Check for updates

Original Research

Pitch Metrics and the Trade-Offs Between Elbow Injury and Performance in Major League Baseball Pitchers

Jonathan S. Slowik,*† PhD, Dev Rupani,† J. Bradford Hall,† BS, Jeffrey R. Dugas,†‡ MD, and Glenn S. Fleisig,† PhD
Investigation performed at the American Sports Medicine Institute, Birmingham, Alabama, USA

Background: Elbow injuries among baseball pitchers continue to rise, with increasing emphasis on velocity, spin, and related pitch metrics as likely contributors. However, the trade-offs between performance and injury burden are not well understood.

Purpose: To evaluate relationships between pitch metrics, elbow injury burden, and performance in Major League Baseball (MLB) pitchers, and to assess trade-offs between these outcomes.

Study Design: Cross-sectional study.

Methods: Publicly available pitch metrics, performance measures, and injury data were analyzed for MLB pitchers during the 2022 to 2025 regular seasons. Pitch metrics included velocity, spin rate, vertical and horizontal movement, release characteristics, pitch-type usage, and pitch quality models (Pitching + , Stuff + , and Location +). Pitch arsenal diversity was quantified using the effective number of pitch types (N_{eff}). Outcomes included elbow injury burden (days on the injured list due to elbow injuries [ElbowDays]), expected earned run average (xERA), and FanGraphs wins above replacement (fWAR). Regression models evaluated associations between pitch metrics and outcomes, adjusting for age, service time, and role (starter/reliever), with effects standardized per standard deviation.

Results: Among 406 pitchers, velocity showed the most consistent effects. A 1-SD increase in average velocity was associated with 36% greater ElbowDays alongside improved performance (–4% xERA; + 0.18 fWAR). Similar trade-offs were observed for 4-seam velocity, sinker velocity, and 4-seam Pitching + . Increased spin rate, induced vertical break, and arm angle were associated with increased ElbowDays but limited or inconsistent performance benefits. Greater arsenal diversity (N_{eff}) was associated with reduced ElbowDays (–26%) but slightly worse xERA (+ 4%) and no significant change in fWAR. Higher sinker usage was associated with reduced ElbowDays (–15%) without significant performance effects.

Conclusion: Velocity, spin, and related metrics are associated with improved MLB pitching performance but increased elbow injury burden, indicating a measurable performance-injury trade-off. In contrast, greater arsenal diversity, increased sinker usage, and lower arm angle may improve durability with minimal performance cost. Future research examining the contextual components of pitch quality models beyond raw metrics is warranted.

Keywords: Statcast; injured list; ulnar collateral ligament; injury risk; pitcher durability; pitching biomechanics

Over the past decade, professional baseball pitching has undergone substantial evolution driven by advances in technology and performance analytics.[20,37] Modern pitching development increasingly emphasizes maximizing "stuff," a broad term used in baseball analytics to describe physical pitch characteristics such as velocity, spin rate, and movement that are believed to contribute to pitch effectiveness.[39]

The widespread adoption of ball-tracking systems such as Trackman and Hawk-Eye has enabled these characteristics to be quantified with unprecedented precision,[20,25] while the development of publicly available analytic metrics such as expected earned run average (xERA) and wins above replacement (WAR) has provided standardized measures of pitching performance.[37] Although the specific ways Major League Baseball (MLB) organizations incorporate these data into player development and decision-making are typically not shared publicly, the increasing availability of pitch-level measurements has coincided with changes in

The Orthopaedic Journal of Sports Medicine, 14(11), 23259671261490766
DOI: 10.1177/23259671261490766
© The Author(s) 2026

This open-access article is published and distributed under the Creative Commons Attribution - NonCommercial - No Derivatives License (https://creativecommons.org/licenses/by-nc-nd/4.0/), which permits the noncommercial use, distribution, and reproduction of the article in any medium, provided the original author and source are credited. You may not alter, transform, or build upon this article without the permission of the Author(s). For article reuse guidelines, please visit SAGE's website at http://www.sagepub.com/journals-permissions.

pitching, including a growing focus on stuff and the development of increasingly novel pitch types.[14,38,39]

At the same time, elbow injuries among pitchers continue to rise and remain a major concern across all levels of baseball.[12] Despite ongoing efforts to reduce injury rates and time lost (eg, pitch-count limits, workload monitoring, and advances in surgical and rehabilitation strategies), the overall burden of these injuries on the baseball community continues to rise. Analyses of MLB data over the past 15 seasons show increasing time lost to the injured list (IL), particularly for elbow injuries, along with corresponding increases in ulnar collateral ligament (UCL) surgery.[22,28] Similarly, injury rates among adolescent pitchers have risen, with studies documenting sharp increases in elbow and throwing-arm injuries.[8,10,29,52] Together, these findings indicate that this issue is not confined to professional play but rather represents a systemic challenge.

Within the baseball community, it has frequently been suggested that a focus on velocity and stuff is associated with the continued rise in elbow injuries. The December 2024 MLB Injury Report, which surveyed over 200 experts across baseball and sports medicine, highlighted the modern pursuit of stuff as a major concern.[39] Respondents suggested that this pursuit has contributed to intensified offseason training, reduced recovery periods, and aggressive pitch-design practices that may impose atypical biomechanical demands, all of which may further exacerbate injury risk. Importantly, they noted that performance incentives at the professional level cascade downstream into collegiate, high school, and youth baseball, creating a culture in which maximal-effort throwing and velocity prioritization are normalized in pursuit of advancement opportunities.[51]

While there is now widespread acknowledgement of a UCL injury epidemic, there is also a growing perception among pitchers that such injuries are an inevitable consequence of high-level pitching performance.[46] Accordingly, many pitchers will knowingly accept an increased injury risk in pursuit of velocity and stuff-related characteristics. However, the scale of the associated performance benefits and injury risks remain poorly understood. Furthermore, pitchers may hold overly optimistic expectations regarding the long-term health and career impacts of these injuries.[1,46] Higher-performing players are both more likely to return to their previous level of competition[14] and more likely to receive disproportionate media coverage.[16] Consequently, failures and/or related performance declines among fringe and lower-level players are less widely reported. This imbalance may reinforce a false sense of security,[46,50] despite substantial variability in long-term outcomes,[6,14] particularly those related to UCL revision procedures,[44] which are becoming increasingly common,[3,9] consistent with rising rates of primary UCL reconstruction and younger age at surgery.[26]

Despite the widely presumed trade-offs between pitching performance and injury risk, relatively little published research has jointly examined both types of outcomes. Previous Statcast-based studies have largely focused either on performance optimization[18,48,49] or on injury risk.[20] Furthermore, injury studies have typically relied on UCL surgery as a binary outcome, which provides an incomplete representation of elbow injury burden.[2] Not all serious elbow injuries result in surgery, and existing surgical data sets are frequently incomplete and prone to misclassification, especially as an increasing proportion of procedures occur before pitchers reach professional baseball. In contrast, IL-based measures allow differentiation of injuries by type and duration, providing a more accurate measure of the practical cost to players and teams.[22]

Modern pitch-tracking systems and publicly available baseball analytics provide an opportunity to examine how specific pitching characteristics relate simultaneously to both performance and injury burden. Therefore, the purpose of the present study was to investigate the relationships of MLB pitch metrics to both injury and performance outcomes within a unified framework. By quantifying these relationships, we aim to clarify the associated trade-offs and to provide clinically and practically relevant insights for player development and pitching evaluation in professional baseball.

METHODS

This study involved a retrospective analysis of publicly available pitch-tracking, performance, and injury data for MLB pitchers from the 2022 to 2025 regular seasons. The study protocol was reviewed by the University of Alabama–Birmingham institutional review board and was determined to not be human subjects research. Included pitchers had made their MLB debut by April 21, 2022 (2 weeks into the 2022 season) and were still under contract with an MLB organization at the end of the 2025 season, allowing for accrual of the outcome variables throughout the study period. To ensure reliable estimation of pitch metrics, pitchers were also required to have thrown $\geq$300 pitches in MLB regular-season games during the study period (Figure 1).

*Address correspondence to Jonathan S. Slowik, PhD, American Sports Medicine Institute, 833 Street, Vincent's Drive, Suite 101, Birmingham, AL 35205, USA (email: jons@asmi.org).
†American Sports Medicine Institute, Birmingham, Alabama, USA.
‡Andrews Sports Medicine & Orthopaedic Center, Birmingham, Alabama, USA.
Final revision submitted September 1, 2026; accepted September 7, 2026.
One or more of the authors has declared the following potential conflict of interest or source of funding: J.R.D. has received consulting fees from Arthrex, Bioventus, DJO, and Royal Biologics; compensation for services other than consulting from Arthrex; and royalties from Arthrex, In2Bones, and Linvatec. G.S.F. has received consulting fees from Major League Baseball.
Ethical approval for this study was obtained from the University of Alabama–Birmingham institutional review board (IRB No. 300015161).

