# Advanced Analytic and Pitch-Tracking Metrics Associated with UCL Surgery in Major League Baseball Pitchers

## A Case-Control Study

Michael A. Mastroianni,* MD, Jennifer A. Kunes,* MD, Dany B. El-Najjar,* BS, Kyle K. Obana,* MD, Sohil S. Desai,* MD, Cole R. Morrissette,* MD, Frank J. Alexander,* MS, ATC, Alexander J. Rondon,* MD, David P. Trofa,* MD, Charles A. Popkin,* MD, William N. Levine,* MD, and Christopher S. Ahmad,*† MD
*Investigation performed at Columbia University Irving Medical Center/NewYork Presbyterian Hospital, New York, New York, USA*

**Background:** Ulnar collateral ligament (UCL) injury rates have been rising steadily, while the recent development of advanced analytics and pitch-tracking analysis now drives player development and evaluation throughout Major League Baseball (MLB).

**Purpose:** To evaluate the association between several advanced analytic and pitch-tracking metrics on UCL surgery rates in MLB pitchers.

**Study Design:** Case-control study.

**Methods:** Included in this study were MLB pitchers who underwent primary UCL reconstruction or repair from April 2018 to November 2023. Exclusion criteria were pitchers without 2 qualifying seasons of preoperative pitch-tracking data and those who previously underwent UCL surgery. Uninjured matched controls were identified in a 2:1 ratio using season, age, position, handedness, and pitch count as covariates. Advanced analytics (eg, FanGraphs wins above replacement [fWAR], expected fielding-independent pitching [xFIP], physical pitch qualities [Stuff+] strike-zone command [Location+], and overall pitching ability [Pitching+]) and various pitch-tracking metrics used commonly in MLB player evaluation were collected from public web sources sponsored by MLB and used in previous studies. Statistical analysis consisted of unpaired *t* tests comparing cases and controls and binary logistic regression.

**Results:** A total of 117 MLB pitchers who underwent primary UCL reconstruction or repair were compared with 234 matched controls. Cases had significantly superior pitch velocity, fWAR, xFIP, Pitching+, and Location+ compared with controls. There was no significant difference between cases and controls in pitch counts, spin, release points, release extension, approach angles, or overall pitch movement. Binary logistic regression identified velocity, Pitching+, and decreased fastball usage as being associated with UCL surgery ($P < .10$ for all).

**Conclusion:** In this analysis of several modern advanced analytic and pitch-tracking metrics, MLB pitchers who underwent UCL surgery threw harder with less fastball usage, and had superior overall pitching ability (Pitching+) and strike-zone command (Location+) than matched controls.

**Keywords:** advanced analytics; Major League Baseball; medial ulnar collateral ligament injury; thrower's elbow; Tommy John surgery; UCL; ulnar collateral ligament; ulnar collateral ligament repair

Ulnar collateral ligament (UCL) injury rates have been rising steadily over the past decade, while the recent development of advanced analytics and pitch-tracking analysis has been widely embraced throughout Major League

The Orthopaedic Journal of Sports Medicine, 13(2), 23259671241302432
DOI: 10.1177/23259671241302432

Baseball (MLB). These new metrics now drive player development and personnel decisions throughout MLB. Since 2014, the league has used high-resolution cameras installed in every stadium to enable detailed pitch-tracking, which has led to the development of new advanced analytics to evaluate player performance compared with more traditional baseball statistics.[2,23] In baseball, with a structured rookie contract and salary arbitration years before reaching free agency, teams can save hundreds of millions of dollars developing a star pitcher rather than signing an established free agent. For players, any improvement in their advanced metrics can increase the value of their next contract, underscoring the importance of player development in MLB.

Nearly every competitive level from youth to professional leagues has seen a rise in UCL injuries.[17,27,33,35] Despite the enormous financial implications,[23] the risk of various pitch-tracking and advanced analytic metrics used widely throughout MLB to drive improvement have been minimally studied. The vast majority of studies have looked only at traditional measures such as velocity, pitch-type usage, and pitcher demographics. Pitch count, overall workload, and age are also all known risk factors for injury.[5,7,19,35] One study found increased risk with a lateralized release point,[10] but analysis of popular advanced analytic and pitch-tracking data is largely missing in MLB.

Pitch-tracking measures such as mean and pitch-specific spin rate, horizontal and vertical movement, approach angle, release point, and release extension have not been evaluated, despite being publicly available since 2014. Advanced analytics such as wins above replacement (WAR), expected fielding-independent pitching (xFIP), and Skill-interactive Earned Run Average (SIERA) have been studied only in regards to surgical outcomes.[30] New pitch-tracking measures and advanced analytics developed in 2020 that measure active spin, spin axis, overall pitch quality (Stuff+), command of the strike zone (Location+), and overall ability (Pitching+) have also not been studied as risk factors for UCL injury.[29] These newly created metrics have shown to be more predictive of future success than traditional statistics, and are thus are widely valued throughout MLB.[21] LaPrade et al[20] presented an overview of the state of advanced data now available in MLB and highlighted the need for further studies to focus on using these more objective data to evaluate risk factors for injury and postoperative surgical outcomes.

The primary objective of this study was to evaluate the association of modern advanced analytic and pitch-tracking metrics in MLB pitchers who underwent UCL surgery compared with matched controls. Our secondary objective was to analyze the association of large changes in these values during the seasons before surgery in cases versus matched controls, providing insight into how rapid improvement may influence UCL surgery rates. Ultimately, we hope this study better informs players and teams on safe player development protocols.

## METHODS

### Study Design

Our study was deemed exempt from institutional review board approval, as human patients at our institution were not involved. Using entirely public data, we conducted a retrospective analysis on all MLB pitchers who underwent primary UCL reconstruction (UCLR) or UCL repair from April 2018 to November 2023. Excluded were pitchers without 2 qualifying seasons (ie >100 pitches in a calendar year) of preoperative data, and those who had previously undergone a surgery on their UCL.

