The Impact of Fatigue on the Kinematics of Collegiate Baseball Pitchers

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Background: Many factors are believed to contribute to throwing injuries in baseball pitchers, in particular overuse and poor throwing mechanics. The impact of fatigue on pitching biomechanics in live-game situations is not well understood.

Hypothesis: Pitchers will demonstrate significant deviation in their pitching motions with increasing levels of fatigue.

Study Design: Descriptive laboratory study.

Methods: Eleven National Collegiate Athletic Association (NCAA) Division I collegiate baseball pitchers were filmed in multiple live-game situations throughout a single season using 2 orthogonal high-speed cameras at 120 Hz. The first fastball of each inning and, when available, the fastball subsequent to the 15th and 30th pitch of each inning were recorded and analyzed for 26 kinematic parameters. Pitch count and velocity were recorded. Kinematic differences were assessed for association with pitch count and subjective fatigue measures over the course of each inning and game through the season.

Results: Twenty-six games were recorded. Pitchers had a mean of 97.2 ± 16.1 pitches per start and 1079 ± 251 pitches per collegiate season. Increased hip lean at hand separation, elbow height at foot contact, and hip flexion and shoulder tilt at maximum external rotation were seen in innings lasting longer than 15 pitches. Maximum external rotation of the shoulder and elbow height at foot contact decreased over the course of a game. Hip lean at hand separation and elbow height at foot contact increased over the course of the season. Season pitch count was weakly correlated with increased shoulder external rotation and shoulder alignment at maximum external rotation and with shoulder abduction at ball release. Elbow flexion decreased with greater season pitch counts.

Conclusion: Hip lean, elbow height, and shoulder external rotation were the most sensitive kinematic parameters to inning, game, and season fatigue. Pitch count and fatigue have a significant impact on live-game pitching kinematics.

Clinical Relevance: Fatigue likely alters pitching mechanics. Recognition of kinematic alterations may better demonstrate fatigue-related injury risk and may assist injury prevention in addition to standardized limitations of innings and pitches thrown.

Keywords: baseball; pitching; throwing; biomechanics; fatigue; injury
35% annual incidence of elbow and shoulder pain, respectively.\textsuperscript{13,14}

In addition to the number of pitches thrown, other factors such as pitch type, velocity, physical condition of the player, and pitching mechanics have been implicated as contributors to the high rate of injuries in baseball. As such, the biomechanics of pitching has been a particularly prominent focus of recent research. Various studies have aimed to quantify the stresses placed on the upper extremity throughout the pitching motion, and authors have concluded that proper mechanics are important for reducing arm strain.\textsuperscript{3-5,22} In particular, excessive humeral internal rotation torque and elbow valgus load have been identified as major causes of stress on the upper extremity during pitching.\textsuperscript{19,20} It is clear that pitching biomechanics affect the degree of stress on the arm of baseball pitchers, and it is important to understand the factors that may affect the pitching motion.

It has been hypothesized that fatigue is a major factor affecting the quality of pitching mechanics. Indeed, it has been shown that a pitcher experiences significant muscle fatigue during an individual game performance,\textsuperscript{14} making it difficult to maintain ideal pitching mechanics. The goal of this study was to determine the role of fatigue on the pitching kinematics of baseball players at the collegiate level in a live-game setting. Specifically, mechanical aspects of pitching were methodically recorded to assess for motion deviations over the duration of an inning, duration of games, and duration of the season. Self-reported levels of fatigue were also collected to assess for an association with changes in the measured parameters. While previous studies have used high-resolution video technology to analyze the pitching motion as pitchers fatigue, 1 study was conducted in a controlled laboratory setting and the other study in individual live-game performances of professional pitchers.\textsuperscript{5,15} The present study maintains the additional stresses inherent to pitching in a live game and also extends analysis of the pitching motion over the entirety of a baseball season. Understanding the impact of fatigue on the biomechanics of the pitching motion may better guide recommendations for adequate rest and help prevent injury in the collegiate-level player. We hypothesized that pitchers would demonstrate significant deviations in pitching motion with increasing levels of fatigue.

