999
Spin rate	–0.002	0.000	0.998 (0.997-1.000)	.089
Total break	0.029	0.059	1.340 (1.199-1.509)	**<.001**
Break angle	–0.019	0.015	0.982 (0.953-1.011)	>.999
Slider				
Velocity	0.046	0.041	1.05 (0.967-1.134)	>.999
Spin rate	–0.002	0.000	0.998 (0.997-0.999)	**.026**
Total break	0.310	0.064	1.360 (1.206-1.554)	**<.001**
Break angle	0.156	0.045	1.170 (1.073-1.278)	**.004**
Curveball				
Velocity	–0.002	0.041	0.998 (0.917-1.074)	>.999
Spin rate	–0.001	0.000	0.999 (0.998 -1.000)	.263
Total break	–0.033	0.042	0.968 (0.886-1.043)	>.999
Break angle	0.029	0.038	1.03 (0.956-1.109)	>.999

[a]Descriptive variables such as age, total pitches, ulnar collateral ligament reconstruction, expected weighted on-base average, and position were not associated significantly with shoulder injury ($P > .999$) in our model and were not reported for the purpose of clarity. Bold *P* values indicate statistical significance ($P < .05$). OR, odds ratio.

that maintains a spin axis tangent to the direction of motion.[30] Although gyrospin does not result in movement as measured via the Statcast system, it is heavily in use in the slider.[27] The presence of gyrospin separates the movement of such pitches from pitches that rely on transverse spin.

The spin axis attained by pitched balls has been shown to be dependent on the orientation of the hand at release.[18] It is possible this fundamental difference is reflected proximally. A similar phenomenon was seen in elite cricket bowlers in which shoulder alignment had a significant effect on spin axis.[8] Our analysis expands existing knowledge regarding the increased torque exerted on the shoulder when throwing different pitch types by suggesting different pitch axes within the same pitch type exert different forces on the shoulder.[12,13] Our results suggest increased association of shoulder injury with increased transverse spin but decreased association of shoulder injury with increased gyrospin. In other words, spin exerted upon release that is more parallel to the direction of motion may put the pitcher's shoulder in a less injury-prone position.

Another potential explanation for the difference between spin and break in this study is the way break is interpreted by the Statcast system, in which gravity is included in the break measurement.[35] This means that a 4-seam fastball with a lower spin will resist gravity less than will a pitch with a higher spin rate, thereby being measured as more downward break. Our data did not support this conclusion for the 4-seam fastball, as the angle of break for the injured group exhibited a significantly less downward angle. Such an effect of lower spin rate directly leading to more break may be the case in the slider, which did exhibit a significantly more downward relative to horizontal movement in the injury group. However, the effects of a slider's resisting gravity are dependent on the release point and specific type of spin imparted on the ball by the individual pitcher and are not as uniform an expectation as with the 4-seam fastball. Although we do not know each pitcher's mechanics and delivery, the fact that increased 4-seam fastball break, increased slider break, and lower slider spin rate were significantly associated with shoulder injury suggests there is a possible common mechanical concern or physical impairment occurring among the injured group.

Our analysis helps fill a gap of risk factors for pitcher injury, as most of the literature on pitching injury risk factors has focused on risk for ulnar collateral ligament injury. With regard to what has been studied in the shoulder, a recent systematic review for risk factors of arm injury in youth baseball pitchers identified age, height, playing for multiple teams, pitch velocity, and arm fatigue.[24] This differs notably from our analysis in which age, pitches thrown, and pitch velocity were not identified as risk factors. The differences in risk factors can be attributed to different stress responses of the developing shoulder and elbow in comparison with the mature arm. Furthermore, it has been shown that kinematic measures between amateur and professional pitchers significantly differ in terms of foot placement, knee flexion, pelvis angular velocity, elbow flexion, shoulder external rotation, and trunk forward tilt.[16] In addition, there was significantly more variability in the biomechanics of youth compared with high-level pitchers.[16] Another major differentiating factor between amateur and professional pitchers is their spin axis, with professional pitchers exhibiting significantly more transverse relative to gyroscopic spin.[1,2] Not only does this finding underscore the importance of spin and pitch movement to pitching performance, but also it supports the notion that professional and amateur pitchers are significantly different populations. Therefore, a cohort of professional pitchers and a cohort of amateur pitchers would be expected to have different risk factors for injury.