A total of 125 MLB pitchers were identified with UCL injuries requiring UCLR or UCL primary repair from April 2018 to November 2023 using the Tommy John Surgery List public database,[29] and cross-referenced with the MLB Reports public database,[25] which has been used previously in other studies and cross-referenced with official press releases.[10,27] Of these pitchers, 8 cases were excluded based on the study criteria. This resulted in 117 MLB pitchers who underwent UCL surgery being included for analysis. Due to power limitations, we did not require 2 qualifying seasons of preoperative data for Stuff+, Location+, and Pitching+, which have been available only since 2020. This resulted in 57 cases and 97 controls being included in the analysis of these 3 variables for the season before surgery, and 72 cases versus 135 controls being included in the analysis of these variables for the index season of surgery. To qualify as an MLB pitcher, players must have had at least 10 innings pitched in MLB during the index season or the year before surgery.

The websites Baseball Savant and Brooks Baseball were used to obtain pitch-tracking data obtained through high-resolution camera systems implemented by MLB.[2,4] These systems are able to measure ball speed, spin, release point, and movement in multiple directions for each pitch in a player's repertoire. The PITCHf/x camera system was used by MLB in all stadiums between 2007 and 2016, while TrackMan has been used since 2017, with the addition of the Hawk-Eye system in 2020. Now, nearly 100% of batted balls

---

†Address correspondence to Christopher S. Ahmad, MD, Columbia University Irving Medical Center/New York Presbyterian Hospital, 622 W 168th Street, PH-11, Room 1118, New York, NY 10032, USA (email: csa4@cumc.columbia.edu) (Twitter/X: @drchrisahmad).

*Columbia University Irving Medical Center/New York Presbyterian Hospital, New York, New York, USA.

Final revision submitted August 9, 2024; accepted September 5, 2024.

One or more of the authors has declared the following potential conflict of interest or source of funding: A.J.R. has received education payments from Arthrex and hospitality payments from Stryker. D.P.T. has received education payments from Arthrex and Smith & Nephew. W.N.L. has received education payments from Arthrex, consulting fees from DePuy/Medical Device Business Services and Zimmer Biomet, and royalties from Zimmer Biomet. C.S.A. has received consulting fees, nonconsulting fees, and royalties from Arthrex. AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.

Ethical approval for this study was waived by Columbia University Medical Center (reference No. AAAU6050(M00Y01)).

TABLE 1
Commonly Used Advanced Analytics in Major League Baseball[a]

| Term | Definition |
|---|---|
| fWAR | fWAR is a qualitative and quantitative metric that measures a player's value in all facets of the game by comparing how many more "wins" he is worth to a team than a replacement-level player, who is a readily available minor leaguer or a free agent. Using statistics from 2022, previous reports have valued 1 WAR to be equivalent to nearly US$7 million in payroll value for pitchers, with an even greater value per WAR as a player exceeds over 2 WAR in a season.[9,24] This metric is affected by the amount played and is named after the developing organization. |
| xFIP and SIERA | Rate-based metrics that aim to measure what a pitcher's earned run average (ERA) would be after standardizing for the strength of defense, ballpark factors, and other possible confounding variables. Not affected by amount played. |
| Stuff+[b] | Stuff+ evaluates the physical qualities of a pitch, including velocity, vertical and horizontal movement, approach angle, and release extension. The most effective pitchers in MLB tend to grade high in Stuff+.[13] |
| Location+[b] | Location+ is a count- and pitch type–adjusted judge of a pitcher's ability to throw pitchers in his desired location, better known as command. Location+ looks at average locations of a specific pitch on a specific pitch count and assumes the pitcher's intent is generally the same across the league. Command is critical for success and is often what distinguishes between the elite pitchers. It is currently unknown whether command is associated with UCL injury. |
| Pitching+[b] | Pitching+ uses the physical qualities (Stuff+), command (Location+), batter handedness, stadium, and count of each pitch thrown to judge overall pitching ability. Pitching+ also captures the impact of pitch sequencing to set up and confuse hitters for future pitches (eg, changing eye levels by throwing a high fastball followed by a low-and-outside slider). Therefore, Pitching+ may also capture the mental process and execution of a pitcher that are otherwise difficult to evaluate, and it has shown to be a strong predictor of future success.[3] |

[a]fWAR, FanGraphs wins above replacement; MLB, Major League Baseball; SIERA, skill-interactive earned run average; UCL, ulnar collateral ligament; xFIP, expected fielding-independent pitching.
[b]For Stuff+, Pitching+, and Location+, a score of 100 represents the approximate league average.

can be tracked, along with more detailed information such as body positioning and pitch spin. Various teams, along with public and private sources, use these new data to drive player development and evaluation. The data from these camera systems are compiled by MLB through its Statcast database and released to the public.[1-3,12,29]

## Data Collection

Player data, including age, height/weight, body mass index, handedness, type of pitcher (starting or relief), draft position, and pitch count were collected from well-regarded public websites such as FanGraphs and Baseball-Reference.com.[3,13] Data regarding advanced analytics were also recorded, including FanGraphs WAR (fWAR), xFIP, SIERA, Stuff+, Pitching+, and Location+. Definitions of these terms are available in Table 1. Data on Stuff+, Pitching+, and Location+ began to be recorded in 2020 and are available on FanGraphs.[13] For these metrics, a score of 100 represents the approximate league average relative to other similar pitches.[29]

Yearly mean velocity, spin rate, active spin, spin axis, horizontal and vertical movement, approach angle, release point, and release extension were obtained via a public database extracted from Baseball Savant from April 2018 to November 2023.[7] Spin rate measures revolutions of the baseball per minute; however, not all spin contributes to pitch movement. For example, a pitch that is thrown with pure topspin or backspin will have 100% of its spin contribute to movement, whereas a football is thrown primarily with gyroscopic spin which contributes minimally to movement.[14] Active spin thus measures the percentage of spin that contributes to movement, while spin axis measures a baseball's axis of rotation or direction of spin in 3 dimensions (Figure 1). Spin axis is often described in terms of a clockface (ie, 5 o'clock), which we converted into degrees to facilitate statistical analysis.