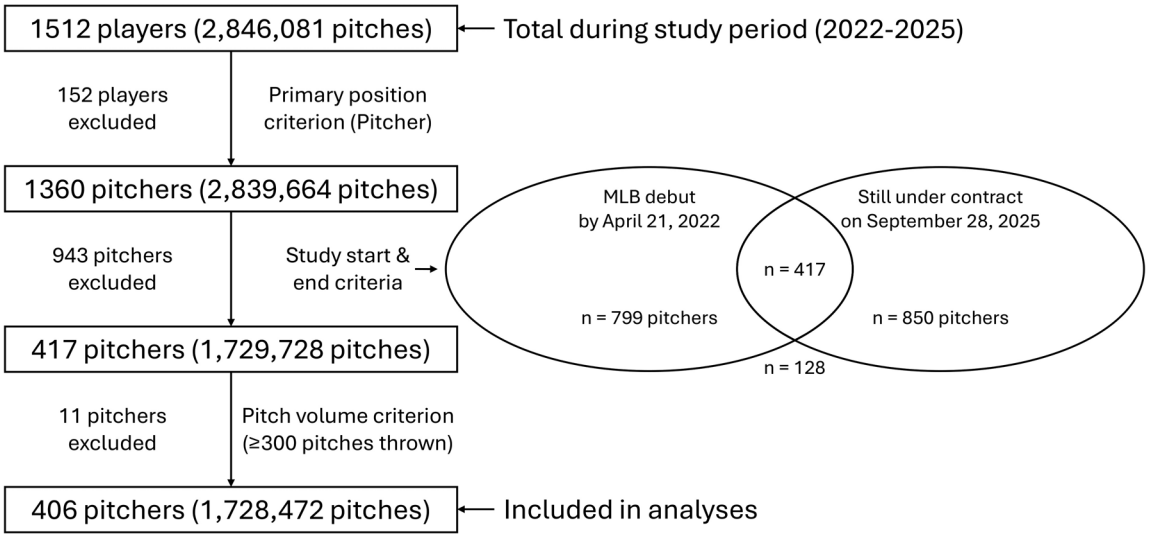


Figure 1. Flowchart illustrating the selection of pitchers included in the study from all Major League Baseball (MLB) players who threw ≥1 pitch during the study period, with the number of players and total pitches shown at each stage.

Pitch Metrics

Statcast data, including velocity, spin rate, release point, and movement characteristics (Tables 1 and 2) were obtained from Baseball Savant for the following pitch-type classifications (Figure 2): 4-seam fastball (FF), sinker (SI), changeup (CH), curveball (CU), splitter (FS), cutter (FC), slider (SL), and sweeper (ST). Full-arsenal values were calculated as pitch count-weighted averages.

The diversity of each pitcher's arsenal was quantified using an "effective number" of pitch types (N_{eff}), defined as the first-order Hill number.[21] This metric reflects both the number of pitch types thrown and the evenness of their usage. For example, a pitcher who throws 3 pitch types equally often (33.3% each) has an N_{eff} of 3.0, but a pitcher with a 70%/20%/10% distribution has an N_{eff} of approximately 2.2, reflecting a less diverse arsenal despite still using 3 pitch types.

For pitch-type-specific analyses, horizontal break values were sign-adjusted within each pitch type to ensure a positive across-pitcher mean, with direction subsequently described as arm-side or glove-side. Similarly, induced vertical break, representing vertical pitch movement after accounting for the effects of gravity, was sign-adjusted, with direction subsequently described as rise (upward movement) or drop (downward movement).

Pitch quality model metrics (Pitching+, Stuff+, and Location+) were obtained from FanGraphs, which provides both full-arsenal and pitch-type-specific values. Stuff+ evaluates the physical characteristics of a pitch independent of its location, Location+ evaluates pitch location independent of physical characteristics, and Pitching+ integrates components of both to estimate overall pitch effectiveness. The FanGraphs pitch types correspond one to one with Statcast pitch classifications for all pitch types except the slider variants (SL and ST). Because the models did not distinguish between these 2 pitch types, pitchers who threw both were excluded from SL- and ST-specific analyses, resulting in smaller groups of pitchers who threw SLs without STs (n = 217) and STs without SLs (n = 62).

Outcome Variables

We defined 3 outcome variables to capture both injury burden and pitching performance. A pitcher's total number of regular season days on the MLB IL due to elbow injury (ElbowDays) was used as the primary outcome. ElbowDays were compiled using MLB transaction logs supplemented by publicly curated data sets (eg, FanGraphs RosterResource) containing detailed injury designations. Pitching performance was assessed using 2 complementary metrics widely used in baseball analytics. xERA estimates expected runs allowed per 9 innings pitched based on strikeouts, walks, and the quality of contact allowed, while FanGraphs WAR (fWAR) captures cumulative player value by incorporating both performance and workload. Individual season values for each metric were obtained from FanGraphs and aggregated across the study period: xERA was averaged using pitch count weighting, while fWAR was simply averaged across all 4 seasons.

Statistical Analysis

Data processing and statistical analyses were performed in Python (Version 3.13) using pandas and numpy for data handling, statsmodels for regression modeling, and matplotlib for visualization. Regression analyses were conducted to evaluate associations between pitch metrics and outcome variables, controlling for demographic

TABLE 1
Study Variable Details for All 406 Pitchers[a]

Outcome Variable	Mean	SD
xERA[b]	4.04	0.77
fWAR[c,d]	0.83	0.96
ElbowDays	53.3	89.0
Covariate	**Mean**	**SD**
Age at study start, y	28.5	3.2
Service time at study start, y	2.8	2.9
Games started, % of appearances	36.0	45.0
Pitch Metric	**Mean**	**SD**
N_{eff}	2.6	0.9
FF_Pct	31.9	18.6
SL_Pct	17.3	15.7
SI_Pct	15.9	17.1
CH_Pct	10.1	11.3
CU_Pct	7.8	10.1
FC_Pct	7.4	12.5
ST_Pct	6.6	11.5
FS_Pct	2.8	7.8
Arm_Angle, above horizontal, deg[e]	37.7	13.1
Extension, from rubber, in inches[f]	76.9	5.0
Spin_Efficiency, active spin %[g]	72.0	9.2
Velocity, mph[h]	89.4	2.7
Spin_Rate, rpm[i]	2278	201
Total_Break, induced movement magnitude, in inches[j]	14.6	1.9
Horizontal_Break, arm-side movement, in inches[j]	3.8	4.1
Induced_Vertical_Break, rise, in inches[j]	7.2	3.3
FanGraphs Pitching +[k]	101.6	7.9
FanGraphs Stuff +[k]	102.1	8.4
FanGraphs Location +[k]	99.8	5.1

[a]CH, changeup; CU, curveball; ElbowDays, days on MLB injured list due to an elbow injury; FC, cutter; FF, 4-seam fastball; FS, splitter; fWAR, FanGraphs wins above replacement; MLB, Major League Baseball; N_{eff}, effective number of pitch types; pct, percent usage; SI, sinker; SL, slider; ST, sweeper; xERA, expected earned run average.
[b]https://www.mlb.com/glossary/statcast/expected-era
[c]https://www.mlb.com/glossary/advanced-stats/wins-above-replacement
[d]https://library.fangraphs.com/misc/war/
[e]https://baseballsavant.mlb.com/leaderboard/pitcher-arm-angles
[f]https://www.mlb.com/glossary/statcast/extension
[g]https://www.mlb.com/glossary/statcast/active-spin
[h]https://www.mlb.com/glossary/statcast/velocity
[i]https://www.mlb.com/glossary/statcast/spin-rate
[j]https://www.mlb.com/glossary/statcast/pitch-movement
[k]https://library.fangraphs.com/pitching/stuff-location-and-pitching-primer/

confounders (age and MLB service time at the beginning of the study period, and percentage of appearances as a starter). Analyses were performed both across all pitchers and within pitch-type groups (pitchers with ≥3% usage of that pitch type). Model selection was based on the observed distribution of each outcome variable: xERA was modeled using a lognormal distribution, fWAR using a normal distribution, and ElbowDays using a negative binomial distribution. Effect estimates were standardized per 1-SD increase in each metric, with 95% CIs reported. Holm correction was applied for multiple testing within each group-by-outcome combination. Forest plots were used to visualize standardized effect sizes and confidence intervals across pitch metrics and outcomes. Effects were expressed as percentage change for ElbowDays and xERA, and as absolute change for fWAR, consistent with model scaling and outcome distributions.

RESULTS

Overview

Summary details (pitch metrics, covariates, and outcome variables) for the 406 pitchers who met the study inclusion criteria are provided in Tables 1 and 2. Regression results are detailed in Figures 3 to 4 and Appendix Figures A1 to A9 using forest plots (standardized effect size estimates with 95% CIs), which illustrate the direction and magnitude of associations across outcomes.

Four pitch metrics showed significant associations with all 3 outcomes (ElbowDays, xERA, and fWAR): full-arsenal average velocity, FF velocity, SI velocity, and FF Pitching + . For all 4 metrics, higher values were associated with improved performance (lower xERA and higher fWAR) but greater injury burden (higher ElbowDays).

Elbow Injury

Ball velocity was the most consistent predictor of ElbowDays across pitch types. A 1-SD increase in full-arsenal average velocity was associated with a 36% increase in ElbowDays, with pitch-specific estimates ranging from 22% to 43% for SIs, CUs, STs, FFs, and SLs.

One-SD increases in full-arsenal induced vertical break, arm angle, and spin rate were associated with 29%, 25%, and 19% increases in ElbowDays, respectively. Similar patterns were observed for FFs, SIs, and CHs.

Additional analyses revealed differences across pitch types. For CHs, greater total break, higher spin efficiency, and increased arm-side horizontal break were associated with increased ElbowDays. For FFs, greater total break, higher percent usage among the subgroup of pitchers who threw them (FF_Pct_Sub), and higher Pitching + were also associated with increased ElbowDays. In contrast, several CU metrics (greater total break, higher spin efficiency, and increased drop) were associated with reduced ElbowDays. For STs, higher Stuff + was associated with increased ElbowDays, but higher Location + was associated with decreased ElbowDays.

At the arsenal level, a greater effective number of pitch types (N_{eff}) was associated with a 26% reduction in ElbowDays, and a higher SI percent usage among *all* pitchers (SI_Pct) was associated with a 15% reduction.

