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Variability of in-game markerless and laboratory marker-based baseball pitching biomechanics

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ABSTRACT

Traditionally, baseball pitching biomechanics have been analyzed in controlled laboratory settings. However, with recent technological advancements, markerless motion capture has made capturing and analyzing in-game pitching biomechanics possible. Pitchers typically throw slower in a laboratory setting than they do in an in-game setting, and it is unknown if pitching biomechanics, including the variability of pitching biomechanics, change between environments. Thus, the purpose of this study was to compare pitching variability between marker-based data captured in a typical laboratory setting and markerless data captured in a typical in-game setting. It was hypothesized that pitching kinematics measured with in-game markerless technology would produce greater variability. Data from 30 collegiate baseball pitchers captured in a biomechanics laboratory were compared to data for 30 NCAA Division I pitchers captured using markerless motion capture during competitive games. Within-subject pitching variability was defined as the standard deviation of the pitcher's kinematics over 10 fastballs. Of the 10 kinematic parameters analyzed, variability was significantly greater for in-game markerless data for two parameters (maximum shoulder external rotation and elbow flexion at that instant). Mean values showed large differences between the markerless and marker-based data, consistent with previously published research. This study provides initial evidence that baseball pitching variability is relatively similar between in-game markerless and in-laboratory marker-based settings.

1. Introduction

Baseball pitching is a highly dynamic movement that requires the coordination of the lower extremities, hips, trunk, and upper extremities to effectively transfer energy for optimal ball velocity, movement, and control without excessive stress on the throwing elbow and shoulder (Aguinaldo and Chambers, 2009; Fleisig et al., 1995; Glanzer et al., 2021; Nicholson et al., 2022; Slowik et al., 2019; Whiteside et al., 2016). Furthermore, maintaining consistency in biomechanics and release can improve a pitcher's effectiveness by increasing the element of deception, making it more challenging for batters to anticipate the type of pitch being thrown to the batter (Escamilla et al., 2017; Fleisig et al., 2006; Fleisig et al., 2016; Lerch et al., 2024b). A repeatable delivery is thought to enhance performance, as research indicates that a consistent release point is associated with sustained performance throughout the season (Whiteside et al., 2016).

While consistency is crucial for performance, it is essential to acknowledge that baseball pitchers inherently exhibit some degree of variability in their pitches (Fleisig et al., 2009). Interestingly, limited research focuses on the biomechanics of within-pitcher variability. A study by Fleisig and colleagues revealed that as competition level increases, within-pitcher biomechanics variability decreases (Fleisig et al., 2009). Additionally, research by Manzi et al. on professional baseball pitchers demonstrated that those with higher pitch location consistency exhibit biomechanical differences compared to those with lower pitch location consistency (Manzi et al., 2021).

A key limitation of prior research on variability in pitching is the lack of ecological validity, as these studies were conducted in controlled laboratory settings (Fleisig et al., 2009; Manzi et al., 2021). In our anecdotal experience, pitchers throw about 5 to 7 miles per hour slower in a laboratory than in a game. This is consistent with the differences between bullpen testing and self-reported velocity, which Erickson et al. (Erickson et al., 2023) reported. Thus, it is logical to assume that biomechanical changes occur between pitching in a controlled laboratory environment and an in-game environment. One such change could be a pitcher's variability, as adrenaline and game factors (e.g., runners

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Fig. 1. Laboratory data collection setup.

on base, score of the game, etc.) could cause increased variability in a pitcher's mechanics that do not occur in a laboratory.

With recent advancements in markerless motion capture technology, capturing and analyzing in-game pitching biomechanics is now possible (Bench et al., 2023; Giordano et al., 2024b). However, no study has investigated the variability of in-game markerless measurements of pitching biomechanics and the variability of gold-standard marker-based measurements. Thus, the purpose of this study was to compare pitching variability between marker-based data captured in a typical laboratory setting and markerless data captured in a typical in-game setting. It was hypothesized that pitching kinematics measured with in-game markerless technology would result in greater variability than pitching kinematics measured in a lab with marker-based motion capture.

2. Methods

This study was a retrospective review of two databases containing biomechanical data of baseball pitching, one consisting of in-game markerless motion capture data and another with in-lab, marker-based motion capture data. This study was approved by Auburn University's IRB (STUDY 00000290).