Horizontal movement and release point are tracked from the catcher's point of view. This means that a right-handed pitcher's horizontal release point will be towards third base, representing a negative value while a left-handed pitcher's horizontal release point will be towards first base, representing a positive value. Horizontal movement can be either positive or negative as different pitches can move towards or away the batter. Vertical approach angle (VAA) captures the angle at which a pitch crosses home plate vertically, while horizontal approach angle (HAA) captures the same horizontally and can be a positive or a negative value despite handedness (albeit right-handed people usually negative, vice-versa for left-handed people). These approach angles are a function of the pitch's release point (starting location), final location, and its velocity and acceleration that determine the pitch's movement through space. Since release point can be altered by a pitcher's position on the mound relative to home plate, HAA above average (HAA-AA) and VAA above average (VAA-AA) normalize for location, handedness, and release point for each pitch type. These values are centered on zero, with "minus" values indicating sharper angles towards right-handed batters and "plus" values indicating

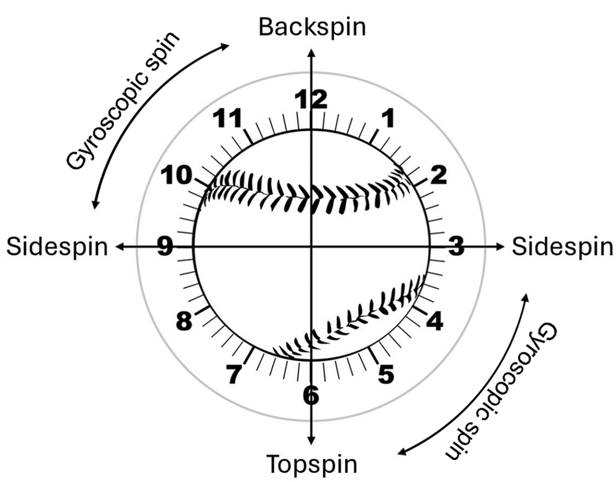


**Figure 1.** Spin pitch-tracking data. The spin axis is described using a clockface, with the direction of spin in 3 dimensions: sidespin, creating horizontal ball movement; topspin or backspin, creating vertical movement; and gyroscopic spin (like a football), which creates minimal movement.[14] For statistical analysis, spin axis was converted into degrees.

sharper angles towards left-handed batters.[8] Release extension quantifies exactly how much closer a pitcher's release point is to home plate; a pitcher with a longer release extension shortens the distance between them and the batter, leading to an increased perceived velocity of the pitch (Figure 2).[1]

The date of surgery was used as the index date for data collection; the calendar year immediately before surgery with a pitch count of >100 pitches was represented as T1, the year before that was represented as T2, and the year before that was represented as T3. Pitchers who started in ≥50% of games for the T1 season were designated as starting pitchers. Pitchers who started in <50% of games in the season before UCL surgery were identified as relief pitchers.

## Control Group

A cohort matched 2:1 by season, age, position, handedness, and pitch count was selected randomly as a control, which is similar to previous studies to control for known risk factors of UCL injury.[10,27,28] Controls were selected first by index year of surgery as the matched pitcher in the UCL surgery cohort. Next, pitching position (starting or relief) and handedness, followed by age and the most comparable number of pitches in the index season were used to generate our matched control group after randomly selecting eligible controls. For pitchers who were hurt in the offseason, data from the year immediately before the injury with >100 total pitches thrown was used, similar to previous studies.[10,27] Any pitcher with a previous UCLR, UCL primary repair, or UCL-related platelet-rich plasma injection was excluded. Descriptive and pitch-tracking data for the control pitchers were collected in the same way as for the UCL surgery cohort.

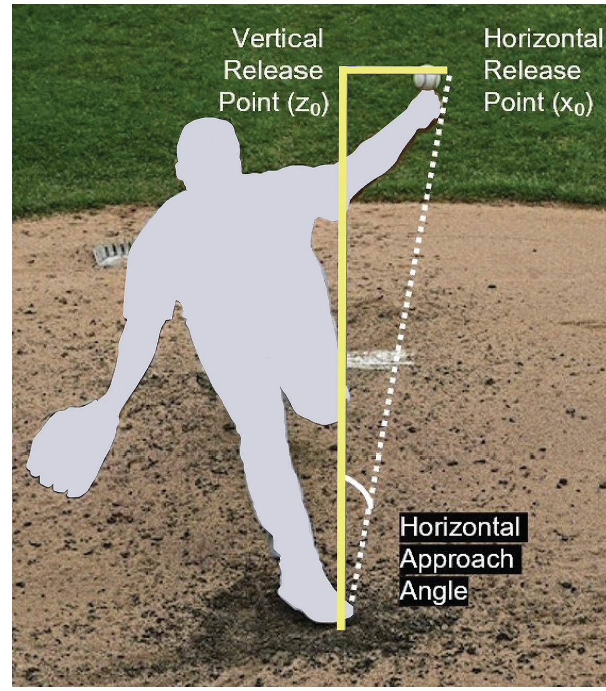


**Figure 2.** Release point, approach angle, and movement pitch-tracking data. These metrics are measured from the catcher's point of view. Horizontal and vertical release point are measured as the distance between the point in which a pitcher releases the ball relative to home plate. Horizontal and vertical movement are the amount a pitch moves from the time a pitcher releases the ball to the moment it crosses home plate. Horizontal approach angle describes the angle from which a pitcher releases the ball to when it crosses home plate horizontally, while vertical approach angle captures the same information vertically. Release extension quantifies how close a pitcher's release point is to home plate.

## Statistical Analysis

Unpaired *t* tests were used to compare continuous variables between the cases and controls, while chi-square tests were used to compare categorical variables. Changes in the 2 or 3 seasons before surgery were also analyzed to see whether large season-to-season changes were independent risk factors for UCL surgery. Binary logistic regression for UCL surgery was conducted to help eliminate confounders and included key pitch-tracking metrics; author judgment was used to exclude certain variables related to each other (eg, Pitching+ is influenced heavily by Stuff+ and Location+). Adjusted odds ratios (aOR) with associated 95% confidence intervals (CIs) were calculated for each variable in the logistic regression. Horizontal movement, release point, HAA, and HAA-AA were all normalized for pitcher handedness,[10,27] similar to previous studies. Although

TABLE 2
Characteristics of the Cases and 2:1 Matched Controls[a]

| | Cases (n = 117) | Controls (n = 234) | P |
|---|---|---|---|
| Age, y | 27.6 ± 3.1 | 28.3 ± 3.3 | .12 |
| Height, cm | 190.1 ± 5.9 | 188.8 ± 5.0 | .98 |
| Weight, kg | 97.0 ± 6.1 | 98.2 ± 11.5 | .18 |
| Right-handed | 73.0 | 73.0 | .99 |
| Starting pitcher | 44.3 | 44.3 | .99 |
| Draft position | 281.8 ± 322.3 | 264.5 ± 270.2 | .69 |
| International free agent[b] | 19.1 | 16.1 | **.03** |
| Innings pitched during T1 | 67.8 ± 57.1 | 57.5 ± 51.7 | .10 |
| Pitch count during T1 | 1064.9 ± 905.7 | 960.0 ± 847.4 | .16 |

[a]Data are presented as mean ± SD or percentage of pitchers. Boldface *P* value indicates statistically significant difference between groups ($P < .05$). T1, season before index season of surgery. MLB, Major Baseball League.