TABLE 2
Study Variable Details for the Pitch-Type Subgroups[a]

Pitch Metric	FF (n = 367)	SL (n = 293[b])	SI (n = 258)	CH (n = 246)	CU (n = 198)	FC (n = 148)	ST (n = 138[c])	FS (n = 61)
Pct_Sub, % usage among the subgroup	35.2 ± 16.4	23.8 ± 13.9	24.8 ± 15.5	16.4 ± 10.6	15.5 ± 9.6	19.9 ± 13.5	19.1 ± 12.3	18.0 ± 11.3
Arm_Angle, above horizontal, deg	39.1 ± 11.7	38.8 ± 12.7	33.7 ± 13.9	36.2 ± 11.2	43.9 ± 10.1	38.6 ± 10.1	31.9 ± 12.4	38.7 ± 9.0
Extension, inches	77.2 ± 5.1	76.7 ± 5.0	76.8 ± 5.2	76.8 ± 4.9	75.9 ± 4.9	76.2 ± 4.2	76.1 ± 5.1	77.6 ± 4.9
Velocity, mph	94.1 ± 2.2	85.5 ± 2.6	93.5 ± 2.5	86.0 ± 2.9	79.8 ± 3.3	89.2 ± 2.5	81.8 ± 2.7	86.5 ± 2.7
Spin_Rate, rpm	2297 ± 136	2416 ± 215	2188 ± 136	1781 ± 258	2519 ± 270	2408 ± 175	2557 ± 217	1356 ± 280
Spin_Efficiency, active spin %	88.9 ± 8.8	33.6 ± 10.5	85.3 ± 8.6	90.0 ± 8.4	68.0 ± 16.3	46.4 ± 12.0	50.5 ± 10.4	82.9 ± 11.6
Total_Break, induced movement magnitude, in inches	17.8 ± 2.0	7.0 ± 2.7	17.8 ± 1.8	16.1 ± 2.0	13.7 ± 4.1	9.0 ± 2.4	14.7 ± 2.3	12.1 ± 2.5
Horizontal_Break, arm-side movement, in inches	7.6 ± 3.4	–4.9 ± 3.2	14.9 ± 2.4	14.4 ± 2.1	–8.6 ± 4.1	–2.4 ± 2.2	–13.9 ± 2.5	10.7 ± 2.7
Induced_Vertical_Break, rise, in inches	15.5 ± 2.5	1.7 ± 3.2	8.3 ± 4.2	5.4 ± 3.9	–9.4 ± 4.3	7.8 ± 2.8	1.4 ± 3.2	3.3 ± 3.0
Pitching +	93.2 ± 12.9	105.7 ± 10.8	103.0 ± 12.5	93.2 ± 14.6	98.1 ± 11.4	101.7 ± 11.6	108.5 ± 8.8	97.8 ± 17.1
Stuff +	95.6 ± 10.8	108.1 ± 11.2	99.5 ± 10.7	92.5 ± 11.6	103.7 ± 13.1	98.0 ± 9.6	114.9 ± 11.0	100.7 ± 13.9
Location +	99.2 ± 8.0	98.9 ± 7.3	100.4 ± 8.7	98.8 ± 9.1	99.5 ± 7.7	99.9 ± 8.9	100.0 ± 7.9	98.1 ± 11.3

[a]Data are presented as mean ± SD. CH, changeup; CU, curveball; FC, cutter; FF, 4-seam fastball; FS, splitter; SI, sinker; SL, slider; ST, sweeper.
[b]n = 217 for SL_Pitching + , SL_Stuff + , and SL_Location + .
[c]n = 62 for ST_Pitching + , ST_Stuff + , and ST_Location + .

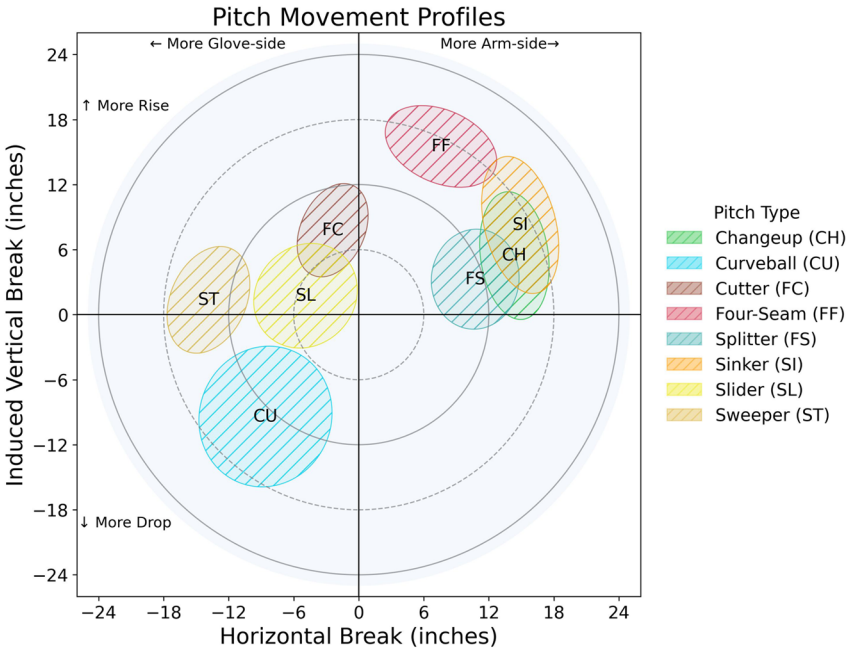


Figure 2. Pitch movement profiles by pitch type. Covariance-based ellipses (68%) represent the distribution of pitchers included in the study, centered at the across-pitcher mean. Colors denote pitch types, with axis labels indicating movement direction. *Note:* Induced vertical break represents vertical movement after accounting for the effects of gravity. Positive values indicate an upward deviation from the movement expected under gravity alone.

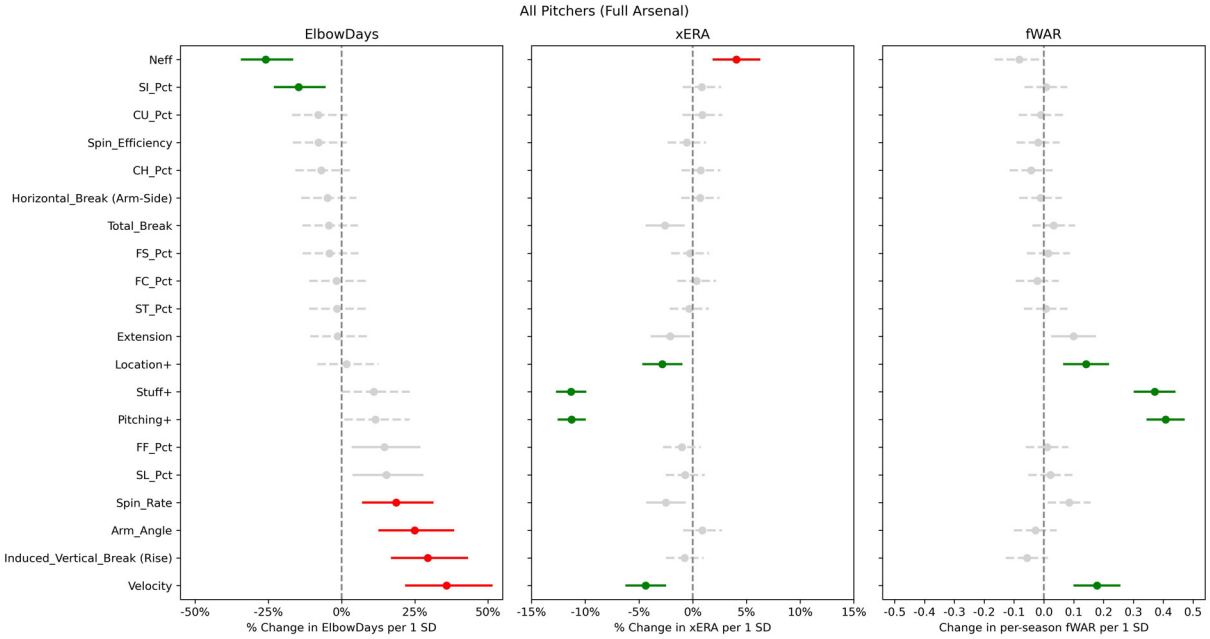


Figure 3. Forest plots showing associations between Statcast-based pitch metrics and performance/injury outcomes across all 406 pitchers (2022-2025 MLB seasons). Points represent effects per SD increase, with 95% CIs. Effects are shown as percentage change for ElbowDays and xERA and as absolute change for per-season fWAR. Color indicates direction of association, with per-outcome Holm correction (green = favorable, red = unfavorable, gray = nonsignificant). Statistical significance based on the less conservative Benjamini-Hochberg false discovery rate correction is indicated by line type, with solid lines representing significant effects and dashed lines representing nonsignificant effects. CH, changeup; CU, curveball; ElbowDays, days on MLB injured list due to an elbow injury; FC, cutter; FF, 4-seam fastball; FS, splitter; fWAR, FanGraphs wins above replacement; MLB, Major League Baseball; N_{eff}, effective number of pitch types; pct, percent usage; SI, sinker; SL, slider; ST, sweeper; xERA, expected earned run average.

Performance

Improved performance was associated with higher full-arsenal Pitching+ (–11% xERA, +0.41 fWAR), Stuff+ (–11% xERA, +0.37 fWAR), velocity (–4% xERA, +0.18 fWAR), and Location+ (–3% xERA, +0.14 fWAR). In contrast, a greater effective number of pitch types (N_{eff}) was associated with a 4% increase in xERA (its −0.08 change in fWAR did not reach statistical significance). Pitch type–specific Pitching+, Stuff+, and velocity demonstrated similar directional relationships across most pitch types, although with smaller effect magnitudes relative to arsenal-level estimates.