MATERIALS AND METHODS

After institutional review board approval, 11 healthy National Collegiate Athletic Association (NCAA) Division I starting pitchers consented to be filmed during the 2012 spring baseball season. Pitchers from 3 different teams were studied (3 pitchers each from 2 teams and 5 pitchers from 1 team) to remove bias from any single preseason conditioning program. All pitchers were uninjured at the beginning of the season and had never undergone surgery on their throwing arms. The mean age was 20.1 ± 0.8 years, mass 90.1 ± 10.2 kg, and height 1.90 ± 0.08 m. The pitchers completed a questionnaire on their off-season throwing activities and physical conditioning.

During regularly scheduled games in the spring intercollegiate season, each pitcher was filmed using 2 high-speed cameras (Qualysis Motion Capture Systems) at 120 Hz. The 2 cameras were positioned off of the baseball field, with 1 camera directly behind home plate and the other perpendicular to the arm side of the pitcher (Figure 1). The camera lateral to the pitcher was estimated to be orthogonal to the plane of the pitch. The cameras were synchronized and stationed at the same positions at each baseball field to allow for consistent measurement of kinematic parameters. The first fastball of each inning was recorded, and when applicable, the first fastball after the 15th pitch and 30th pitch of the inning were also recorded. Filming commenced with the first pitch of the game and was completed when the pitcher’s performance was done. Data such as pitch count, duration of each inning, duration of rest between innings, and pitch velocity were recorded. After the game, each pitcher completed a questionnaire rating subjective measures of fatigue. Data included a binary self-assessment of the pitcher’s ability to continue pitching and a rating of the degree of fatigue felt at the beginning and at the end of the game. Fatigue was quantified using a 10-point visual analog scale, with the player marking his level of energy on a 10-cm line between “completely fatigued” and “fully rested.”

Each recorded fastball was analyzed using Dartfish software. Twenty-six kinematic points were measured based on similar studies.\textsuperscript{5,7} The throwing motion was divided into 6 phases: balance point, hand separation, foot contact, maximum external rotation, ball release, and follow through (Figure 2). As noted in Tables 1 through 4, multiple measurements were performed at each of the 6 phases of throwing. Angles were measured using joint centers, with hip and shoulder alignments and hip flexion measured with reference to a horizontal axis (Figures 3 and 4). Of note, elbow height was measured as the distance from the elbow to the shoulder from an orthogonal view. Therefore, any
increase in this value was interpreted in a drop in elbow height with reference to the ground, as is often referenced by pitchers and coaches. To determine the precision of the measurements using this methodology, 6 independent trials separated by at least 1 week were performed. Each trial consisted of measuring all 26 parameters of 1 recorded pitch. The standard deviation of linear measurements resulted in a mean of 0.01 m (range, 0.00-0.02 m) and mean of 2.26° (range, 1.19°-5.01°) for angular measures. All measurements were performed by a single member of the research team to avoid interobserver error.

Statistical analysis was performed using SPSS software (IBM Corp) to determine significant changes in the kinematic parameters. Analysis was performed to determine differences in parameter measures within each inning, game, and the season. Wilcoxon signed-rank tests were used to compare individual parameters at different time points. Analysis also included F tests to compare the variability of each parameter at the beginning versus the end of games and early versus late in the season. Finally, the Pearson correlation was used to discover trends as game and seasonal pitch counts increased. Statistical significance was established at \( P < .05 \).

RESULTS

Demographics

Eleven starting pitchers from 3 NCAA Division I collegiate baseball programs were filmed in 26 starts throughout the 2012 regular season. Nine pitchers were right-handed. They pitched for 1.6 ± 0.5 teams per year, which included their collegiate team and possibly an additional team during the summer, and reported playing no other positions. Seven of 11 pitchers reported a history of arm injuries that included ulnar collateral ligament inflammation, bursitis, tendinitis, partial labrum tear, and impingement; however, none of them were injured during the 2012 season.

Off-Season and Conditioning

The off-season for the pitchers consisted of 1.4 ± 0.8 months without throwing and 2.4 ± 0.8 months away from pitching. On average, they resumed throwing an average 1.9 months before the start of the season. Weight lifting was performed 3.6 ± 1.0 times per week, shoulder exercises 4.7 ± 1.6 times, and cardiovascular exercise 5.2 ± 1.3 times. The physical conditioning was continued during the baseball season for all athletes.