[b]Signed as an amateur international free agent rather than acquired via the MLB draft.

horizontal movement can be positive or negative, we used absolute values instead of relative values given that positive or negative horizontal movement is determined by batter and pitcher handedness, which would confound our analyses. Given that VAA-AA is not affected by handedness, positive or negative values were included. All data analysis was performed using R statistical software (The R Project for Statistical Computing), Excel for Mac (Microsoft Corp), and SPSS Version 26 (IBM Corp). Statistical significance was set at $P < .05$ for *t* tests and $P < .10$ for logistic regression.

## RESULTS

The 117 MLB pitchers who underwent primary UCLR or UCL repair were compared with 234 matched controls. The mean age was 27.4 ± 3.1 years for the cases and 28.3 ± 3.3 years for the controls, with 72.8% being right-handed and 44.8% being starting pitchers. There were no differences in pitch counts or innings pitched during T1 between cases and controls (*P* = .16 and .10, respectively) (Table 2).

During both the T1 and/or index season, cases had significantly superior velocity, fWAR, xFIP, SIERA, Pitching+, and Location+ compared with controls (Tables 3 and 4). There were no differences in spin, release points, approach angles, movement, or release extension (Table 4).

Statistically significant increases in Pitching+ in the 2 seasons before surgery were seen in cases compared with controls (*P* = .02) (Table 5). Binary logistic regression analysis identified velocity (aOR = 1.20 [95% CI, 1.01-1.42]), Location++ (aOR = 1.11 [95% CI, 1.02-1.20]), and decreased fastball usage (aOR = 0.07 [95% CI, 0.005-0.97]) as being significantly associated with increased risk of UCL surgery ($P < .10$ for all) (Table 6).

## DISCUSSION

Overall, we found that MLB pitchers who underwent UCL surgery threw harder with less fastball usage, and had superior overall pitching ability (Pitching+) and strike-zone command (Location+) than matched controls. Superior performance-based metrics such as fWAR and xFIP were also seen in cases compared with controls, while there was no difference in pitch counts, spin, release points, approach angles, release extension, or overall pitch movement between the groups. In this analysis, several modern advanced analytic and pitch-tracking metrics used widely throughout MLB to drive player evaluation and development were examined as potential risk factors for UCL surgery. Although the clinical significance of these metrics still needs to be determined, teams and players should consider these findings to develop safer player development protocols.

Recently, LaPrade et al[20] highlighted the need to incorporate advanced technology and pitch tracking used throughout MLB into injury and return to play analyses. To date, most studies on MLB pitchers have focused primarily more on traditional descriptive statistics (such as wins, innings pitched, return to competition level) or rate-based performance statistics with inherent variability (such as ERA or walks and hits per inning pitched [WHIP]).[11,22,30,32,34] xFIP and SIERA are regarded as more predictive than FIP, ERA, or WHIP as they are not confounded by factors such as fielder positioning and stadium size. Without the abundance of pitch-tracking data now publicly available, previous studies have focused primarily on variables such as velocity, pitch count, and pitch type/usage. Prodromo et al[27] found that increased pitch velocity increased risk of UCL injury, while others found that increased fastball or curveball usage were risk factors for injury or arm pain.[2,3,5 -7,11,15,19,29,31] In the current study, we found that increased velocity and less fastball usage were the strongest factors associated with UCL surgery. For every 1 mile per hour increase in velocity, the odds of undergoing UCL surgery were nearly 20% increased. Together, these findings could imply that the trend of increasing velocity in off-speed pitches throughout the league could be contributing significantly to the rise of UCL surgeries. There were no other differences in pitch distribution in our study, and future pitch-specific studies should investigate whether increased velocity in historically slower pitches such as sliders, curveballs, changeups, and sinkers are associated with injury.

Increasing spin rate has been a major goal for player development in recent years,[16,25] with increased spin leading to enhanced perceived velocity, differing ball trajectories, and worse hitting performance.[21,26] Mayo et al[21] is the only known study to examine the impact of spin rate on injury, finding small differences in spin rates of fastballs and cutters in the 15 games before injury. No study has analyzed the effect of season-to-season spin rate on UCL injury rates, along with both active spin and spin axis, which were developed recently with the addition of the Hawk-Eye camera system in 2020. Active spin

TABLE 3
Comparison of Preinjury Advanced Analytics for Pitchers Who Underwent UCL Surgery Versus Matched Controls[a]

| | Season Before Surgery (T1) | | | Season of Surgery | | |
|---|---|---|---|---|---|---|
| Variable | UCL Surgery (n = 117) | Control (n = 234) | *P* | UCL Surgery (n = 117) | Control (n = 234) | *P* |
| fWAR | 0.97 ± 1.38 | 0.67 ± 1.05 | **.04** | 0.54 ± 1.02 | 0.47 ± 1.00 | .56 |
| xFIP | 4.11 ± 0.88 | 4.49 ± 1.13 | **<.01** | 4.35 ± 1.02 | 4.59 ± 0.98 | **.04** |
| SIERA | 3.96 ± 0.90 | 4.23 ± 1.01 | **.01** | 4.17 ± 0.99 | 4.33 ± 1.01 | **.01** |
| Stuff+[b] | 105.34 ± 19.68 | 101.78 ± 12.80 | .23 | 102.14 ± 14.76 | 99.19 ± 18.34 | .21 |
| Pitching+[b] | 102.05 ± 5.87 | 98.95 ± 6.23 | **<.01** | 100.10 ± 5.75 | 97.46 ± 13.18 | **.04** |
| Location+[b] | 100.69 ± 4.53 | 98.40 ± 6.36 | **.01** | 99.06 ± 5.12 | 97.06 ± 12.72 | **.01** |

[a]Data are presented as mean ± SD. Boldface *P* values indicate statistically significant difference between groups ($P < .05$). fWAR, FanGraphs wins above replacement; SIERA, skill-interactive earned run average; UCL, ulnar collateral ligament; xFIP, expected fielding-independent pitching; UCL, ulnar collateral ligament. See Table 1 for definitions of advanced analytics terms.