Additional pitch type–specific associations were observed. Higher spin rate was associated with lower xERA for FFs, SIs, and CHs. Increased release extension was associated with higher fWAR for FFs and FSs, while higher Location+ was associated with increased fWAR for FFs. Higher fWAR was also associated with reduced rise for CHs and greater drop for CUs. Notably, these latter 2 pitch metrics represented the small subset of metrics that showed significant associations across all 3 outcome variables with consistent directionality (favorable or unfavorable).

DISCUSSION

The purpose of this study was to simultaneously investigate relationships between pitch metrics and both elbow injury burden and performance outcomes. Previous Statcast-based studies have largely relied on group-based comparisons (eg, UCL vs non-UCL or preinjury vs postinjury).[5,14,17,32-36,40,42] In contrast, the present regression-based approach evaluated associations across continuous and count-based variables, capturing a spectrum of elbow injury burden rather than reducing it to a binary outcome. The results demonstrate that several pitch metrics are associated with both improved performance (lower xERA, higher fWAR) and increased elbow injury burden (greater ElbowDays). These findings suggest a measurable trade-off between performance enhancement and injury risk in modern pitching.

Ball velocity was the most consistent predictor across outcome variables. Higher velocities of the full arsenal and specific pitch types were associated with increased ElbowDays (CU, FF, SI, SL, and ST), as well as better xERA (FC, FF, and SI) and fWAR (FC, FF, SI, and SL). These findings are consistent with prior biomechanical

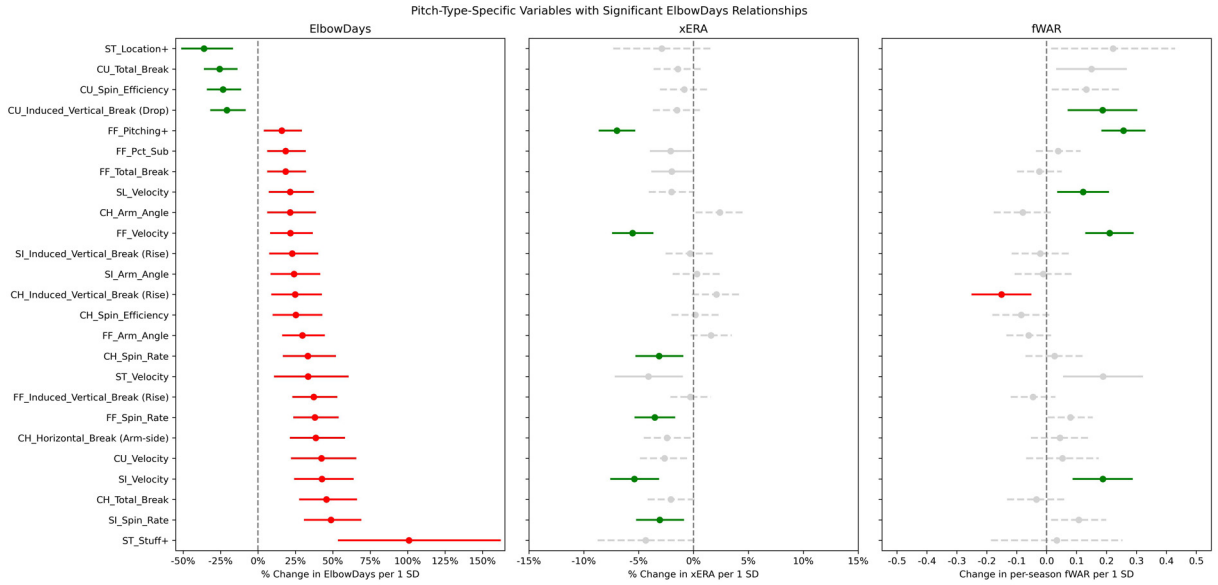


Figure 4. Forest plots of Statcast-based pitch metrics with significant associations with number of ElbowDays within pitch-type-specific groups (2022-2025 MLB seasons). Points represent effects per SD increase, with 95% CIs. Effects are shown as percentage change for ElbowDays and xERA and as absolute change for per-season fWAR. Color indicates direction of association, with per-outcome Holm correction (green = favorable, red = unfavorable, gray = nonsignificant). Statistical significance based on the less conservative Benjamini-Hochberg false discovery rate correction is indicated by line type, with solid lines representing significant effects and dashed lines representing nonsignificant effects. CH, changeup; CU, curveball; ElbowDays, days on MLB injured list due to an elbow injury; FC, cutter; FF, 4-seam fastball; FS, splitter; fWAR, FanGraphs wins above replacement; MLB, Major League Baseball; N_{eff}, effective number of pitch types; pct, percent usage; SI, sinker; SL, slider; ST, sweeper; xERA, expected earned run average.

and epidemiologic evidence linking higher velocity to increased elbow loading and injury risk.[4,30,43] While these results reinforce the importance of velocity in pitcher evaluation and development, they also highlight the risks associated with continued emphasis on velocity maximization.

Beyond velocity, several pitch metrics demonstrated less consistent associations across outcomes. Notably, higher full-arsenal Location + was associated with improved xERA and fWAR without increased ElbowDays, suggesting that pitch location may offer an avenue for improving performance without durability trade-offs. Although these favorable associations were not consistently statistically significant across individual pitch types, the overall pattern merits additional investigation. Conversely, a higher arm angle was associated with increased ElbowDays at the arsenal level and within several pitch types (FF, SI, and CH), while showing no significant associations with xERA or fWAR. Prior work has suggested that higher arm slots may be associated with increased elbow valgus loading,[7,11] which appears consistent with the elevated injury burden observed in the present study.

Spin rate and induced vertical break showed associations with injury burden similar to arm angle, with increased ElbowDays at both the arsenal level and within FF, SI, and CH. However, unlike arm angle, both metrics also showed some associations with performance outcomes. Spin rate showed favorable pitch type–specific associations with xERA for FF, SI, and CH, consistent with modern pitch-design principles. Surprisingly, induced vertical break showed no favorable performance associations for FFs, despite the widely held presumption that greater rise is advantageous. Instead, favorable associations were limited to greater drop in CUs and reduced rise in CHs (both associated with higher fWAR). These relationships likely reflect improved separation from a pitcher's primary fastball (Figure 2), as downward shifts move both pitches further from fastball movement profiles (FF/SI/FC). Collectively, these findings suggest that maximizing stuff metrics may enhance pitch effectiveness in specific contexts but does not uniformly translate into improved xERA or fWAR.

For some variables, even the direction of the observed relationships was not always consistent across pitch types. For example, increased spin efficiency and total break were associated with increased ElbowDays for CHs but decreased ElbowDays for CUs. These differences likely reflect divergences in the underlying biomechanical demands and intended movement profiles of each pitch type. One potential contributor is forearm orientation: CHs are typically thrown with greater forearm pronation, while CUs involve more supination.[19,27,31] Such slight biomechanical differences may affect elbow valgus loading patterns and the relative contribution of stabilizing structures, although the precise relationships are not yet well understood.[45]

A previous study reported that greater fastball usage was associated with UCL injury,[23] although fastball subtypes (FF/SI/FC) were not differentiated, likely because of historical Statcast classifications. In the present study, a higher proportion of SIs was associated with a decrease in ElbowDays among all pitchers, while a higher proportion of FFs was associated with an increase in ElbowDays among pitchers who threw them. Together, these findings suggest that the relative usage of these 2 fastball types may influence injury burden, although the underlying mechanisms remain uncertain and may relate to differences in mechanical demands and/or batted-ball outcomes (eg, groundball vs flyball rates).

Interestingly, a greater effective number of pitch types (N_{eff}) was associated with a 26% reduction in ElbowDays, a modest increase in xERA (4%), and no significant change in fWAR. This is consistent with a prior case-control study reporting 33% lower odds of UCL reconstruction with each additional pitch type thrown[47] and suggests that greater pitch arsenal diversity may distribute mechanical workload across a broader set of movement patterns, potentially reducing repetitive stress without substantial performance trade-offs.

The ST showed both the strongest protective and the strongest harmful associations with ElbowDays, for Location+ and Stuff+, respectively. These results suggest that better ST command may be associated with decreased injury risk, while higher raw stuff may be associated with increased risk. However, interpretation is limited by the FanGraphs models not fully distinguishing between SLs and STs and the resulting reduction in sample size. Only 31 of 62 pitchers in the ST-without-SL group spent time on the IL, further limiting statistical stability. These findings should therefore be interpreted cautiously but warrant further investigation as ST usage continues to increase in MLB.[41]

Pitching+ and Stuff+ metrics generally demonstrated stronger relationships with performance than did individual metrics such as velocity, spin, and break, while their unfavorable associations with ElbowDays were generally weaker (with the exception of ST Stuff+). Notably, these models incorporate interactions across pitches within a pitcher's arsenal and contextual information such as pitch location and ball-strike count. As a result, they may capture contributions from sequencing (ie, the intentional ordering of pitches to disrupt batter timing), tunneling (ie, the alignment of initial pitch trajectories to reduce the time available for batter recognition and reaction), and other forms of pitch deception. Indeed, the most statistically robust results observed in this study were for the relationships of Pitching+ and Stuff+ to xERA, which was to be expected given that these models specifically incorporate run prevention outcomes in their design. However, this also highlights a limitation of current pitch evaluation frameworks: they implicitly assume pitcher availability and do not incorporate durability or injury risk. This omission may reflect the prevailing approach to managing injury risk at the organizational level. Increased roster maneuverability and pitching depth may allow teams to absorb injuries with limited competitive disruption, potentially reducing organizational incentives to prioritize individual pitcher health and encouraging a "next man up" mentality. Whether more restrictive roster rules (eg, limiting 60-day IL relief) could better align these incentives falls outside the scope of the present study, but we believe that it is an important direction for future research.