Inning Fatigue

The 26 games filmed consisted of 162 innings during which the starting pitcher remained in the game. Sixty-two of these innings lasted more than 15 pitches, and 5 innings lasted more than 30 pitches. To determine whether there were differences in pitchers’ mechanics early in an inning compared with late in an inning, statistical analysis was performed to compare the parameters of the first fastball of an inning against that of the fastball following the 15th pitch of an inning within each game. Long innings (those lasting more than 15 pitches) showed increases in hip lean at hand separation, stride length at foot contact, and hip flexion at maximum external rotation and ball release. The elbow height at foot contact was elevated with respect to the ground, and the shoulders had greater tilt at maximum external rotation. Decreases in drive knee flexion at maximum external rotation and shoulder abduction (mean, 1.7°) at ball release were found at the end of long innings as well (Table 1).
For all games with multiple innings lasting longer than 15 pitches (n = 23), the measures of the innings’ first fastballs were averaged and compared with the average measurements of the fastballs recorded after the 15th pitch. Similar differences as shown among individual innings were seen when averaged, except the drive knee flexion at maximum external rotation was no longer significant. In addition, the hand height and glove height relative to the pitching rubber significantly decreased in innings lasting more than 15 pitches.

The variability of the pitchers’ mechanics was determined by analyzing the standard deviations of each parameter between the first fastball and the fastball following the 15th pitch of the inning within each game. Between the first fastball and fastball following the 15th pitch of each inning, the variance decreased in elbow flexion and hip alignment at maximum external rotation. The variance increased in stride length at foot contact and stride knee flexion and shoulder alignment at maximum external rotation.

### Game Fatigue

The subjects pitched an average of 96.7 ± 16.1 pitches per game, or 6.3 ± 1.6 full innings, yet always reported in the questionnaires that they could have continued pitching regardless of pitch count. Despite a mean increase of 17.8% ± 14.1% in subjective fatigue reported at the end of games, there was not a significant decline in velocity from the beginning of games to the end (38.6 ± 1.5 vs 38.4 ± 1.5 m/s, respectively).

Analysis was performed to compare the mechanical parameters of the first fastball of the first inning versus the first fastball of the last inning pitched. There was a statistically significant decrease in maximum shoulder external rotation by 2.3° and glove height at ball release and follow through at the end of the game. Similar results were found when the average of the first 3 innings’ first fastballs were compared with the average of the first fastball in the last 3 innings in games lasting at least 6 innings (Table 2).

The variance of mechanical measurements in the first 3 innings differed from the last 3 complete innings pitched (in performances lasting at least 6 innings, n = 17) with decreased variation at the end of the game in the stride knee flexion at balance point, hip lean as the hands separate, and elbow flexion and glove height at ball release. Increased variance was seen late in the game in the maximum shoulder external rotation.

As pitch counts increased, there was a weak negative association with elbow height at foot contact (r = 0.32), indicating the height of the elbow was at a lower position. Correlating the parameters with the subjective change in fatigue over the course of the game, there was a weak negative association with stride knee flexion at maximum external rotation (r = −0.51) and a weak positive association with glove height at follow through (r = 0.46) as subjective fatigue increased.

### Season

Over the course of the collegiate baseball regular season, the 11 pitchers averaged 1079 ± 251 pitches. Analyzing the parameters for the first fastball of every game revealed increased lean with the hips at hand separation and stride knee flexion at ball release as the season progressed. A 5° increase in hip lean as the hand separates from the glove was also found when comparing the mean of the fastballs from the first 3 innings from games early in the season against those late in the season. Late-in-the-season changes were also seen at the end of games through analysis of the first fastball thrown in the last inning of each performance, revealing an elevation of elbow height of 1.7 cm with respect to the ground at foot contact. There is also a decrease in the glove height at ball release in the last inning at the end of the season (Table 3).

At the end of the season, the variability early in games increased in the stride knee flexion at balance point; however, the elbow flexion at ball release and stride knee flexion at maximum external rotation showed decreased variability. The end of games revealed increased variability.

