

Fastball Velocity and Elbow-Varus Torque in Professional Baseball Pitchers

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Context: High loads in the elbow during baseball pitching can lead to serious injuries, including injuries to the ulnar collateral ligament. These injuries have substantial implications for individual pitchers and their teams, especially at the professional level of competition. With a trend toward increased ball velocity in professional baseball, controversy still exists regarding the strength of the relationship between ball velocity and elbow-varus torque.

Objective: To examine the relationship between fastball velocity and elbow-varus torque in professional pitchers using between- and within-subjects statistical analyses.

Design: Cross-sectional study.

Setting: Motion-analysis laboratory.

Patients or Other Participants: Using the previously collected biomechanical data of 452 professional baseball pitchers, we performed a retrospective analysis of the 64 pitchers (52 right-hand dominant, 12 left-hand dominant; age = 21.8 ± 2.0 years, height = 1.90 ± 0.05 m, mass = 94.6 ± 7.8 kg) with fastball velocity distributions that enabled between- and within-subjects statistical analyses.

Main Outcome Measure(s): We measured ball velocity using a radar gun and 3-dimensional motion data using a 12-camera automated motion-capture system sampling at 240 Hz. We calculated elbow-varus torque using inverse-dynamics techniques and then analyzed the relationship between ball velocity and elbow torque using both a simple linear regression model and a mixed linear model with random intercepts.

Results: The between-subjects analyses displayed a weak positive association between ball velocity and elbow-varus torque ($R^2 = 0.076$, $P = .03$). The within-subjects analyses showed a considerably stronger positive association ($R^2 = 0.957$, $P < .001$).

Conclusions: When comparing 2 professional baseball pitchers, higher velocity may not necessarily indicate higher elbow-varus torque due to the confounding effects of pitcher-specific differences (eg, detailed anthropometrics and pitching mechanics). However, within an individual pitcher, higher ball velocity was strongly associated with higher elbow-varus torque.

Key Words: biomechanics, pitching, throwing, ulnar collateral ligament, Tommy John surgery

Key Points

- Across large groups of professional baseball pitchers, higher velocity was associated with higher elbow-varus torque; however, when comparing 2 individuals, higher velocity may not necessarily indicate higher elbow-varus torque.
- Within-subjects analyses suggested that a deliberate reduction in velocity will reduce the load on an individual pitcher's elbow.
- Pitchers should focus on using good mechanics, developing command, and learning to vary their velocity for each pitch based on the game situation.
- Future researchers should explore the relationship between ball velocity and performance through both between- and within-subjects analyses.

Baseball pitching is a highly dynamic task that places high loads on joints and structures throughout the body, especially in the throwing arm. Through comprehensive coordination of their muscles and joints, professional baseball pitchers are able to release the baseball at speeds approaching and sometimes exceeding 100 miles per hour (approximately 45 m/s).¹ This requires the upper extremity to achieve extraordinary angular velocities (ie, faster than any other human motion)² and endure hazardous loads (eg, elbow-varus torque >100 Nm).³ Therefore, it is not surprising that professional pitchers are frequently injured and have an upper extremity injury incidence rate almost 3 times higher than that of their position-player counterparts.⁴ Roughly two-thirds of all injuries to pitchers affect the shoulder or elbow.⁴ However,

whereas shoulder injuries are slightly decreasing, elbow injuries are increasing.⁵ The prevalence of ulnar collateral ligament (UCL) injuries is of particular concern, as 25% of all Major League Baseball (MLB) pitchers have a history of UCL reconstruction surgery,⁶ and this surgery typically requires a long recovery period (12–24 months).^{6–8}

Physicians, baseball professionals, and the media lately have suggested that the recent surge in ball velocity in MLB may be responsible for the concurrent rise in UCL injuries.^{9,10} Researchers^{11–16} have begun to address this possible relationship using a variety of statistical methods. Overall, the results of these studies have suggested that increased velocity does increase the injury risk. However, they have also suggested that this relationship is complicated by factors such as between-subjects differences (ie,

velocity explains a small minority of the between-subjects variance). Considering that investigators¹⁷ have suggested that injury risk may be correlated with elbow loading, an understanding of the influence of velocity on elbow-varus torque may help clarify the connection between velocity and injury. Authors of 2 recent studies^{18,19} examined the relationship between velocity and varus torque but in pitchers at lower levels of competition (ie, collegiate and high school pitchers). Furthermore, the authors disagreed about the strength of the relationship between velocity and varus torque and whether the relationship was statistically significant. Post et al¹⁹ proposed that this discrepancy may have been due to the influence of confounding factors, such as between-subjects differences (eg, pitching mechanics). Therefore, the purpose of our study was to examine the relationship between ball velocity and elbow-varus torque in professional baseball pitchers through both between- and within-subjects statistical analyses. We hypothesized that ball velocity would explain (1) only a small percentage of the between-subjects variance in elbow-varus torque but (2) a much higher percentage of the within-subjects variance in elbow-varus torque.