These findings also suggest that pitching injury prevention strategies may need to extend beyond traditional approaches and more directly consider which pitch characteristics are being emphasized and rewarded, with the goal of better understanding and managing their associated trade-offs rather than indiscriminately promoting or condemning these characteristics. Modern pitching culture prioritizes velocity, spin rate, and related stuff metrics because of their perceived performance benefits.[39] These priorities influence how pitchers are selected and coached, encouraging greater emphasis on sustained high-intensity pitching at all levels. Collectively, our findings suggest that safe and effective pitching development may be better achieved by balancing pitch location and command, arsenal diversity, and context-dependent pitch usage rather than solely maximizing individual stuff metrics. They also highlight the potential value in identifying pitchers who can generate high-level stuff without needing to rely on it consistently in all game situations.

Explicitly incorporating durability-related factors into player development and scouting frameworks should theoretically help reduce injury burden across all levels of play. However, as this study analyzed only MLB data, the generalizability of these findings to lower levels of play is unknown. Future studies should examine whether similar relationships exist among younger and less experienced pitchers. Historically, such studies have been difficult to conduct because of limited availability of comprehensive pitch-level and injury data, but advances in tracking technology and potential collaboration with organizations that oversee leagues and tournaments may make them increasingly feasible. These questions may be particularly relevant at the high school level, where players increasingly emulate professional pitching trends despite lower physical readiness and fewer medical resources.[24,39] Further investigation of the relationships among pitch arsenal, performance, and injury could provide insight into when and under what circumstances new pitch types should be introduced during youth pitching development, an area of ongoing debate.[13,15]

Limitations

Additional study limitations should be acknowledged. Injury burden was assessed specifically for elbow injuries and did not include other pitching-related injuries; thus, the observed associations may not extend to nonelbow injuries. Next, the study period (2022-2025) was restricted to avoid pandemic-era confounding of the primary study variables; however, the unusual conditions and data quality issues associated with the COVID-19 pandemic still made it impractical to accurately collect and incorporate prior-season injury or workload history, both of which could

have influenced injury and performance during the study period. Workload during the study period was also not included in the analyses because it is inherently related to the injury outcome: while greater workload may increase injury risk, injury simultaneously reduces a pitcher's opportunities to accumulate pitches. While the inclusion criteria (see Figure 1) were designed to ensure sufficient pitch volume to reliably estimate within-pitcher characteristics and comparable opportunity for accruing injury and performance outcomes, they may have underrepresented pitchers with shorter MLB careers and resulted in smaller sample sizes, particularly for less common pitch types.

Next, many pitch metrics are highly interrelated, and therefore univariable regression models were used; as a result, estimates should be interpreted as descriptive associations rather than independent or causal effects. Additionally, although our results suggest that sequencing, tunneling, and other pitch mix interactions may contribute to pitcher outcomes, these were not explicitly examined in the present study and thus merit further investigation. Finally, the rapidly evolving nature of pitch design introduces an inevitable lag between innovation and evaluation, such that findings from 2022 to 2025 may not be fully generalizable to future seasons.

CONCLUSION

This study provides evidence of a performance-injury trade-off in professional pitching, with velocity and other stuff-oriented pitch metrics generally associated with greater elbow injury burden but improved performance. However, these trade-offs are not uniform across pitch types or design features, with certain characteristics (eg, lower arm angle, greater pitch mix diversity, and higher relative usage of SI) potentially improving durability without sacrificing performance. Overall, these findings highlight the importance of considering injury risk and long-term durability alongside performance in modern pitch design and MLB player evaluation.

ORCID iDs

Jonathan S. Slowik https://orcid.org/0000-0002-3823-6786
Dev Rupani https://orcid.org/0009-0008-0006-6225
Glenn S. Fleisig https://orcid.org/0000-0002-9029-8749

REFERENCES

1. Ahmad CS, Grantham WJ, Greiwe RM. Public perceptions of Tommy John surgery. *Phys Sportsmed*. 2012;40(2):64-72. doi:10.3810/PSM.2012.05.1966
2. Bahr R, Clarsen B, Ekstrand J. Why we should focus on the burden of injuries and illnesses, not just their incidence. *Br J Sports Med*. 2018;52(16):1018-1021. doi:10.1136/BJSPORTS-2017-098160
3. Camp CL, Desai V, Conte S, et al. Revision ulnar collateral ligament reconstruction in professional baseball: current trends, surgical techniques, and outcomes. *Orthop J Sports Med*. 2019;7(8):2325967119864104. doi:10.1177/2325967119864104
4. 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. doi:10.1177/0363546516634305
5. 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. doi:10.1177/23259671211065756
6. 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. doi:10.1177/0363546518798768
7. Dong M, Li M, Qu Q, Kim Y, Kim S. Arm slot angles affect elbow and shoulder joint torque in elite college pitchers. *Sports Biomech*. 2025;24(8):2166-2183. doi:10.1080/14763141.2024.2431927
8. Erickson BJ, Bach BR, Cohen MS, et al. Ulnar collateral ligament reconstruction: the Rush experience. *Orthop J Sports Med*. 2016;4(1):2325967115626876. doi:10.1177/2325967115626876
9. Erickson BJ, Camp CL, Chalmers PN, et al. Outcomes of revision elbow medial ulnar collateral ligament reconstruction in professional baseball players: an analysis of 191 pitchers from 2010 to 2023. *Am J Sports Med*. 2025;53(5):1210-1215. doi:10.1177/03635465251322780
10. Erickson BJ, Nwachukwu BU, Rosas S, et al. Trends in medial ulnar collateral ligament reconstruction in the United States. *Am J Sports Med*. 2015;43(7):1770-1774. doi:10.1177/0363546515580304
11. Escamilla RF, Slowik JS, Diffendaffer AZ, Fleisig GS. Differences among overhand, 3-quarter, and sidearm pitching biomechanics in professional baseball players. *J Appl Biomech*. 2018;34(5):377-385. doi:10.1123/JAB.2017-0211
12. Fleisig GS. Baseball has an elbow injury problem: biomechanics may have the solution. *Sports Biomech*. Published online June 18, 2026. doi:10.1080/14763141.2026.2689508
13. Freehill MT. Is it safe to throw a breaking ball? An editorial. *Sports Health*. 2023;15(4):476. doi:10.1177/19417381231172762
14. Fury MS, Oh LS, Linderman SE, et al. Return to performance after ulnar collateral ligament reconstruction in Major League Baseball pitchers: a case-control assessment of advanced analytics, velocity, spin rates, and pitch movement. *Orthop J Sports Med*. 2021;9(9):23259671211035753. doi:10.1177/23259671211035753
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. doi:10.1177/1941738113501984
16. Haidar LA, Kortlever JTP, Ring D. Misinformation in news coverage of professional and college athlete musculoskeletal ailments. *Arch Bone Jt Surg*. 2020;8(1):33. doi:10.22038/ABJS.2019.34844.1916
17. Harrell M, Rahaman C, Dayal D, et al. Increased pitch-specific velocity, spin rate, and horizontal movement lead to increased odds of undergoing ulnar collateral ligament reconstruction in professional baseball pitchers using Baseball Savant data. *Arthroscopy*. 2025;41(12):5068-5074. doi:10.1016/J.ARTHRO.2025.07.022
18. Healey G, Zhao S. Using PITCHf/x to model the dependence of strikeout rate on the predictability of pitch sequences. *J Sports Anal*. 2017;3(2):93-101. doi:10.3233/JSA-170103
19. Hodakowski AJ, Dowling B, Streepy JT, et al. Pitch types and their influence on elbow varus torque and spin rate in professional baseball pitchers. *Am J Sports Med*. 2025;53(3):543-548. doi:10.1177/03635465241309316
20. Huang JH, Hsu YC. A multidisciplinary perspective on publicly available sports data in the era of big data: a scoping review of the literature on Major League Baseball. *Sage Open*. 2021;11(4):21582440211061566. doi:10.1177/21582440211061566
21. Jost L. Entropy and diversity. *Oikos*. 2006;113(2):363-375. doi:10.1111/J.2006.0030-1299.14714.X
22. Kang L, Meta F, Paparesta N, et al. Injury rates and financial dollars lost due to injury continue to rise in Major League Baseball: an analysis of injured list data over 15 seasons from 2010 to 2024. *Arthroscopy*. 2026;42(3):598-609. doi:10.1002/ARJ.70065