### Table 1

| Parameter                                      | 1st vs 15th Pitch of an Inning* | Mean    | SD     |
|------------------------------------------------|---------------------------------|---------|--------|
| 2. Hand separation                             |                                 | 0.022   | 0.007  | 0.299  |
| Hip lean                                      |                                 | >.999   | >.999  | >.999  |
| Hand on top of ball                            |                                 | >.999   | >.999  | >.999  |
| 3. Foot contact                                |                                 | <.001   | 0.002  | <.001  |
| Stride length                                 |                                 | 0.691   | 0.394  | 0.704  |
| Drive knee flex                                |                                 | 0.843   | 0.808  | 0.940  |
| Elbow height                                  |                                 | 0.038   | 0.042  | 0.293  |
| Stride toward plate                            |                                 | >.999   | >.999  | >.999  |
| 4. Max external rotation                       |                                 | 0.462   | 0.433  | 0.030  |
| Elbow flex                                    |                                 | 0.233   | 0.455  | 0.018  |
| Hip alignment                                 |                                 | 0.048   | 0.048  | 0.014  |
| Shoulder alignment                             |                                 | 0.112   | 0.224  | 0.243  |
| Max external rotation                         |                                 | 0.987   | 0.648  | 0.010  |
| Drive knee flex                                |                                 | 0.049   | 0.181  | 0.254  |
| Hip flex                                      |                                 | 0.002   | 0.013  | 0.022  |
| 5. Ball release                                |                                 | 0.009   | 0.017  | 0.103  |
| Shoulder abd                                   |                                 | 0.717   | 0.455  | 0.277  |
| Elbow flex                                    |                                 | 0.369   | 0.361  | 0.914  |
| Glove height                                  |                                 | 0.418   | 0.670  | 0.011  |
| Stride knee flex                               |                                 | 0.217   | 0.287  | 0.534  |
| Drive knee flex                                |                                 | <.001   | 0.004  | 0.352  |
| Hip flex                                      |                                 | 0.116   | 0.036  | 0.127  |
| Glove height                                  |                                 | 0.059   | 0.021  | 0.134  |

*Boldfaced values indicate statistically significant difference between 1st and 15th pitch (P < .05). Abd, abduction; flex, flexion; max, maximum.

*Measurement taken from camera orthogonal to pitcher.

*Measurement taken from camera behind home plate.
in stride knee flexion at foot contact, drive knee flexion at ball release, and glove height at follow through. Hip lean at hand separation was more consistent at the end of games at the end of the season than at the beginning of the season (Table 4).

As the season pitch count increased, the parameters with weakly positive association were stride knee flexion at foot contact (\( r = 0.41 \)); maximum shoulder external rotation, shoulder alignment, and stride knee flexion at maximum external rotation (\( r = 0.42, 0.29, \) and 0.24, respectively); and shoulder abduction and stride knee flexion at ball release (\( r = 0.22 \) and 0.19, respectively). Greater hip lean at hand separation (\( r = -0.28 \)) and hip flexion at ball release (\( r = -0.21 \)) were also correlated with greater season pitch counts. Weak negative correlations were found for drive knee flexion at balance point (\( r = -0.27 \)), drive knee flexion at maximum external rotation (\( r = -0.23 \)), and elbow flexion at ball release (\( r = -0.34 \)).

### DISCUSSION

Baseball pitchers are susceptible to arm injuries as the throwing motion puts considerable strain on the shoulder and elbow, which is compounded by repetition.\(^{12,16,21}\) Several studies have shown that overuse is a major factor, increasing the risk of significant injury.\(^{8,13,14,16,17}\) Lyman et al\(^{14}\) found that pitching for more than 8 months a year led to a 5-fold increase in the risk of elbow surgery in youth baseball players, while throwing more than 80 pitches per game led to a 4-fold increase in their surgery risk. To combat this trend, many rules have been implemented with intent to reduce pitch count, limit innings pitched, and require a specific number of days off between performances.\(^{18,23}\) In addition to overuse, poor mechanics have been shown to increase the strain on the arm.\(^4\) Davis et al\(^4\) performed a study to determine the effect of common biomechanical errors on upper extremity joint stress in