[b]Due to power limitations, we did not require 2 qualifying seasons of preoperative data for Stuff+, Location+, and Pitching+, which have been available only since 2020. This resulted in 57 cases and 97 controls being included in the analysis of these variables for the season before surgery, and 72 cases versus 135 controls being included in the analysis of these variables for the index season of surgery.

TABLE 4
Comparison of Preinjury Pitch-Tracking Data for Pitchers Who Underwent UCL Surgery Versus Matched Controls[a]

| | Season Before Surgery (T1) | | | Season of Surgery | | |
|---|---|---|---|---|---|---|
| Variable | UCL Surgery (n = 117) | Control (n = 234) | *P* | UCL Surgery (n = 117) | Control (n = 234) | *P* |
| Velocity, mph (kph) | 89.90 ± 3.02 (144.68 ± 4.86) | 89.07 ± 2.57 (143.34 ± 4.14) | **.01** | 89.58 ± 3.07 (144.17 ± 4.94) | 88.70 ± 2.66 (142.74 ± 4.28) | **.01** |
| Spin rate, RPM | 2254.68 ± 196.95 | 2242.16 ± 178.35 | .58 | 2248.12 ± 197.70 | 2238.58 ± 192.51 | .68 |
| Active spin, % | 76 ± 10 | 76 ± 10 | .92 | 76 ± 11 | 73 ± 12 | .08 |
| Spin axis, deg | 218.10 ± 81.48 | 212.21 ± 90.80 | .64 | 209.83 ± 77.83 | 211.34 ± 77.27 | .88 |
| Horizontal movement, inch (cm) | 5.34 ± 3.12 (13.56 ± 7.92) | 5.25 ± 3.29 (13.34 ± 8.36) | .81 | 5.54 ± 3.22 (14.07 ± 8.18) | 5.18 ± 3.24 (13.16 ± 8.23) | .35 |
| Vertical movement, inch (cm) | 8.20 ± 3.35 (20.83 ± 8.51) | 8.22 ± 3.23 (20.88 ± 8.20) | .97 | 7.97 ± 3.39 (20.24 ± 8.61) | 7.61 ± 3.37 (19.33 ± 8.56) | .35 |
| Horizontal release point, feet (m) | -1.87 ± 0.73 (-0.57 ± 0.22) | -1.91 ± 0.72 (-0.58 ± 0.22) | .62 | -1.88 ± 0.71 (-0.57 ± 0.20) | -1.87 ± 0.74 (-0.57 ± 0.22) | .89 |
| Vertical release point, feet (m) | 5.90 ± 0.50 (1.80 ± 0.15) | 5.86 ± 0.57 (1.79 ± 0.17) | .51 | 5.88 ± 0.49 (1.79 ± 0.15) | 5.84 ± 0.59 (1.78 ± 0.18) | .47 |
| HAA, deg | -0.88 ± 1.63 | -1.11 ± 1.52 | .22 | -0.31 ± 1.83 | -0.47 ± 1.80 | .45 |
| HAA above average, deg | -0.51 ± 1.51 | -0.49 ± 1.19 | .90 | -0.18 ± 1.09 | -0.24 ± 1.09 | .61 |
| VAA, deg | -6.48 ± 0.65 | -6.52 ± 0.67 | .53 | -6.52 ± 0.65 | -6.61 ± 0.73 | .27 |
| VAA above average, deg | -2.49 ± 3.38 | -1.91 ± 3.14 | .13 | -1.06 ± 2.54 | -1.06 ± 2.58 | .99 |
| Release extension, feet (m) | 6.16 ± 0.41 (1.88 ± 0.12) | 6.16 ± 0.41 (1.88 ± 0.12) | .66 | 6.21 ± 0.46 (1.89 ± 0.14) | 6.22 ± 0.41 (1.90 ± 0.12) | .79 |

[a]Data are presented as mean ± SD. Horizontal metrics were normalized for right-handers, yielding negative values. Boldface *P* values indicate statistically significant difference between groups ($P < .05$). HAA, horizontal approach angle; RPM, revolutions per minute; UCL, ulnar collateral ligament; VAA, vertical approach angle.

influences horizontal movement and has been theorized to help explain why quarterbacks face less risk to their UCL than pitchers, who have more valgus stress on their elbow.[15,36] A popular player development trend is encouraging "opposite" pitches being released on the same spin axis, such as pure back spin on a fastball and pure front spin on a curveball. In our analysis, there were no differences in spin rate, active spin, or spin axis between the UCL surgery and control groups. Although many players and executives have cited the increased emphasis on maximizing spin throughout baseball as a likely contributing factor to injuries, our data suggest that it may not be the case.

Previous pitch-tracking studies have also theorized that a sidearm delivery may predispose to UCL injury.[1] Whiteside et al[35] and Cohen et al[10] previously utilized PITCHf/x pitch-tracking data to examine the impact of release point on UCL injury risk, with the MLB replacing PITCHf/x with TrackMan cameras in 2017, which enabled the recording of additional metrics. We normalized to right-