23. 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. doi:10.1016/J.JSE.2015.12.027
24. Kenyon C. Physical development and workload considerations for youth and adolescent baseball athletes. *Curr Phys Med Rehabil Rep*. 2024;12(3):299-306. doi:10.1007/S40141-024-00464-4
25. Kriz PK, Staffa SJ, Kriz JP, DeFroda S. Ulnar collateral ligament tear in elite baseball pitchers: are high school showcase exposures associated with injury? *Am J Sports Med*. 2022;50(11):3073-3082. doi:10.1177/03635465221113859
26. Kriz PK, Staffa SJ, Kriz JP, Kocher MS. Early-career ulnar collateral ligament reconstruction in elite baseball pitchers: impact on professional career performance, longevity, and earning potential. *JSES Int*. 2026;10(1):101391. doi:10.1016/J.JSEINT.2025.09.011
27. Lerch BG, Nebel AR, Shannon DM, Bordelon NM, Oliver GD. Comparison of in-game trunk and upper extremity kinematics between fastballs, breaking balls, and changeups in NCAA Division I collegiate baseball pitchers. *Orthop J Sports Med*. 2024;12(12):23259671241298309. doi:10.1177/23259671241298309
28. Lezak BA, Chalmers PN, Erickson BJ, Romeo AA. Major League Baseball Health and Injury Tracking System (HITS): a review of MLB injuries documented in the HITS database since its inception. *Orthop J Sports Med*. 2026;14(3):23259671261419846. doi:10.1177/23259671261419846
29. Mahure SA, Mollon B, Shamah SD, Kwon YW, Rokito AS. Disproportionate trends in ulnar collateral ligament reconstruction: projections through 2025 and a literature review. *J Shoulder Elbow Surg*. 2016;25(6):1005-1012. doi:10.1016/J.JSE.2016.02.036
30. Manzi J, Kew M, Zeitlin J, et al. Increased pitch velocity is associated with throwing arm kinetics, injury risk, and ulnar collateral ligament reconstruction in adolescent, collegiate, and professional baseball pitchers: a qualitative systematic review. *Arthroscopy*. 2023;39(5):1330-1344. doi:10.1016/J.ARTHRO.2023.01.004
31. Manzi JE, Dowling B, Wang Z, et al. Forearm pronation at foot contact: a biomechanical motion-capture analysis in high school and professional pitchers. *Orthop J Sports Med*. 2023;11(4):23259671221145233. doi:10.1177/23259671221145233
32. Mastroianni MA, Dillon MR, Frappa N, et al. Pitch-tracking risk factors and warning signs for ulnar collateral ligament injuries in Major League Baseball pitchers. *Am J Sports Med*. 2026;54(3):694-704. doi:10.1177/03635465251411298
33. Mastroianni MA, Dillon MR, Reyes JL, et al. Return to play and performance following UCL reconstruction and repair in Major League Baseball position players. *Orthop J Sports Med*. 2026;14(3):23259671251413601. doi:10.1177/23259671251413601
34. Mastroianni MA, Kunes JA, Dillon MR, et al. Pitch performance after ulnar collateral ligament surgery in Major League Baseball pitchers. *Orthop J Sports Med*. 2026;14(4):23259671261424264. doi:10.1177/23259671261424264
35. Mastroianni MA, Kunes JA, El-Najjar DB, et al. Advanced analytic and pitch-tracking metrics associated with UCL surgery in Major League Baseball pitchers: a case-control study. *Orthop J Sports Med*. 2025;13(2):23259671241302432. doi:10.1177/23259671241302432
36. Mastroianni MA, Kunes JA, El-Najjar DB, et al. Return to performance after ulnar collateral ligament surgery in Major League Baseball pitchers. *Am J Sports Med*. 2025;53(1):104-114. doi:10.1177/03635465241289142
37. Mizels J, Erickson B, Chalmers P. Current state of data and analytics research in baseball. *Curr Rev Musculoskelet Med*. 2022;15(4):283-290. doi:10.1007/S12178-022-09763-6
38. Moore RC, Dowling B, Avedesian JM, Mitchell EC, Boswell MA, Gurchiek RD. Predicting peak elbow varus torque from ball tracking release metrics with machine learning in professional baseball pitchers. *NPJ Artif Intell*. 2026;2(1). doi:10.1038/S44387-026-00112-3
39. Office of the Commissioner of Baseball. *MLB Releases Report on Injuries to Pitchers*. Published December 17, 2024. Last Accessed June 8, 2026. http://www.documentcloud.org/documents/25460405-mlb-pitching-injuries/
40. 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. doi:10.1177/2325967119826540
41. Puga T, Scigliano N, Box M, Riehl J. The Major League Baseball pitch clock: first year analysis of pitcher injuries. *J Orthop*. 2024;57:133. doi:10.1016/J.JOR.2024.06.022
42. Quinn M, Ge J, Ham J, et al. Effect of ulnar collateral ligament reconstruction on performance in Major League Baseball pitchers: a 2-year analysis of advanced pitching statistics, velocity, and spin rate. *Am J Sports Med*. 2025;53(6):1460-1468. doi:10.1177/03635465251326907
43. 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. doi:10.4085/1062-6050-558-17
44. 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. doi:10.1177/2325967120966310
45. Van Trigt B, Vliegen L, Leenen T, Veeger DJ. The ulnar collateral ligament loading paradox between in-vitro and in-vivo studies on baseball pitching (narrative review). *Int Biomech*. 2021;8(1):19-29. doi:10.1080/23335432.2021.1916405
46. Vance DD, Alexander FJ, Kunkle BW, Littlefield M, Ahmad CS. Professional and amateur pitchers' perspective on the ulnar collateral ligament injury risk. *Orthop J Sports Med*. 2019;7(6):2325967119850777. doi:10.1177/2325967119850777
47. 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. doi:10.1177/0363546516643812
48. Whiteside D, Martini DN, Zernicke RF, Goulet GC. Ball speed and release consistency predict pitching success in Major League Baseball. *J Strength Cond Res*. 2016;30(7):1787-1795. doi:10.1519/JSC.0000000000001296
49. Whiteside D, Martini DN, Zernicke RF, Goulet GC. Changes in a starting pitcher's performance characteristics across the duration of a Major League Baseball game. *Int J Sports Physiol Perform*. 2016;11(2):247-254. doi:10.1123/IJSPP.2015-0121
50. Yu JS, Carr JB, Thomas J, et al. Trends in patient, physician, and public perception of ulnar collateral ligament reconstruction using social media analytics. *Orthop J Sports Med*. 2021;9(3):2325967121990052. doi:10.1177/2325967121990052
51. Zaremski JL, Farmer KW, Horodyski M. Workload, injury prevention and the quest for greater pitching velocity in adolescent baseball players: the sports medicine conundrum. *Br J Sports Med*. 2026;60(9):621-622. doi:10.1136/BJSPORTS-2025-110670
52. Zaremski JL, McClelland JA, Vincent HK, Horodyski MB. Trends in sports-related elbow ulnar collateral ligament injuries. *Orthop J Sports Med*. 2017;5(10):2325967117731296. doi:10.1177/2325967117731296

APPENDIX

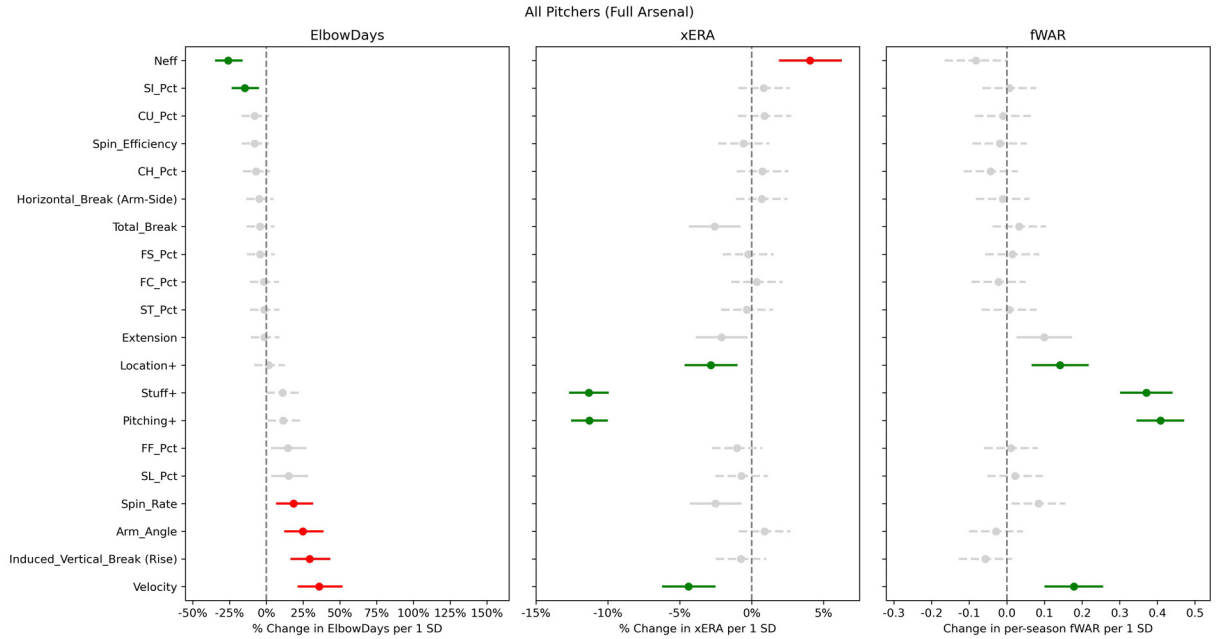


Figure A1. Forest plots showing associations between Statcast-based pitch metrics and performance/injury outcomes across all pitchers (2022-2025 MLB seasons; n = 406). Points represent effects per SD increase, with 95% CIs. Effects are shown as percentage change for ElbowDays and xERA and as absolute change for per-season fWAR. Color indicates direction of association, with per-outcome Holm correction (green = favorable, red = unfavorable, gray = nonsignificant). Statistical significance based on the less conservative Benjamini-Hochberg false discovery rate correction is indicated by line type, with solid lines representing significant effects and dashed lines representing nonsignificant effects. CH, changeup; CU, curveball; ElbowDays, days on MLB injured list due to an elbow injury; FC, cutter; FF, 4-seam fastball; FS, splitter; fWAR, FanGraphs wins above replacement; MLB, Major League Baseball; N_{eff}, effective number of pitch types; pct, percent usage; SI, sinker; SL, slider; ST, sweeper; xERA, expected earned run average.