2.1. Laboratory data

Data from 30 healthy collegiate baseball pitchers previously tested in the biomechanics laboratory at the American Sports Medicine Institute (Birmingham, AL) were included in this study. Each participant wore only skin-tight athletic shorts, socks, athletic shoes, and a baseball hat during the motion capture session. A total of 39 reflective markers were attached bilaterally at the distal end of the third metatarsal, lateral malleolus, medial malleolus, heels, lateral femoral epicondyle, medial femoral epicondyle, greater trochanter, anterior superior iliac spine, posterior superior iliac spine, lateral superior tip of the acromion, sternal end of clavicle, lateral humeral epicondyle, medial humeral epicondyle, forearm, ulnar styloid and radial styloid with double-sided tape (Fig. 1). Additional markers were placed on the dorsal surface of the throwing hand, inferior angle of the throwing-side scapula and C7 of the spine. Four additional markers were attached to a baseball hat on the front, top, and bilateral sides of the head. The subject then warmed up as he would before pitching in a game and when he indicated he was ready, he threw 10 full-effort fastballs from an indoor pitching mound to a strike zone located above a home plate 18.44 m from the pitching rubber. Each subject threw from either the windup or stretch positions during testing; pitchers who only throw from the stretch position were instructed to do the same during testing, while all others were instructed to throw from the windup position during testing. Motion of the reflective markers

Fig. 2. Markerless motion capture cameras permanently mounted in the stadium.

during each pitch were captured at 240 Hz by twelve synchronized cameras (Motion Analysis Corporation, Rohnert Park, CA), while ball velocity was measured with a radar gun (Stalker Sports Radar, Plano, TX, USA). Three-dimensional position-vs-time data of each reflective marker were filtered with a 13.4 Hz fourth-order Butterworth low-pass filter. Joint centers of the elbows, wrists, knees, and ankles were defined as the midpoints between their respective medial and lateral markers, while shoulder and hip joint centers were calculated employing techniques described previously (Fleisig, 1994; Zheng et al., 2004).

2.2. In-Game data

Data collected during Division I baseball games at Auburn University were also included in this study (Fig. 2). Data were limited to pitching data collected during competitive games; practice and scrimmage data were not included in this analysis. Kinematic data were recorded using an eight-camera KinaTrax markerless motion capture system permanently mounted in the university's baseball stadium sampling at 300 Hz. Kinematics and event detections (instants of front foot contact, maximum shoulder external rotation, and ball release) were calculated using Visual 3D (C-Motion Inc., Germantown, MD, USA) and proprietary KinaTrax protocols. Kinematics were calculated according to ISB recommendations (Giordano et al., 2024a). Pitch type and velocity were recorded using a Trackman V3 Game Tracking unit (Scottsdale, AZ, USA). Custom python scripts were created to search the Trackman database to identify pitches of interest. Then additional python scripts were used to extract biomechanical data for those pitches from the markerless motion capture database.

To be included in this analysis, pitchers were selected if they had thrown at least 20 fastballs in a single game; other pitch types were not included due to kinematic differences between pitch types (Lerch et al., 2024a). Of these 20 fastballs, the first 10 fastballs were chosen for analysis. A total of 72 pitchers met the initial inclusion criteria. To match the sample size of the in-lab group, a random sample of 30 pitchers was selected from those 72 pitchers.

2.3. Kinematic parameters

While the laboratory and in-game systems each computed dozens of measurements, ten kinematic parameters calculated by both systems were selected for comparison. Included were four measurements at the instant of front foot contact, two at the maximum shoulder external rotation, and four at ball release. Kinematics from the markerless motion capture system were defined using proprietary KinaTrax protocols. For the marker-based system, kinematic definitions are provided below:

Stride length was measured as the distance from the back foot ankle when the front knee was at its maximum height to the front foot ankle at the instant of foot contact; stride length was normalized by each pitcher's height. Foot placement was the distance (in cm) to the "closed side" (third base side for a righthanded pitcher, first base side for a lefthanded pitcher) that the front foot landed, relative to where the back foot ankle when the front knee was at its maximum height. Knee flexion was the angle between the distal directions of the front leg thigh and the front leg shank. Shoulder rotation was measured as the rotation of the forearm about the long axis of the upper arm. Shoulder rotation was defined as zero degrees when the forearm was pointed in the anterior direction of the trunk, positive for shoulder external rotation and negative for shoulder internal rotation. Elbow flexion was the angle

Table 1
Comparison of in-game markerless pitching kinematics with in-lab marker-based pitching kinematics.