METHODS

Participants

We obtained the data for this study via a retrospective review of the pitching biomechanics database at the American Sports Medicine Institute (ASMI). This database consists of baseball pitchers' biomechanical data previously collected by ASMI. At the time of the retrospective review, the database included 452 professional (ie, major and minor league) pitchers. For their data to be included in our study, pitchers must not have had a *substantial injury*, which we defined as one requiring them to miss playing time in the 12 months before testing. In addition, during the testing session, all included pitchers threw at least 5 fastball trials, exhibited a velocity range of at least 2.2 m/s (5.0 mi/h), and had no single pitch trial that accounted for more than half of the velocity range. These inclusion criteria ensured that all pitchers analyzed in this study had ball-velocity distributions that enabled both between- and within-subjects statistical analyses. We performed subsequent analyses on the data from the 64 professional baseball pitchers (52 right-hand dominant, 12 left-hand dominant; age = 21.8 ± 2.0 years, height = 1.90 ± 0.05 m, mass = 94.6 ± 7.8 kg) who met the inclusion criteria. We defined the *dominant hand* as the hand with which the players pitched. The Institutional Review Board at St Vincent's Health System (Birmingham, AL) approved this study.

Biomechanical Data

At the time of testing, participants wore tight-fitting elastane shorts, socks, and athletic shoes. We attached a set of 38 retroreflective markers (Motion Analysis Corp, Santa Rosa, CA) to participants²⁰ that included markers placed on the throwing arm at the lateral superior tip of the acromion, elbow epicondyles (lateral and medial), proximal third of the ulna, styloid processes (ulnar and radial), and between the second and third distal metacarpals. Before data collection began, participants conducted their typical pregame warmup routines, which generally involved stretching, nonthrowing

drills, and throwing drills. Next, they threw an unspecified number of warmup pitches until they were ready to pitch with full effort. Participants threw pitches (warm-up pitches and subsequent full-effort pitches) off a mound toward a target strike zone located above home plate. Mound height and slope and the distance between the pitching rubber and home plate conformed to MLB regulations.

After concluding their warmups, participants threw a minimum of 5 full-effort fastballs at a self-selected pace, during which ball velocity, pitch location, and pitcher kinematic data were collected. Ball velocity for each pitch was recorded using a radar gun (Stalker Sports Radar, Plano, TX), and 3-dimensional motion data were collected using an automated motion-capture system (Motion Analysis Corp) sampling at 240 Hz. Marker position-time data were filtered using a fourth-order low-pass Butterworth filter with a cutoff frequency of 13.4 Hz.³ For each pitch, we calculated the varus torque at the throwing elbow throughout the pitch motion in BioPitch software (ASMI, Birmingham, AL), using the motion data; estimated mass properties of the arm, forearm, hand, and ball^{1,3}; and standard inverse-dynamics equations.¹ The baseball was modeled as a 0.142-kg point mass, fixed to the hand, and present only until the instant of ball release.¹ For each pitch, we determined the maximum elbow-varus torque and normalized it (ie, expressed it as a percentage of the product of body weight and height) to enable between-subjects comparisons.

Statistical Analyses

To determine if a relationship existed between ball velocity and normalized maximum elbow-varus torque, a set of statistical analyses were performed. To ensure no systematic differences were present in the quality of pitches thrown at high or low velocity by each player, we calculated each player's mean ball velocity and standard deviation (SD) and then categorized each pitch as *low*, *average*, or *high velocity* within each respective pitcher. Next, we compared these 3 categories of pitches against pitch location (ball versus strike) using a 1-way repeated-measures analysis of variance.