### TABLE 2

| Parameter | 1st Inning Mean, Early Innings SD, Early Innings Mean, Late Innings SD, Late Innings With Game Pitch Count With Subjective Fatigue Correlation (\( r \)) |
|-----------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| 1. Balance point | | | | | |
| Max knee height | .293 | .569 | .394 | 0.027 | -0.035 |
| Stride knee flex | .747 | .246 | .005 | -0.033 | 0.193 |
| Drive knee flex | .667 | .981 | .206 | -0.060 | 0.040 |
| Glove height | .944 | .798 | .620 | 0.039 | -0.398 |
| 2. Hand separation | | | | | |
| Hip lean | .830 | .332 | .016 | -0.089 | -0.310 |
| Hand on top of ball | >.999 | >.999 | >.999 | 1.000 | 1.000 |
| 3. Foot contact | | | | | |
| Stride length | .443 | .072 | .904 | 0.000 | -0.386 |
| Stride knee flex | .242 | .301 | .099 | 0.004 | -0.075 |
| Drive knee flex | .513 | .463 | .466 | 0.110 | 0.076 |
| Elbow height | .156 | .059 | .060 | 0.322 | -0.090 |
| Stride toward plate | >.999 | >.999 | >.999 | 1.000 | 1.000 |
| 4. Max external rotation | | | | | |
| Elbow flex | .946 | .356 | .227 | -0.016 | -0.257 |
| Hip alignment | .331 | .234 | .774 | -0.028 | 0.251 |
| Shoulder alignment | .927 | .102 | .948 | -0.021 | 0.097 |
| Max external rotation | .002 | .031 | .024 | 0.038 | -0.023 |
| Stride knee flex | .429 | .776 | .777 | 0.014 | -0.505 |
| Drive knee flex | .465 | .435 | .728 | -0.017 | -0.046 |
| Hip flex | .543 | .756 | .558 | -0.091 | -0.102 |
| 5. Ball release | | | | | |
| Shoulder add | .957 | .246 | .787 | -0.031 | -0.128 |
| Elbow flex | .853 | .332 | .006 | -0.031 | 0.384 |
| Glove height | .001 | .041 | .008 | -0.014 | 0.250 |
| Stride knee flex | .891 | .663 | .370 | 0.039 | -0.407 |
| Drive knee flex | .638 | .943 | .352 | -0.057 | -0.014 |
| Hip flex | .574 | .196 | .351 | -0.085 | -0.375 |
| 6. Follow through | | | | | |
| Hand height | .244 | .740 | .075 | 0.142 | 0.242 |
| Glove height | .012 | .052 | .810 | -0.077 | 0.462 |

*a* Boldfaced values indicate statistically significant difference between fastballs at the beginning and at the end of a game (\( P < .05 \)). Correlations are reported using Pearson coefficient. Abd, abduction; flex, flexion; max, maximum.

*b* Measurement taken from camera behind home plate.

*c* Measurement taken from camera orthogonal to pitcher.
youth pitchers, focusing on those parameters that are likely to represent excess stress. They found that pitchers who lead with their hips toward home plate in the early cocking phase of pitching have increased humeral internal rotation torque and elbow valgus load. Proper throwing mechanics are subsequently encouraged at all levels of baseball; however, even with learning the correct technique, fatigue from competition may alter the pitcher's mechanics, placing him at risk for injury. Murray et al\textsuperscript{15} aimed to quantify the impact of fatigue on professional players by measuring various pitching parameters over a course of a live game and found significant differences in parameters between early- and later-inning pitches. This and other longitudinal studies prompted Fleisig et al\textsuperscript{8,11} to make the following recommendations to prevent elbow injuries in young pitchers: watch and respond to signs of fatigue, do not pitch competitively more than 8 months in a year, follow limits for pitch counts, and teach proper throwing mechanics.\textsuperscript{13,14,16} Further validating such concerns with live-game analysis, this study discovered several differences in collegiate pitchers' mechanics as innings, games, and the season progressed.

Analysis of the pitching kinematics in innings lasting greater than 15 pitches found a greater hip lean as the hands separate, which has been shown to increase torque on the shoulder and elbow valgus load.\textsuperscript{4} Long innings also resulted in the throwing elbow being elevated with respect to the ground as the pitchers tended to lean more toward their glove hand, allowing for less shoulder abduction. The shoulder tilt was not only more prominent but also more variable after the 15th pitch. The increase in hip flexion and changes in stride length indicate a different position of the torso near the time of ball release. Kinematic differences in