	In-Game Markerless Data (N = 30)	In-Lab Marker-Based Data (N = 30)	p-value	Effect Size
Height (m)	1.87 ± 0.06	1.89 ± 0.07	0.352	
Mass (kg)	91.1 ± 9.9	92.2 ± 8.4	0.636	
Pitch Velocity (mph)	91.2 ± 3.8	85.2 ± 1.5	< 0.001*	0.529
@Foot Contact				
Stride Length (% height)	88.9 ± 5.4	82.5 ± 5.5	< 0.001*	0.261
Foot Placement (cm)	5.8 ± 11.7	18.8 ± 13.4	< 0.001*	0.209
Knee Flexion (°)	50.1 ± 5.6	44.7 ± 10.7	0.017	0.095
Shoulder External Rotation (°)	35.6 ± 24.5	53.3 ± 24.7	0.007*	0.118
@Maximum Shoulder External Rotation				
Shoulder External Rotation (°)	182.9 ± 11.2	163.7 ± 10.5	< 0.001*	0.448
Elbow Flexion (°)	78.1 ± 8.4	101.1 ± 11.1	< 0.001*	0.584
@Ball Release				
Knee Flexion (°)	46.5 ± 13.1	35.0 ± 14.8	0.002*	0.149
Trunk Forward Tilt (°)	35.7 ± 9.5	34.2 ± 7.4	0.506	0.008
Trunk Side Tilt (°)	13.9 ± 14.1	23.1 ± 9.5	0.005*	0.130
Shoulder Abduction (°)	98.4 ± 5.5	87.6 ± 9.2	< 0.001*	0.347

Data for each group are presented as mean ± standard deviation. P-value was considered a significant difference when $p < 0.005$.

between the distal directions of the upper arm and forearm of the throwing arm. At ball release, the superior direction of the trunk was determined by a vector from the mid-hips to the mid-shoulders. Trunk forward tilt was the angle between the superior direction of the trunk and vertical, in the global plane defined by vertical and the forward direction (i.e. from the pitching rubber to home plate). Similarly, trunk side tilt was the angle between the superior direction of the trunk and vertical, in the global plane defined by vertical and the sideways direction (i.e. from first base to third base). Trunk forward tilt was positive when the trunk was tilted towards home plate. Trunk side tilt was positive when the trunk was tilted towards the glove hand side. Shoulder abduction was the angle between the distal direction of the upper arm and the inferior direction of the trunk in the trunk's frontal plane.

2.4. Statistical analysis

Independent-sample t-tests were used to compare height and weight between groups. A one-way multivariate analysis of variance (MANOVA) was used to compare the mean kinematic parameters between groups. The Box M test revealed that the assumption of homogeneity of variance–covariance was violated (Box's M = 127.290, F (66, 10726.242) = 1.537, $p = 0.003$), so Pillai's Trace was used to interpret the MANOVA. Bartlett's Test of Sphericity showed that the data were sufficiently correlated to conduct the MANOVA (Approximate Chi Squared (65) = 500.491, $p < 0.001$).

Within-pitcher variability was defined as the standard deviation of each pitcher's kinematic values during their 10 fastballs (Fleisig et al., 2009; Glanzer et al., 2021). A second one-way MANOVA was used to compare within-pitcher variability between groups. The Box M test revealed that the assumption of homogeneity of variance–covariance was violated (Box's M = 159.217, F (66, 10726.242) = 1.923, $p <$ 0.001), so Pillai's Trace was also used to interpret this MANOVA. Bartlett's Test of Sphericity showed that the data were sufficiently correlated to conduct the MANOVA (Approximate Chi Squared (65) = 983.506, $p < 0.001$).

Table 2
Within-subject variability (i.e. within-subject standard deviation) compared between in-game markerless data and in-lab marker-based data.

	Variability of In-Game Markerless Data (N = 30)	Variability of In-Lab Marker-Based Data (N = 30)	p-value	Effect Size
Pitch Velocity (mph)	1.1 ± 0.7	0.9 ± 0.3	0.159	0.034
@Foot Contact				
Stride Length (% height)	1.5 ± 0.7	1.6 ± 0.8	0.521	0.007
Foot Placement (cm)	3.1 ± 1.0	3.1 ± 1.0	0.677	0.003
Knee Flexion (°)	2.0 ± 0.8	3.6 ± 3.2	0.012	0.104
Shoulder Rotation (°)	6.9 ± 2.9	9.1 ± 5.2	0.053	0.063
@Maximum Shoulder External Rotation				
Shoulder Rotation (°)	2.0 ± 0.9	1.4 ± 0.5	0.001*	0.162
Elbow Flexion (°)	2.8 ± 0.5	1.5 ± 0.4	< 0.001*	0.680
@Ball Release				
Knee Flexion (°)	5.5 ± 2.6	4.8 ± 2.1	0.268	0.021
Trunk Forward Tilt (°)	1.5 ± 0.5	1.6 ± 0.5	0.512	0.007
Trunk Side Tilt (°)	1.6 ± 0.6	1.6 ± 0.5	0.915	0.000
Shoulder Abduction (°)	1.2 ± 0.3	1.0 ± 0.3	0.023	0.086