We established the between-subjects relationship between ball velocity and normalized maximum elbow-varus torque using simple linear regression between each player's mean ball velocity and mean normalized maximum elbow-varus torque. Similarly, we established the within-subjects relationship between ball velocity and normalized maximum elbow-varus torque using a mixed linear model with random intercepts. An R^2 statistic was calculated for this model by comparing its residual variance (residual $\text{Var}_{\text{model}}$) against the residual variance of the random intercept alone (residual Var_{int})²¹:

$$R^2 = (\text{Residual Var}_{\text{int}} - \text{Residual Var}_{\text{model}}) / \text{Residual Var}_{\text{int}}.$$

The α level for all tests was set a priori at .05. All statistical analyses were performed using SAS (version 9.4; SAS Institute Inc, Cary, NC).

RESULTS

We observed no systematic differences in the quality of pitches thrown at low, average, or high velocity ($P > .05$).

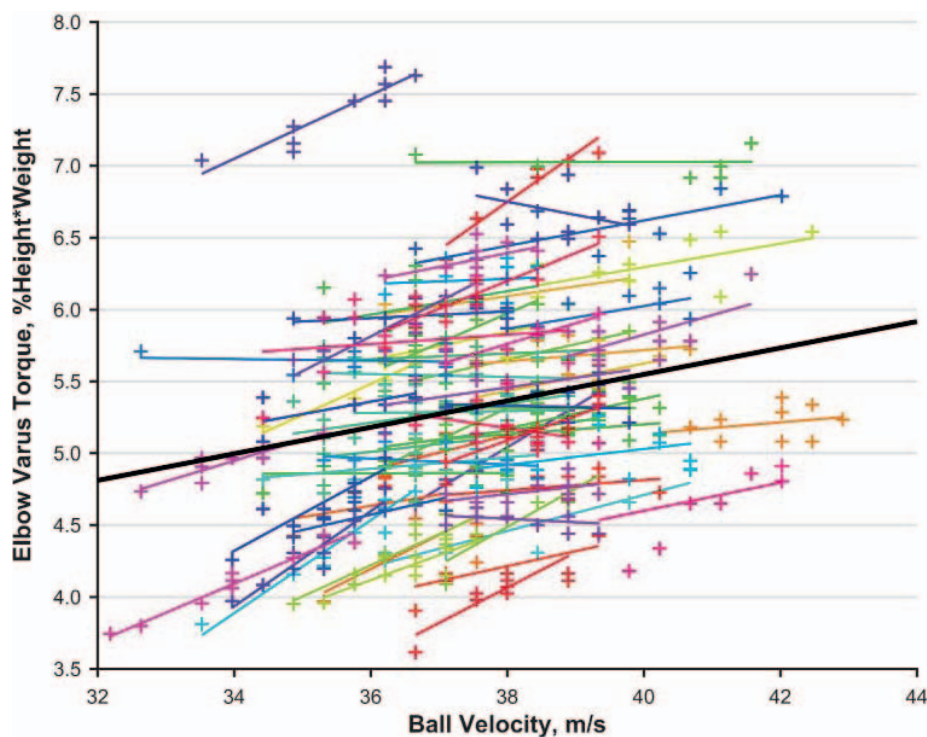


Figure 1. Plot of normalized maximum elbow-varus torque versus ball velocity. Each pitcher is represented by a series of points and the best-fit line in one color, whereas the regression line from the linear mixed model is represented by the thick black line. This model suggested a strong positive relationship between varus torque and velocity ($R^2 = 0.957$).

Across all pitchers, the mean fastball velocity was 37.6 ± 1.5 m/s (84.1 ± 3.5 mi/h), and the within-subjects range of fastball velocity was 2.84 ± 0.72 m/s (6.36 ± 1.61 mi/h). The between-subjects mean value for normalized maximum elbow-varus torque was $5.33\% \pm 0.74\%$ body weight \times height. The results of the statistical analyses are provided in the Table. The simple linear regression model indicated a weak positive association between ball velocity and elbow-varus torque at the between-subjects level. The linear mixed model (with random intercepts) indicated a considerably stronger positive association between ball velocity and elbow-varus torque when performing within-subjects comparisons. A plot of normalized maximum elbow-varus torque versus ball velocity for all pitch trials is provided in Figure 1.

DISCUSSION

Whereas both sets of analyses showed associations, ball velocity explained only 7.6% of the between-subjects variance in elbow-varus torque but 95.7% of the within-subjects variance. These results confirmed our hypotheses and suggested that, whereas between-subjects variability makes it unwise to assume that 1 pitcher has a higher varus torque than another based solely on their ball velocities, a deliberate reduction in velocity without compromising

mechanics will likely reduce the load on an individual pitcher's elbow.