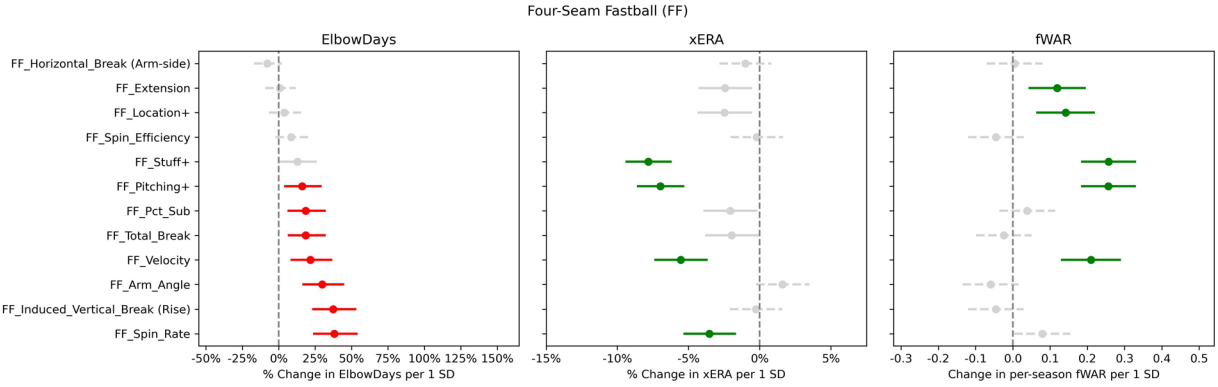


Figure A2. Forest plots showing associations between Statcast-based pitch metrics and performance/injury outcomes across pitchers who threw 4-seam fastballs (2022-2025 MLB seasons; n = 367). Points represent effects per SD increase, with 95% CIs. Effects are shown as percentage change for ElbowDays and xERA and as absolute change for per-season fWAR. Color indicates direction of association, with per-outcome Holm correction (green = favorable, red = unfavorable, gray = nonsignificant). Statistical significance based on the less conservative Benjamini-Hochberg false discovery rate correction is indicated by line type, with solid lines representing significant effects and dashed lines representing nonsignificant effects. ElbowDays, days on MLB injured list due to an elbow injury; FF, 4-seam fastball; fWAR, FanGraphs wins above replacement; MLB, Major League Baseball; N_{eff}, effective number of pitch types; pct, percent usage; xERA, expected earned run average.

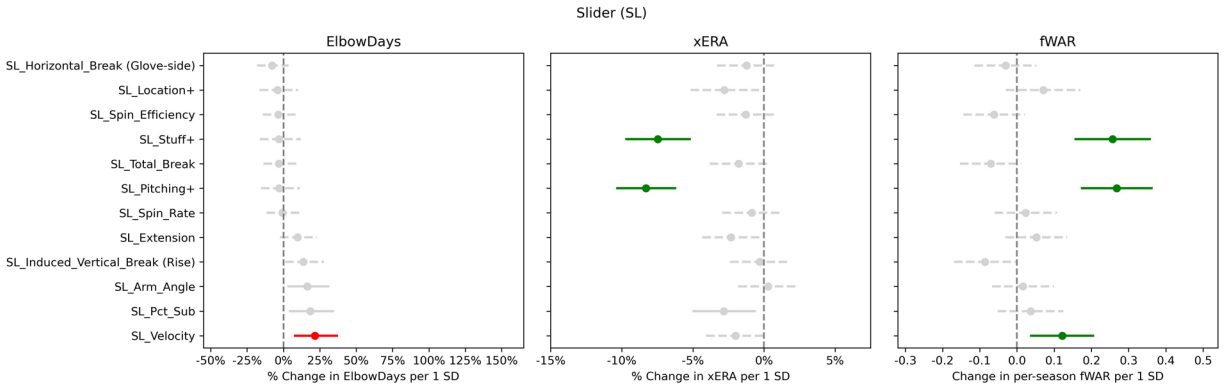


Figure A3. Forest plots showing associations between Statcast-based pitch metrics and performance/injury outcomes across pitchers who threw sliders (2022-2025 MLB seasons; n = 293 for all metrics except n = 217 for SL_Pitching+, SL_Stuff+, and SL_Location+). Points represent effects per SD increase, with 95% CIs. Effects are shown as percentage change for ElbowDays and xERA and as absolute change for per-season fWAR. Color indicates direction of association, with per-outcome Holm correction (green = favorable, red = unfavorable, gray = nonsignificant). Statistical significance based on the less conservative Benjamini-Hochberg false discovery rate correction is indicated by line type, with solid lines representing significant effects and dashed lines representing nonsignificant effects. ElbowDays, days on MLB injured list due to an elbow injury; fWAR, FanGraphs wins above replacement; MLB, Major League Baseball; N_{eff}, effective number of pitch types; pct, percent usage; SL, slider; xERA, expected earned run average.

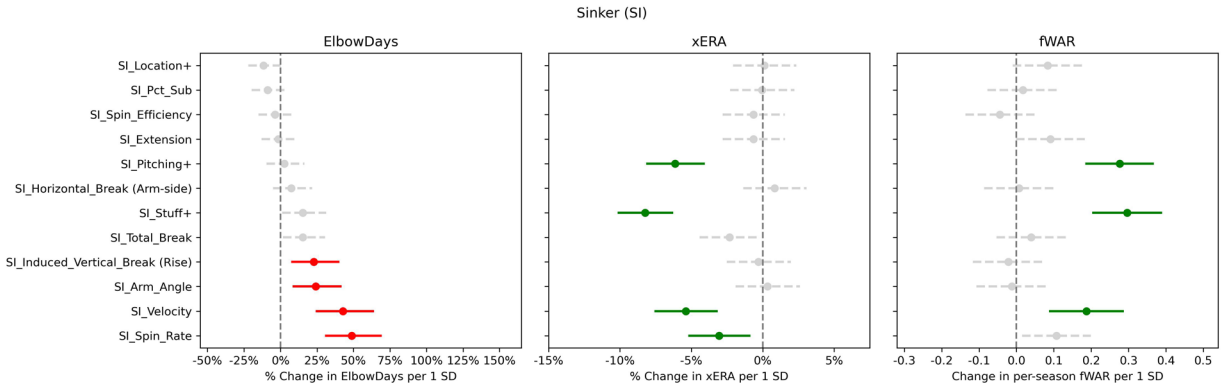


Figure A4. Forest plots showing associations between Statcast-based pitch metrics and performance/injury outcomes across pitchers who threw sinkers (2022-2025 MLB seasons; n = 258). Points represent effects per SD increase, with 95% CIs. Effects are shown as percentage change for ElbowDays and xERA and as absolute change for per-season fWAR. Color indicates direction of association, with per-outcome Holm correction (green = favorable, red = unfavorable, gray = nonsignificant). Statistical significance based on the less conservative Benjamini-Hochberg false discovery rate correction is indicated by line type, with solid lines representing significant effects and dashed lines representing nonsignificant effects. ElbowDays, days on MLB injured list due to an elbow injury; fWAR, FanGraphs wins above replacement; MLB, Major League Baseball; N_{eff}, effective number of pitch types; pct, percent usage; SI, sinker; xERA, expected earned run average.

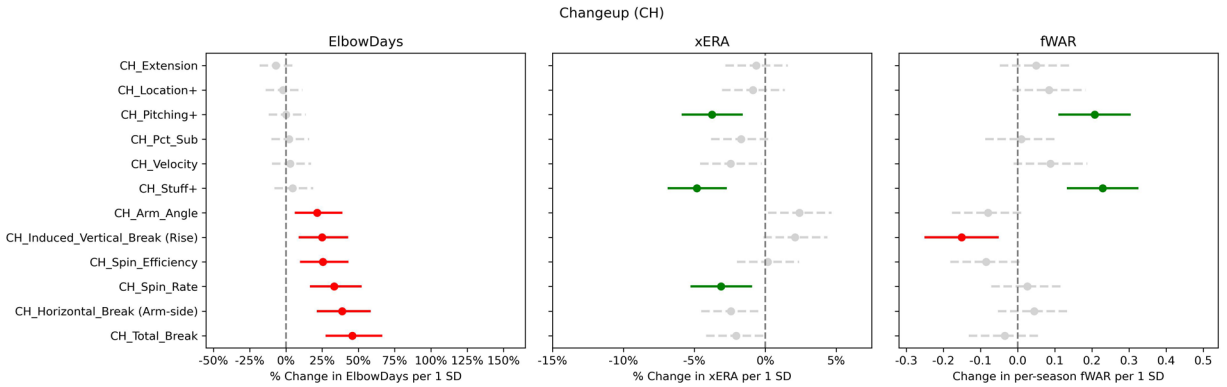


Figure A5. Forest plots showing associations between Statcast-based pitch metrics and performance/injury outcomes across pitchers who threw changeups (2022-2025 MLB seasons; n = 246). Points represent effects per SD increase, with 95% CIs. Effects are shown as percentage change for ElbowDays and xERA and as absolute change for per-season fWAR. Color indicates direction of association, with per-outcome Holm correction (green = favorable, red = unfavorable, gray = nonsignificant). Statistical significance based on the less conservative Benjamini-Hochberg false discovery rate correction is indicated by line type, with solid lines representing significant effects and dashed lines representing nonsignificant effects. CH, changeup; ElbowDays, days on MLB injured list due to an elbow injury; fWAR, FanGraphs wins above replacement; MLB, Major League Baseball; N_{eff}, effective number of pitch types; pct, percent usage; xERA, expected earned run average.