Data in each column represent the mean ± standard deviation of variability for the pitchers in the group. P-value was considered a significant difference when $p < 0.005$.

Follow-up univariate tests were used to determine kinematic differences between groups. To account for multiple follow-up univariate tests being run, a Bonferroni correction was used to adjust the alpha level to 0.005 to account for the 10 kinematic parameters that were assessed.

3. Results

Descriptive statistics are compared in Table 1. There were no differences in height and mass between the two groups. The kinematic mean MANOVA was significant (F (11,48) = 39.663, $p < 0.001$, partial eta squared = 0.901). The within-pitcher variability MANOVA was also significant (F (11,48) = 15.942, $p < 0.001$, partial eta squared = 0.785). Fastball velocity was greater for the in-game group ($p < 0.001$). The groups had significant differences in most kinematic measurements.

Within-subject variability is compared in Table 2. Of the ten kinematic parameters, variability was significantly greater for the markerless data for two parameters (maximum shoulder external rotation and elbow flexion at the instant of maximum shoulder external rotation).

4. Discussion

The hypothesis that pitching biomechanics would show greater variability within in-game markerless data than within in-lab marker-based data was partially supported. Only two of the ten kinematic parameters analyzed showed greater variability within the in-game markerless data. Differences in variability were not significant for the other eight parameters, although two showed a trend ($p < 0.05$). It's difficult to know how many differences between the two groups were due to motion capture technology and how much was due to the testing setting. Fleisig et al. published a comparison of markerless and marker-based