The weak positive association between ball velocity and elbow-varus torque across professional pitchers suggested that increased velocity contributes to increased torque but that additional factors may confound individual comparisons. These results were consistent with those reported by previous researchers^{18,19} who investigated lower levels of competition (ie, collegiate and high school pitchers). Among 26 high school pitchers, Hurd et al¹⁸ found a slightly stronger positive association between ball velocity and elbow-varus torque ($R^2 = 0.373$, $P < .01$). Post et al¹⁹ observed no difference and a lower coefficient of determination in their analysis of 67 collegiate pitchers ($R^2 = 0.040$, $P = .053$). In 3 recent evaluations of fastball velocity in MLB pitchers before UCL injury and matched controls, investigators reported slightly higher ball velocity in the UCL injury group, but they disagreed about whether the small difference was statistically significant (UCL group = 40.9 m/s, control group = 40.8 m/s, $P = .69$ ¹²; UCL group = 41.0, control group = 40.7 m/s, $P = .014$ ¹³; and UCL group = 41.2 m/s, control group = 40.8 m/s, $P > .05$ [the exact P value was not reported]¹⁴). Using a univariate logistic regression model, Prodromo et al¹⁴ also noted that fastball velocity was a predictor of UCL reconstruction in MLB pitchers ($P = .001$). Researchers^{15,16} using multivariate regression reported that their models, which incorporated ball velocity and other important predictors, could only explain a small amount of the variance (7%–20%). The authors^{15,16,19} of many of these studies theorized that between-subjects differences may have obscured the effect of ball velocity. This theory is supported by our results and by investigators who showed that between-subjects differ-

Table. Correlation of Ball Velocity to Normalized Maximum Elbow-Varus Torque

Statistical Test	R^2 Value	P Value
Between subjects (simple linear regression)	0.076	.03
Within subjects (linear mixed model)	0.957	<.001