### Table 3

| Parameter                  | 1st Inning of Early Season vs Late Season | Last Inning of Early Season vs Late Season | Mean, Early Innings of Early Season vs Late Season | Mean, Late Innings of Early Season vs Late Season |
|----------------------------|------------------------------------------|-------------------------------------------|----------------------------------------------------|---------------------------------------------------|
| Balance point              |                                          |                                           |                                                    |                                                    |
| Max knee height\textsuperscript{b} | .440                                    | .159                                      | .916                                               | .498                                              |
| Stride knee flex\textsuperscript{c} | .944                                    | .441                                      | .249                                               | .116                                              |
| Drive knee flex\textsuperscript{c} | .326                                    | .440                                      | .173                                               | .345                                              |
| Glove height\textsuperscript{b}  | .305                                    | .214                                      | .593                                               | .273                                              |
| Hand separation            |                                          |                                           |                                                    |                                                    |
| Hip lean\textsuperscript{c}   | .021                                    | .110                                      | .028                                               | .028                                              |
| Hand on top of ball\textsuperscript{c} | >.999                              | >.999                                      | >.999                                              | >.999                                              |
| Foot contact               |                                          |                                           |                                                    |                                                    |
| Stride length\textsuperscript{c} | .123                                    | .259                                      | .249                                               | .600                                              |
| Stride knee flex\textsuperscript{c} | .612                                    | .594                                      | .345                                               | .753                                              |
| Drive knee flex\textsuperscript{c} | .553                                    | .314                                      | .345                                               | .046                                              |
| Elbow height\textsuperscript{c}  | .102                                    | .016                                      | .115                                               | .058                                              |
| Stride toward plate\textsuperscript{b} | >.999                                | >.999                                      | >.999                                              | >.999                                              |
| Max external rotation      |                                          |                                           |                                                    |                                                    |
| Elbow flex\textsuperscript{b}  | .263                                    | .859                                      | .173                                               | .753                                              |
| Hip alignment\textsuperscript{b} | .735                                    | .362                                      | .116                                               | .116                                              |
| Shoulder alignment\textsuperscript{b} | .484                                    | .859                                      | .600                                               | .753                                              |
| Max external rotation\textsuperscript{c} | .735                                    | .674                                      | .917                                               | .600                                              |
| Stride knee flex\textsuperscript{c} | .866                                    | .139                                      | .463                                               | .463                                              |
| Drive knee flex\textsuperscript{c} | .735                                    | .514                                      | .753                                               | .917                                              |
| Hip flex\textsuperscript{c}   | .128                                    | .260                                      | .753                                               | .753                                              |
| Ball release               |                                          |                                           |                                                    |                                                    |
| Shoulder abd\textsuperscript{b}  | .779                                    | .086                                      | .463                                               | .249                                              |
| Elbow flex\textsuperscript{b}  | .069                                    | .192                                      | .463                                               | .345                                              |
| Glove height\textsuperscript{b}  | .068                                    | .011                                      | .058                                               | .028                                              |
| Stride knee flex\textsuperscript{c} | .499                                    | .374                                      | .345                                               | .753                                              |
| Drive knee flex\textsuperscript{c} | .028                                    | .214                                      | .345                                               | .917                                              |
| Hip flex\textsuperscript{c}   | .091                                    | .374                                      | .753                                               | .753                                              |
| Follow through             |                                          |                                           |                                                    |                                                    |
| Hand height\textsuperscript{b}  | .751                                    | .733                                      | .345                                               | .528                                              |
| Glove height\textsuperscript{b}  | .671                                    | .154                                      | .753                                               | .753                                              |

\textsuperscript{a}Boldfaced values indicate statistically significant difference between fastballs at the beginning and at the end of the season ($P < .05$). Abd, abduction; flex, flexion; max, maximum.

\textsuperscript{b}Measurement taken from camera behind home plate.

\textsuperscript{c}Measurement taken from camera orthogonal to pitcher.
long innings were subtle and the most difficult to interpret. Changes may be due to other factors, such as runners on base, and not just attributable to fatigue.

Over the course of a game, the maximum shoulder external rotation decreased, which is consistent with findings by Murray et al.15 While this may be a protective change in mechanics, the greater variance suggests that it is more likely related to fatigue in some pitchers. While Murray et al15 found decreased knee flexion at ball release, our study did not reveal such an association. Elbow height with respect to the ground at foot contact decreased as pitch counts increased during the game, consistent with conventional baseball theory that the elbow drops as pitchers become tired. As well, the glove height decreased as the ball was released and during follow through, yet the height of the throwing hand remained consistent. The glove height may not place additional strain on pitchers’ arms, but it could be an indicator of fatigue at the end of games. However, this result was mixed as the glove height increased when correlating with subjective fatigue.