Camp et al[5] analyzed range of motion measures in the shoulders of professional pitchers to identify risk factors for shoulder and elbow injury in high-level pitchers. None of the variables measured, including shoulder flexion, horizontal adduction, external rotation, internal rotation, or elbow flexion/extension were associated with risk for shoulder injury.[5] Erickson et al[11] supported these findings in MLB pitchers by investigating biomechanical factors (throwing-side carrying angle, nonthrowing-side carrying angle, and side-to-side difference in carrying angle) to identify risk factors for shoulder or elbow injury. Again, this analysis showed none of the measured variables to be predictive of shoulder injury.[11] These analyses highlight the need for further information identifying specific risk factors for shoulder injury in high-level pitchers, as the more general biomechanical measures investigated by Camp et al and Erickson et al have not shown enough sensitivity to predict injury. Our analysis adds detailed and specific metrics for individual pitch trajectories to generate a more informative model.

Spin rate, spin axis, and the resulting pitch movement are critical aspects to a pitcher's performance. These advanced metrics have recently been major focuses of performance analysis for data-driven player development for both amateurs and professionals.[26] Even upon attaining professional status, some of the MLB's top pitchers have manipulated their spin rate and spin axis to improve performance. For example, after his move to the analytics-driven Houston Astros organization, Justin Verlander appears to have made a conscious effort to not only improve his spin rate but also change his fastball spin axis to add more transverse spin relative to gyroscopic spin.[26] As a result, his career has experienced a renaissance in Houston, as he has posted the highest strikeout rates of his career in his 14th through 16th seasons. Our analysis suggests the underlying mechanical changes that allow such improved performance may also lead to increased injury risk. Verlander also showed developments in his curveball and slider in this time period. He exhibited an increased curveball spin rate (2894 vs 2803 rpm) and increased break (16.4 vs 13.8 inches) in 2018 versus 2017; both changes were not associated with increased shoulder injury in our model. Simultaneously, he increased his slider spin rate (2684 vs 2528 rpm) and decreased his slider movement (5.4 vs 7.7 inches) in 2018 versus 2017, suggesting a greater amount of gyroscopic spin. In addition, his increased spin rate and decreased break suggest he inadvertently decreased his risk of shoulder injury. Both pitch changes likely contributed to a simultaneous increase in strikeouts per 9 innings (12.20 vs 9.57),[1] allowing him to optimize his performance while aging and reducing his injury risk.

Our study carries several limitations. The specific population of MLB pitchers rendered these results not generalizable to all baseball pitchers or overhead throwing athletes. Utilizing publicly accessible data also limited the ability to specify which shoulder pathologies were being studied; therefore, shoulder injuries sustained by those in the experimental group were likely heterogeneous, as evidenced by the variety and lack of detail in the shoulder injuries listed in Table 2. Furthermore, the injury list in the MLB is primarily a roster management tool that may underestimate true injury incidence if an injured player does not reach the management threshold for IL placement. Minor League Baseball data were unavailable and would have increased our sample size. Despite these limitations, the large amount of data was able to identify shoulder injury association with advanced pitching analytics. We cannot ultimately demonstrate causality, but by identifying injury associations, players, coaches, and trainers may start to identify at-risk individuals prior to injury.

CONCLUSION

Greater pitch break with the 4-seam fastball and slider was associated with greater shoulder injury. There was a discrepancy between the incidence of shoulder injury associated with spin rate and pitch break. The increased association of injury with pitch break suggests that differences in spin axis could lead to differences in shoulder injury risk. These findings add to the understanding of throwing injury and suggest the ability to detect risk using recent advances in ball tracking technology. Future studies can prospectively examine more detailed injury reports using these pitching metrics to continue to refine the association of pitching metrics and injury.

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APPENDIX

TABLE A1
Multiple Logistic Regression Slider Metrics With Spin Rate Removed to Evaluate Potential Suppressor Effects[a]

Factor	Coefficient	SE	OR (95% CI)	*P* Value, Bonferroni Adjusted
Age	–0.028	0.035	0.972 (0.909-1.041)	>.999
xwOBA	0.604	2.76	1.829 (0.008-415.059)	>.999
Total pitches in season	0.000	0.000	1.000 (0.998-1.000)	>.999
Underwent UCLR	–0.090	0.252	0.914 (0.557-1.495)	>.999
Starting pitcher	–0.240	0.281	0.787 (0.452-1.362)	>.999
Velocity	0.022	0.039	1.022 (0.946-1.104)	>.999
Total break	0.291	0.063	1.338 (1.187-1.521)	**<.001**
Break angle	0.195	0.043	1.215 (1.119-1.326)	**<.001**

[a]Bold *P* values indicate statistical significance ($P < .05$). OR, odds ratio; UCLR, ulnar collateral ligament reconstruction; xwOBA, expected weighted on-base average.