TABLE 5
Changes in Advanced Analytic and Pitch-Tracking Metrics in the Seasons Before UCL Surgery[a]

| Variable | Δ(T1 – T3) | *P* | Variable | Δ(T1 – T3) | *P* |
|---|---|---|---|---|---|
| Pitch count | | .34 | HAA, deg | | .53 |
| UCL surgery | -104.12 ± 768.11 | | UCL surgery | 0.13 ± 0.49 | |
| Control | -260.75 ± 756.63 | | Control | 0.05 ± 0.58 | |
| Velocity, mph (kph) | | .95 | HAA above average, deg | | .59 |
| UCL surgery | -0.58 ± 1.78 (-0.93 ± 2.86) | | UCL surgery | 0.13 ± 0.53 | |
| Control | -0.61 ± 2.06 (-0.98 ± 3.32) | | Control | 0.07 ± 0.55 | |
| Spin rate, RPM | | .98 | VAA, deg | | .64 |
| UCL surgery | 0.54 ± 1.25 | | UCL surgery | -0.09 ± 0.44 | |
| Control | -0.13 ± 1.46 | | Control | -0.14 ± 0.40 | |
| Active spin, % | | .09 | VAA above average, deg | | .35 |
| UCL surgery | 10 ± 0.14 | | UCL surgery | -0.16 ± 0.33 | |
| Control | -8 ± 0.17 | | Control | -0.09 ± 0.35 | |
| Spin axis, deg | | .45 | Release extension, feet (m) | | .84 |
| UCL surgery | -15.45 ± 19.90 | | UCL surgery | 0.18 ± 0.23 (0.05 ± 0.07) | |
| Control | -18.08 ± 21.35 | | Control | 0.17 ± 0.27 (0.05 ± 0.08) | |
| Horizontal release point, feet (m) | | .54 | Stuff+[b] | | .08 |
| UCL surgery | 0.16 ± 0.49 (0.05 ± 0.15) | | UCL surgery | 7.82 ± 16.79 | |
| Control | 0.10 ± 0.47 (0.03 ± 0.14) | | Control | 1.80 ± 8.86 | |
| Vertical release point, feet (m) | | .57 | Location+[b] | | .10 |
| UCL surgery | 0.00 ± 0.14 (0.00 ± 0.04) | | UCL surgery | 2.47 ± 5.54 | |
| Control | 0.03 ± 0.19 (0.01 ± 0.06) | | Control | -0.49 ± 6.46 | |
| | | | Pitching+[b] | | **.02** |
| | | | UCL surgery | 4.59 ± 7.40 | |
| | | | Control | -0.46 ± 7.13 | |

[a]Data are presented as mean ± SD. *P* values were calculated via unpaired *t* test of the overall change between the UCL surgery and control cohorts for each variable; boldface *P* value indicate statistically significant difference between groups ($P < .05$). RPM, revolutions per minute; T1, season immediately before season of surgery; T2, season immediately before T1; T3, season immediately before T2; UCL, ulnar collateral ligament.

[b]For Stuff+, Location+, and Pitching+ Δ(T1 - T2) was used for analysis given these statistics have been available only since 2020.

handed people yielding negative values, similarly to Cohen et al[10] and Portney et al[27], who found a more horizontal release point to be a risk factor for injury, whereas Whiteside et al[35] found a more horizontal release point to be protective of injury. In our analysis, horizontal release point was not found to be associated with UCL surgery. Given that a pitcher can vary their horizontal release point and approach angle simply by shifting their starting position on the mound, the clinical significance of these metrics is unclear. It is also unknown how common pitchers alternate their stance on the mound, but HAA-AA normalizes for these potential confounders and gives insight into the approach angle of the pitch secondary to the pitcher's mechanics.[8] In our analysis, neither HAA nor HAA-AA were associated with UCL surgery, which, to our knowledge, has not been analyzed previously.

Vertical release point and approach angle were also investigated. Unlike HAA, vertical release point and VAA

TABLE 6
Association of Pitch-Tracking Metrics with UCL Surgery[a]

| Variable | Coefficient | *P* | aOR (95% CI) |
|---|---|---|---|
| Velocity | 0.18 | **.03** | 1.20 (1.01-1.42) |
| Pitch count | <0.001 | .29 | 1.26 (1.00-1.001) |
| Spin rate | 0.001 | .37 | 1.00 (1.00-1.003) |
| Location+ | 0.10 | **.02** | 1.11 (1.02-1.20) |
| Stuff+ | -0.004 | .77 | 1.00 (0.97-1.03) |
| Fastball usage | -2.62 | **.05** | 0.07 (0.005-0.97) |

[a]Binary logistic regression of key pitch-tracking variables; author judgment was used to exclude certain variables related to each other (i.e., Stuff+ and Location+ are both related to Pitching+). Boldface *P* values indicate statistical significance ($P < .10$). aOR, adjusted OR; CI, confidence interval; HAA, horizontal approach angle above average; ns, not significant; OR, odds ratio; UCL; ulnar collateral ligament.

cannot be altered easily without dramatically changing pitching mechanics (and all the pitch characteristics that result from them). While VAA and VAA-AA were not associated with UCL surgery, higher vertical release points were found to be associated in our study. Consistent with previous studies from Portney et al[27] and Whiteside et al,[35] we found no difference in vertical release location between cases and controls. Both studies analyzed public data before 2017, which required calculating release point by extracting coordinates from the previously used PITCHf/x cameras, adding an extra step for potential error in analysis. After 2017, MLB switched from PITCHf/x to TrackMan cameras, which are higher resolution and no longer require calculation of release point from coordinates. The majority of our release point data comes from after 2017 and thus use these higher-resolution cameras sponsored by MLB, making our release point data more technologically up to date with current MLB-sponsored pitch-tracking data. Furthermore, neither VAA or VAA-AA were found to be associated with injury, which, to our knowledge, has also not been characterized in regards to injury risk.

In addition, no known study has analyzed the effect of pitch movement or release extension on UCL injuries. In modern baseball, teams and pitchers are constantly tweaking grips, release points, spin rates, and pitch velocities to influence both vertical and horizontal movement. While influenced by all of these factors, in our study we found that neither vertical or horizontal pitch movement was linked to surgery, which is reassuring that certain movement profiles themselves are not associated. Release extension is a measure of how close a pitcher is to the batter when he releases the ball and may be a surrogate of a number of factors including stride length, arm extension, and release point; there was also no difference found between cases and controls in our study. Altogether, more detailed biomechanical analysis of elbow and shoulder range of motion using the already installed TrackMan and Hawk-Eye cameras in every stadium is warranted and could be valuable for future performance and injury risk analysis.