Finally, at the end of the spring collegiate season, pitchers had greater hip lean than at the beginning. Once again, this likely produces greater torque on the shoulder and valgus stress on the elbow. More aggressive leading with the hips was also positively correlated with pitch count, as was hip flexion. Contrary to analysis of intragame mechanics, elbow height with respect to the ground was increased at foot contact at the end of the season. This may be the result of the increase in shoulder tilt and shoulder abduction, raising their arm angle and, thus, the elbow. On the other hand, our data may indicate that pitchers may not experience cumulative fatigue throughout the season. Perhaps later in the season they have the ability to correct mechanical flaws through coaching instruction and increased conditioning. Similarly,
maximum external rotation of the shoulder increased as the season pitch count increased, which may be due to corrective changes throughout the season. Interestingly, many of the parameters studied became more consistent, contrary to the expectation that fatigue would increase variability in mechanics. This might be secondary to pitchers becoming more comfortable as innings, games, and the season progressed.

A major limitation of this study is accurately quantifying fatigue. Several approaches were attempted in the study—time points, pitch count, and subjective reports—yet these are not direct measures of fatigue. Therefore, while the kinematic differences found in this study are likely secondary to fatigue, it is also possible that they are adaptive changes to protect the arm. These deviations in pitching motion may be normal and natural to change throughout
an inning, game, and season. To potentially address this difficulty in future studies, measuring the kinetics associated with the biomechanical changes could help exclude adaptive changes as a possible explanation. Additionally, quantification of the loads on the elbow and shoulder would provide better understanding of injury risk associated with the kinematic changes.

The intrigue of studying live-game pitching to accommodate all of the stresses felt by pitchers also produced several limitations. While it allowed for longitudinal study of pitchers in their natural environment, the study could only collect data on days when pitchers were scheduled to perform. Data were only recorded during games at the home fields of the teams participating to minimize changes in camera angles. Since these teams primarily travel at the beginning of their spring baseball season, the first several games of the season were not captured. Ideally, all pitchers would have been recorded at the same time points, but the schedule did not allow for this level of consistency.

The study only included the spring collegiate season and did not capture the additional games that each pitcher would participate in over the summer and fall. It is possible that these pitchers could experience even more fatigue by the end of the year. However, studying collegiate baseball pitchers allowed analysis of players who have well-developed pitching mechanics, minimizing natural variability of the throwing motion. In addition to their much practiced mechanics, these pitchers were well-conditioned via weight training, cardiovascular exercise, and rotator cuff strengthening. While they only pitched once per week because of the collegiate baseball schedule, they still showed changes in their mechanics over the course of innings, games, and the season. Many youth pitchers will pitch even more frequently with less rehearsed mechanics, placing them at additional risk of fatigue impacting their pitching motion.

This study sheds light on the impact that fatigue may have on the throwing mechanics of pitchers. The pitchers admitted to feeling 17.8% ± 14.1% more fatigue at the end of games while maintaining their fastball velocities, and all were willing to continue pitching. Despite feeling more fatigued, they would not have voluntarily removed themselves from games based on their level of fatigue. This unwillingness to self-limit makes it that much more important for coaches to watch for kinematic signs of fatigue that may place the pitcher at risk for injury. Each pitcher’s mechanics may respond differently to fatigue; however, increase in hip lean or decrease in shoulder external rotation and elbow height were the most consistent parameters that may indicate that rest is necessary. Such markers may be more accurate and individualized than total pitch count or number of innings pitched. Further investigation is needed to interpret whether these kinematic changes translate into additional strain and injury to pitchers.

CONCLUSION

Hip lean, elbow height, and shoulder external rotation were the most sensitive kinematic parameters to correlate with measures of intra-inning, intragame, and season fatigue for collegiate baseball pitchers. While some degree of variability was noted for individual pitchers within each inning, game, and season, the overall kinematics of the pitching motion remained relatively consistent for the group. Fatigue has a significant impact on live-game kinematics of collegiate baseball pitchers, but pitchers are not able to reliably gauge their own levels of fatigue. Measurements may better demonstrate fatigue-related mechanical breakdown on an individualized basis than standardized limitations of innings and pitches thrown.

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