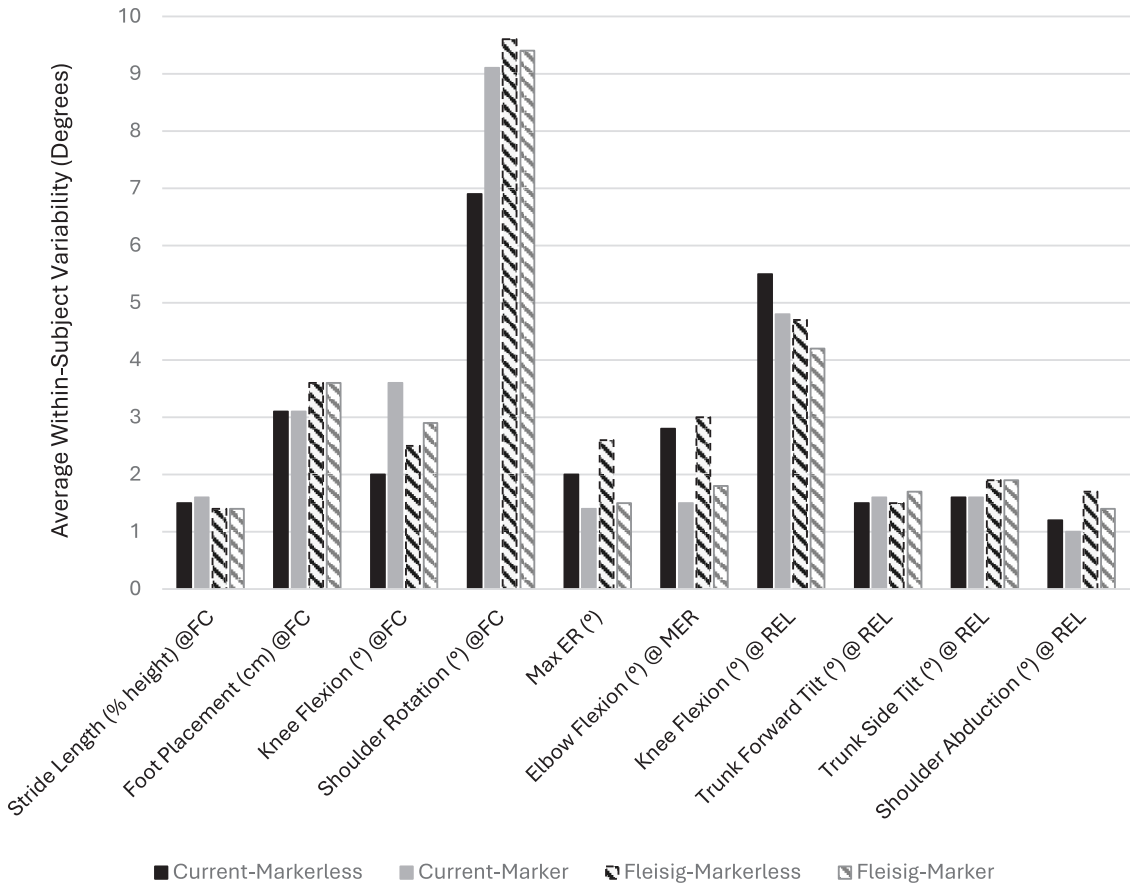

Fig. 3. Variability in current study and Fleisig et al. (Fleisig et al., 2022). Note that the markerless system in the current study (KinaTrax) is a different markerless system than the one used in Fleisig et al. (DARI Motion, Overland Park, KS).

pitching biomechanics simultaneously collected in a lab setting (Fleisig et al., 2022). Thus, that study evaluated the isolated effect of motion capture technology. Unlike the current study of collegiate pitchers, the Fleisig et al. study included 30 pitchers ranging from youth to professional level. Furthermore, they used the Bland-Altman analyses instead of a MANOVA to test the differences between the two technologies (Fleisig et al., 2022). As shown in Fig. 3, the variability for markerless and marker-based data was extremely similar in the current study. This suggests that the differences in variability between the two groups found in the current study were likely primarily due to technology, as both the markerless system in this study and the Fleisig et al. study found increased variability in the measurement of maximum shoulder external rotation and elbow flexion at the time of maximum shoulder external rotation (Fleisig et al., 2022). Altogether, these results provide initial evidence that collegiate pitchers may not have greater variability in their pitching biomechanics during a game than during a laboratory collection.

While variability between the two groups showed few statistical differences, the mean values between the two groups showed many differences. While some of these differences may be due to the six MPH difference in fastball velocity between groups, the fact that the markerless in-game data and marker-based lab data showed significant differences in mean values is consistent with the findings of Fleisig et al. (Fleisig et al., 2022). These findings suggest that pitching data from markerless data capture and marker-based data should not be compared or combined.

An unfortunate limitation of this study was that the two sets of data used different cohorts due to logistical challenges, and thus, a within-subjects analysis was not possible. Thus, although a between-subjects analysis of pitching variability has limitations, it could still provide insights into how pitching biomechanics may vary between in-game and laboratory settings. Given that changes in pitching biomechanics between environments is a topic of great interest in the field, we believe this study provides the first step in understanding how biomechanics change between the laboratory and the field. Indeed, although the pitchers in the in-game cohort threw faster than the in-lab cohort, pitching variability was relatively similar. Future researchers should consider performing within-subject analyses to better understand the effect of the collection environment on biomechanics (Ripic et al., 2022).

Another limitation was that there were two factors differentiating the two data sets – setting (game vs. lab) and technology (markerless vs. marker-based). While this study design cannot isolate differences due to each factor, comparing in-game markerless data to in-lab marker-based data has great practical significance as these are common data capture situations for future and past pitching studies, respectively. Finally, it must be noted that the markerless and marker-based systems computed kinematic parameters with different algorithms. As such, the primary purpose of the current study was to compare within-subject variability, not kinematic measurements.

5. Conclusion

In general, variability measured for collegiate baseball pitchers in-game and in the laboratory were similar. The only significant differences were maximum shoulder external rotation and elbow flexion during maximum shoulder external rotation, which displayed greater variability in an in-game setting. This study provides the first step in understanding how pitching biomechanics may differ between in-game and laboratory settings. Future research should consider utilizing

within-subject analyses and consistent motion capture technologies to better understand how mechanics and variability of those mechanics differ between laboratory and in-game settings.

CRediT authorship contribution statement

Benjamin G. Lerch: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Glenn S. Fleisig:** Methodology, Investigation, Writing – review & editing, Data curation, Conceptualization. **Jonathan S. Slowik:** Methodology, Investigation, Writing – review & editing, Formal analysis, Conceptualization. **Gretchen D. Oliver:** Writing – review & editing, Supervision, Software, Resources, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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