In addition, novel advanced analytics developed in 2020 such as Stuff+, Location+, and Pitching+ were analyzed as risk factors for UCL surgery. These metrics have shown to be the most predictive of future success for MLB pitchers and thus are used widely for player evaluation,[22] but have not yet been analyzed in regards to injury risk. Stuff+ is a surrogate for overall pitch movement, velocity, and other physical pitch characteristics. The most effective pitchers in MLB tend to grade high in Stuff+.[13] In our analysis, there was no significant differences in Stuff+ between cases and controls, although mean Stuff+ was higher in cases. Command (Location+) is also critical for success and is often what distinguishes elite pitchers, but, despite this, there have been no known reports investigating whether pitchers who can command the baseball more effectively are at increased risk for UCL injury. Pitching+ uses the physical characteristics (Stuff+), command (Location+), as well as game situations and other factors to judge overall pitching ability. To our knowledge, no study has investigated these factors in association with UCL injury or surgery. Overall, we found that superior strike-zone command (Location+) and pitching ability (Pitching+) were associated with UCL surgery. Although it is unclear how command could influence injury, increased strain and effort associated with improved accuracy could theoretically increase the risk of injury. Pitching+ is also a surrogate for overall pitching ability and takes into account many advanced analytic and pitch-tracking variables,[21] and may reflect how incremental improvement in multiple metrics may have an additive effect on injury risk.

Finally, our secondary objective was to analyze whether large season-to-season changes in advanced analytic or pitch-tracking metrics were associated with UCL surgery. The significant financial stakes of performing in MLB has put increased pressure on player development, without fully understanding the potential risk of injury with rapid improvement. Weighted ball programs are used frequently to gain velocity, despite many pitchers attributing injuries to the regimen and some evidence of increased injury risk.[1] Training facilities equipped with high-resolution cameras and biomechanical sensors that enable pitchers to experiment with different pitches, release points, grips and more are now commonplace. Pitchers can more commonly make significant improvements in just 1 offseason, but the potential injury risk of this improvement and increased stress on a pitcher's elbow is unknown. In our cohort, large yearly increases in Pitching+ were statistically significant in our *t* test analysis. Future research aimed to identify safe "thresholds" for improvement is key to preserve player health while also maximizing their career aspirations.

## Limitations

This study is not without limitations. Although statistical significance was obtained for some metrics, the clinical significance of our findings is unknown and should be a focus of future research. The results of individual *t* tests should be interpreted cautiously given the large number of variables in this analysis, although our logistic regression results accounted for testing multiple variables at once. So as not to dilute or confound the findings of our logistic regression, we tried to avoid variables that were closely related to each other and included only key pitch-tracking metrics. For several of these metrics, no previous investigations have examined the association with UCL surgery, and we hope our study establishes the need to further elucidate the potential mechanism of increased risk as the pitch-tracking data continues to accumulate and advance. Formal biomechanical analysis analyzing the clinical impact of various pitch-tracking variables is warranted.

Data for this study were obtained entirely from public sources, although these sources have been used in multiple previous studies and the pitch-tracking data released directly to the public by MLB.[10,19,27] We also reported on UCL surgeries to serve as a proxy to gain insight into the association of these metrics with UCL injuries, but this omits UCL injuries in MLB pitchers who were treated nonoperatively. Although we acknowledge this limitation and understand that inconsistencies in public injury data have been noted,[18] Inclan et al[18] focused on ACL injuries in National Football League (NFL) players before 2015 and found most inconsistencies with lesser known players such as linemen. With the rapid expansion of sports media in recent years and the public focus on UCL injuries in MLB pitchers, which require long-term absence and, most often, surgery, public injury data are likely more reliable in this cohort than ACL injuries in National Football League linemen.

Our study included only patients who had at least 2 years of qualifying preinjury data, resulting in the exclusion of pitchers injured in their rookie MLB season. In addition, data collection in this study was limited to pitches thrown in a live MLB game and did not consider pitches thrown during warm-ups, practice, or offseason training regimens, which likely affected injury risk. Although draft and international free agent status were outlined, data on pre-MLB pitching history was limited and may have affected our results, although this limitation is difficult to control for in any MLB study.

## CONCLUSION

In this study, MLB pitchers who underwent UCL surgery threw harder with less fastball usage, and had superior overall pitching ability (Pitching+) and strike-zone command (Location+) than matched controls. There was no difference in pitch counts, spin rate, active spin, spin axis, release points, approach angles, release extension, or overall pitch movement between cases and controls. While the clinical significance of these metrics still needs to be determined, teams and players should consider these findings to develop safer player development protocols.

## ACKNOWLEDGMENT

The authors acknowledge Eno Sarris of *The Athletic* and Max Bay as the developers of the statistics Stuff+, Location+, and Pitching+ referenced in this article. They also acknowledge Alex Chamberlain and Jon Anderson for their public data collection and insights into the data analysis used in this study.