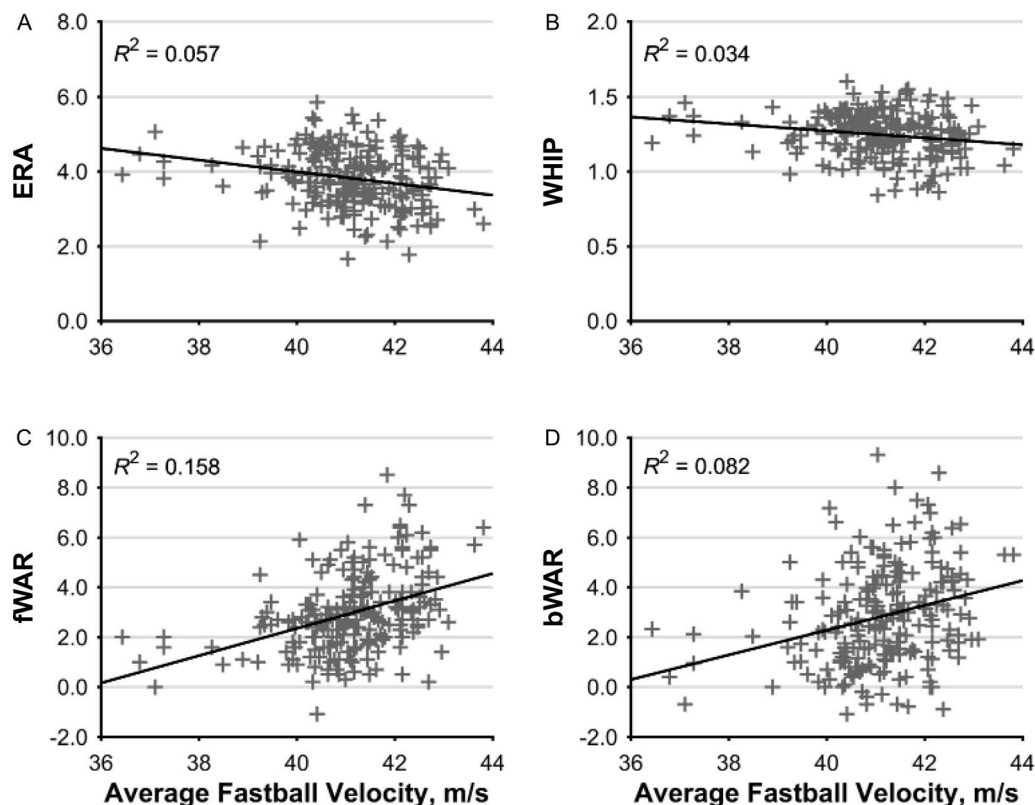


Figure 2. Plots of pitching performance metrics versus average fastball velocity for 2015–2017 Major League Baseball pitchers who qualified for the earned-run-average (ERA) title, including simple linear-regression best-fit lines. A, ERA. B, Walks plus hits per inning pitched (WHIP). C, Fangraphs wins above replacement (fWAR; <https://www.fangraphs.com/>). D, Baseball Reference wins above replacement (bWAR; <https://www.baseball-reference.com/>). All metrics showed associations with velocity ($P < .05$), but the coefficient of determination (R^2) values were low. Whereas commonly used in the baseball community to assess player performance, wins above replacement does not have 1 standardized formula. This Figure includes plots for the 2 most widely accepted versions: from Fangraphs and Baseball Reference. Data for average fastball velocity, ERA, and WHIP were also obtained from the Fangraphs Web site.

ences (eg, pitching mechanics^{22–24} and anthropometrics^{25,26}) affected elbow-varus torque.

In contrast to previous researchers, we also used a more detailed statistical model that examined within-subjects variation while accounting for between-subjects differences (ie, a linear mixed model with random intercepts), and these results revealed a considerably stronger association between ball velocity and elbow-varus torque. Whereas the model allowed for a different intercept for each pitcher to account for unmodeled between-subjects differences, the slope of the best-fit line remained fixed across participants. The model, therefore, suggested that for every 1.0-m/s increase in ball velocity, varus torque increased by 0.092% (body weight \times height). For the average pitcher in our study (height = 1.90 m, mass = 94.6 kg), this would equate to a 1.62-Nm increase in elbow-varus torque for every 1.0 m/s increase in ball velocity. Considering the fact that many MLB pitchers throw more than 3000 pitches each season and the extensive literature on the dangers of pitch volume and the resulting accumulated load,^{9,13,27–30} these findings indicated that a pitcher may be able to reduce his elbow-injury risk by deliberately varying the velocity at which he throws each pitch.

Given that the prevailing assumption among baseball professionals of a strong, positive relationship between fastball velocity and performance¹⁰ will likely discourage pitchers from deliberately moderating their fastball velocity, we examined this potential relationship with a set of

post hoc analyses of MLB pitcher performance over 3 seasons (2015–2017) using both traditional (earned run average and walks plus hits per inning pitched) and emerging (wins above replacement) performance metrics. Fastball velocity was weakly correlated with these metrics (Figure 2), which suggests that the strength of the relationship between ball velocity and performance may be overstated. Researchers should further explore these relationships by including measures of velocity variability or individual pitch velocities and outcomes.

Our study had a few potential limitations. First, ball velocities were somewhat diminished from reported in-game velocities, similar to the findings reported by previous authors³¹ who collected data in non-game settings. Whereas this may have also led to a slight underestimate of elbow-varus torque compared with in-game values, the overall trends and study conclusions were likely unaffected. In-game data collection is not currently feasible, but emerging technologies may remove this limitation in the future. Second, the inverse-dynamics model that we used assumes similar body anthropometrics across participants, scaling only for size differences (eg, height, weight, and limb lengths). Whereas potentially uncaptured anthropometric differences could have contributed to the weakness of the between-subjects correlation, they should have minimally influenced the within-subjects results. Third, although net elbow-varus torque is frequently used as a surrogate for load on the UCL, the ligament does not absorb the entire

load, as muscular and osseous structures can contribute. Future biomechanical modeling is needed to calculate specific loads on the UCL and other tissues and structures. Fourth, we examined the relationship between ball velocity and elbow-varus torque but did not attempt to directly relate ball velocity to elbow-injury rate. Researchers should examine the association of within-subjects velocity variance and injury development. Fifth, we exclusively examined the fastball, only 1 of a number of pitches that professional baseball pitchers employ. Researchers should investigate the influence of velocity on elbow-varus torque in other throws (eg, curveballs, changeups, and other pitch types as well as warmup and training throws).

CONCLUSIONS

Our results suggested that, whereas between-subjects comparisons were obscured by participant-specific attributes, a deliberate reduction in velocity without compromising mechanics will likely reduce the load on an individual pitcher's elbow. We believe that pitchers should focus on using good mechanics, developing command, determining the minimum level of pitch intensity necessary to obtain the outcome they desire for each of their pitches, and learning to recognize when using maximum velocity becomes necessary. Major League Baseball teams with the ability to recognize when pitchers lack these attributes (ie, pitchers who require "maximum effort" for success) may be able to avoid potentially costly mistakes.

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