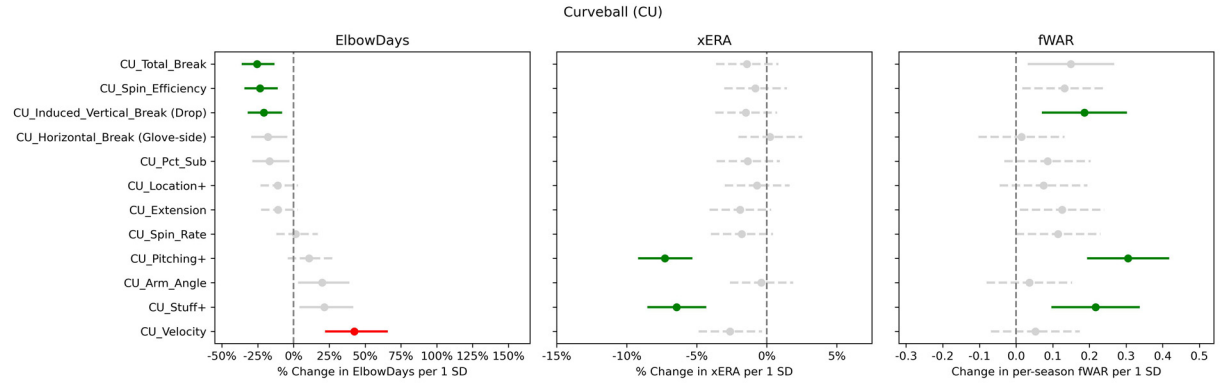


Figure A6. Forest plots showing associations between Statcast-based pitch metrics and performance/injury outcomes across pitchers who threw curveballs (2022-2025 MLB seasons; n = 198). Points represent effects per SD increase, with 95% CIs. Effects are shown as percentage change for ElbowDays and xERA and as absolute change for per-season fWAR. Color indicates direction of association, with per-outcome Holm correction (green = favorable, red = unfavorable, gray = nonsignificant). Statistical significance based on the less conservative Benjamini-Hochberg false discovery rate correction is indicated by line type, with solid lines representing significant effects and dashed lines representing nonsignificant effects. CU, curveball; ElbowDays, days on MLB injured list due to an elbow injury; fWAR, FanGraphs wins above replacement; MLB, Major League Baseball; N_{eff}, effective number of pitch types; pct, percent usage; xERA, expected earned run average.

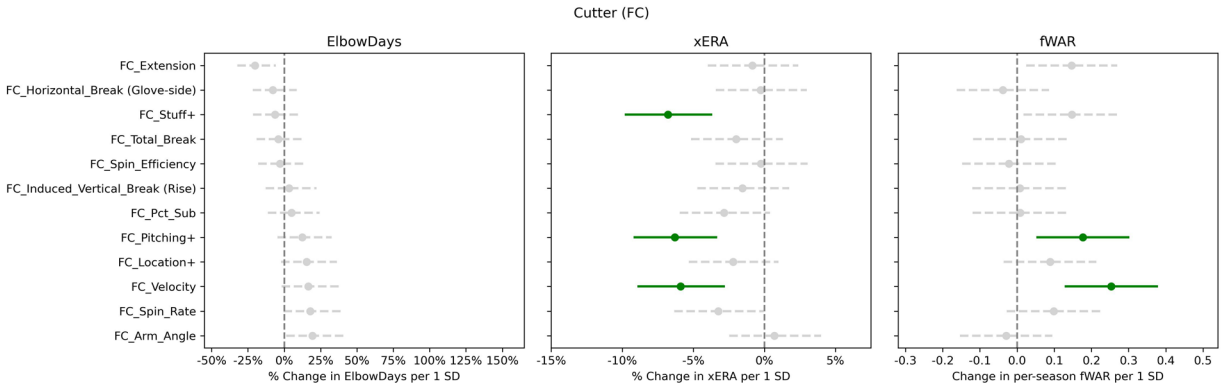


Figure A7. Forest plots showing associations between Statcast-based pitch metrics and performance/injury outcomes across pitchers who threw cutters (2022-2025 MLB seasons; n = 148). Points represent effects per SD increase, with 95% CIs. Effects are shown as percentage change for ElbowDays and xERA and as absolute change for per-season fWAR. Color indicates direction of association, with per-outcome Holm correction (green = favorable, red = unfavorable, gray = nonsignificant). Statistical significance based on the less conservative Benjamini-Hochberg false discovery rate correction is indicated by line type, with solid lines representing significant effects and dashed lines representing nonsignificant effects. ElbowDays, days on MLB injured list due to an elbow injury; FC, cutter; fWAR, FanGraphs wins above replacement; MLB, Major League Baseball; N_{eff}, effective number of pitch types; pct, percent usage; xERA, expected earned run average.

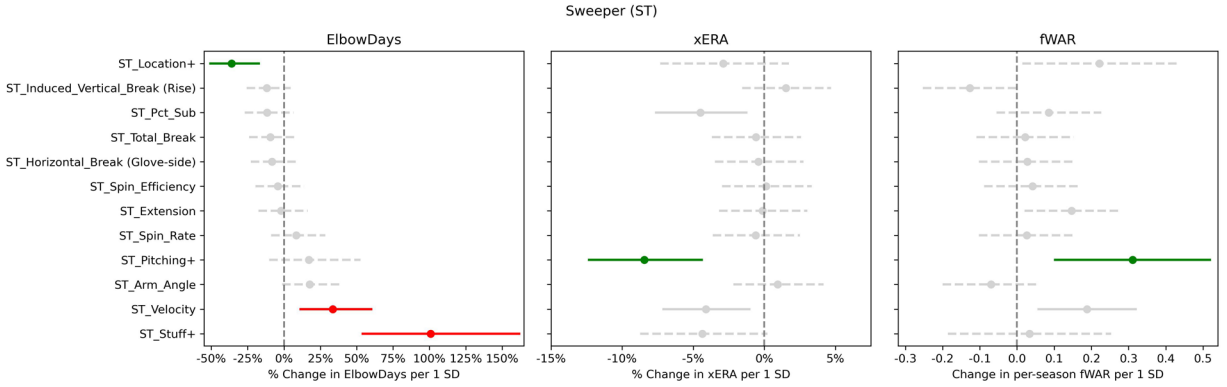


Figure A8. Forest plots showing associations between Statcast-based pitch metrics and performance/injury outcomes across pitchers who threw sweepers (2022-2025 MLB seasons; n = 138 for all metrics except n = 62 for ST_Pitching+, ST_Stuff+, and ST_Location+). Points represent effects per SD increase, with 95% CIs. Effects are shown as percentage change for ElbowDays and xERA and as absolute change for per-season fWAR. Color indicates direction of association, with per-outcome Holm correction (green = favorable, red = unfavorable, gray = nonsignificant). Statistical significance based on the less conservative Benjamini-Hochberg false discovery rate correction is indicated by line type, with solid lines representing significant effects and dashed lines representing nonsignificant effects. ElbowDays, days on MLB injured list due to an elbow injury; fWAR, FanGraphs wins above replacement; MLB, Major League Baseball; N_{eff}, effective number of pitch types; pct, percent usage; ST, sweeper; xERA, expected earned run average.

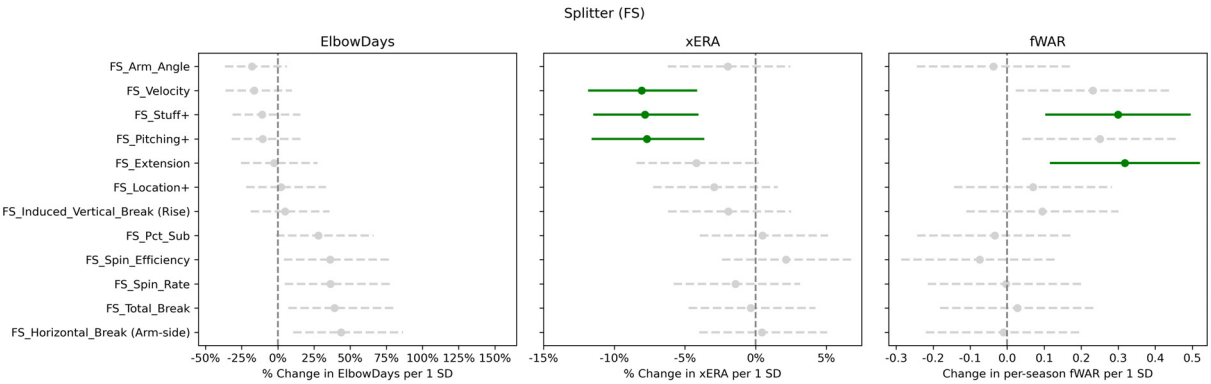


Figure A9. Forest plots showing associations between Statcast-based pitch metrics and performance/injury outcomes across pitchers who threw splitters (2022-2025 MLB seasons; n = 61). Points represent effects per SD increase, with 95% CIs. Effects are shown as percentage change for ElbowDays and xERA and as absolute change for per-season fWAR. Color indicates direction of association, with per-outcome Holm correction (green = favorable, red = unfavorable, gray = nonsignificant). Statistical significance based on the less conservative Benjamini-Hochberg false discovery rate correction is indicated by line type, with solid lines representing significant effects and dashed lines representing nonsignificant effects. ElbowDays, days on MLB injured list due to an elbow injury; FS, splitter; fWAR, FanGraphs wins above replacement; MLB, Major League Baseball; N_{eff}, effective number of pitch types; pct, percent usage; xERA, expected earned run average.