## ORCID iD

Cole R. Morrissette https://orcid.org/0000-0001-5667-5056

## REFERENCES

1. Aguinaldo AL, Chambers H. Correlation of throwing mechanics with elbow valgus load in adult baseball pitchers. *Am J Sports Med*. 2009;37(10):2043-2048.
2. Baseball Savant. https://baseballsavant.mlb.com. Accessed December 2, 2023.
3. Baseball-Reference. https://www.baseball-reference.com. Accessed December 2, 2023.
4. Brooks Baseball. https://www.brooksbaseball.net. Accessed December 2, 2023.
5. 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(4):728-732.
6. Chalmers PN, Erickson BJ, Ball B, Romeo AA, Verma NN. Fastball pitch velocity helps predict ulnar collateral ligament reconstruction in Major League Baseball pitchers. *Am J Sports Med*. 2016;44(8):2130-2135.
7. Chamberlain A. Pitch leaderboard. Version 5. https://public.tableau.com/app/profile/chamb117/viz/PitchLeaderboardv5/Dashboard. Accessed December 2, 2023.
8. Chamberlain A. A visual primer on horizontal approach angle (HAA). https://blogs.fangraphs.com/a-visual-primer-on-horizontal-approach-angle-haa/. Accessed December 4, 2023.
9. Clemens B. What are teams paying per WAR in Free Agency? FanGraphs; December 14, 2021. https://blogs.fangraphs.com/what-are-teams-paying-per-war-in-free-agency/ Accessed August 24, 2024.
10. Cohen SA, Portney DA, Cohen LE, Bolia-Kavouklis I, Weber AE, Saltzman MD. Using pitch-tracking data to identify risk factors for medial ulnar collateral ligament reconstruction in Major League Baseball pitchers. *Orthop J Sports Med*. 2022;10(3):23259671211065756.
11. Coughlin RP, Gohal C, Horner NS, et al. Return to play and in-game performance statistics among pitchers after ulnar collateral ligament reconstruction of the elbow: a systematic review. *Am J Sports Med*. 2019;47(8):2003-2010.
12. Cross AG, Khalil LS, Swantek AJ, et al. Athletes perceive weighted baseballs to carry a notable injury risk, yet still use them frequently: a multicenter survey study. *J Am Acad Orthop Surg Glob Res Rev*. 2022;6(9):e21.00306.
13. FanGraphs. www.fangraphs.com. Accessed December 2, 2023.
14. Fleisig GS, Escamilla RF, Andrews JR, Matsuo T, Sattenwhite Y, Barrentine SW. Kinematic and kinetic comparison between baseball pitching and football passing. *J Appl Biomech*. 1996;12(2):207-224.
15. Grantham WJ, Iyengar JJ, Byram IR, Ahmad CS. The curveball as a risk factor for injury: a systematic review. *Sports Health*. 2015;7(1):19-26.
16. Higuchi T, Morohoshi J, Nagami T, Nakata H, Kanosue K. The effect of fastball backspin rate on baseball hitting accuracy. *J Appl Biomech*. 2013;29(3):279-284.
17. Hodgins JL, Vitale M, Arons RR, Ahmad CS. Epidemiology of medial ulnar collateral ligament reconstruction: a 10-year study in New York State. *Am J Sports Med*. 2016;44(3):729-734.
18. Inclan PM, Chang PS, Mack CD, et al. Validity of research based on public data in sports medicine: a quantitative assessment of anterior cruciate ligament injuries in the National Football League. *Am J Sports Med*. 2022;50(6):1717-1726.
19. Keller RA, Marshall NE, Guest JM, Okoroha KR, Jung EK, Moutzouros V. Major League Baseball pitch velocity and pitch type associated with risk of ulnar collateral ligament injury. *J Shoulder Elbow Surg*. 2016;25(4):671-675.
20. LaPrade CM, Cinque ME, Safran MR, Freehill MT, Wulf CA, LaPrade RF. Using advanced data to analyze the impact of injury on performance of Major League Baseball pitchers: a narrative review. *Orthop J Sports Med*. 2022;10(7):23259671221111169.
21. Mayo BC, Miller A, Patetta MJ, et al. Preventing Tommy John surgery: the identification of trends in pitch selection, velocity, and spin rate before ulnar collateral ligament reconstruction in Major League Baseball pitchers. *Orthop J Sports Med*. 2021;9(6):23259671211012364.
22. McGratten O. Stuff+, Location+, and Pitching+ primer. Fangraphs. March 10, 2023. https://library.fangraphs.com/pitching/stuff-location-and-pitching-primer. Accessed December 4, 2023.
23. Meldau JE, Srivastava K, Okoroha KR, Ahmad CS, Moutzouros V, Makhni EC. Cost analysis of Tommy John surgery for Major League Baseball teams. *J Shoulder Elbow Surg*. 2020;29(1):121-125.
24. Miller K. Inside the rising cost of winning in MLB free agency. Bleacher Report; February 3, 2023. https://bleacherreport.com/articles/10063324-inside-the-rising-cost-of-winning-in-mlb-free-agency.

25. MLB Reports. TJ surgery: AllTime MLB list. https://mlbreports.com/tj-surgery. Accessed August 17, 2020.
26. Passan J. Spider Tack, goo cops and an open secret: answering 20 questions about MLB's foreign-substance mess. ESPN. June 9, 2021. http://www.espn.com/mlb/insider/story/_/id/31596907/spider-tack-goo-cops-open-secret-answering-20-questions-mlb-foreign-substance-mess. Accessed December 4, 2024.
27. Portney DA, Buchler LT, Lazaroff JM, Gryzlo SM, Saltzman MD. Influence of pitching release location on ulnar collateral ligament reconstruction risk among Major League Baseball pitchers. *Orthop J Sports Med*. 2019;7(2):2325967119826540.
28. Prodromo J, Patel N, Kumar N, Denehy K, Tabb LP, Tom J. Pitch characteristics before ulnar collateral ligament reconstruction in major league pitchers compared with age-matched controls. *Orthop J Sports Med*. 2016;4(6):2325967116653946.
29. Roegele J. Tommy John surgery list. https://docs.google.com/spreadsheets/d/1gQujXQQGOVNaiuwSN680Hq-FDVsCwvN-3Aazy-kOBON0/edit#gid¼0. Accessed May 15, 2023.
30. Selley RS, Portney DA, Lawton CD, et al. Advanced baseball metrics indicate significant decline in MLB pitcher value after Tommy John surgery. *Orthopedics*. 2019;42(6):349-354.
31. Slowik JS, Aune KT, Diffendaffer AZ, Cain EL, Dugas JR, Fleisig GS. Fastball velocity and elbow-varus torque in professional baseball pitchers. *J Athl Train*. 2019;54(3):296-301.
32. Thomas SJ, Paul RW, Rosen AB, et al. Return-to-play and competitive outcomes after ulnar collateral ligament reconstruction among baseball players: a systematic review. *Orthop J Sports Med*. 2020;8(12):2325967120966310.
33. Tommy John FAQ. Pitch Smart USA Baseball. October 1, 2014. https://www.mlb.com/pitch-smart/tommy-john-faq. Accessed February 28, 2023.
34. van der List JP, Camp CL, Sinatro AL, Dines JS, Pearle AD. Systematic review of outcomes reporting in professional baseball: a call for increased validation and consistency. *Am J Sports Med*. 2018;46(2):487-496.
35. Whiteside D, Martini DN, Lepley AS, Zernicke RF, Goulet GC. Predictors of ulnar collateral ligament reconstruction in Major League Baseball pitchers. *Am J Sports Med*. 2016;44(9):2202-2209.
36. Wick H, Dillman CJ, Werner S, et al. A kinematic comparison between baseball pitching and football passing. *Sports Med Update*. 1991;6(2):13-16.