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Pitching kinematics have direct and indirect effects on pitch location in NCAA baseball

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ABSTRACT

Kinematics and release parameters are important factors of throw location; yet an understanding of their relationship has yet to be achieved. This study sought to explore this relationship. Kinematic data were collected for 77 collegiate pitchers. Fifty-seven kinematic parameters were included in path analyses for horizontal and vertical plate locations. Release angles were set as mediating variables (MED) between independent and dependent variables. Eleven kinematic variables directly (13 indirectly) affected the vertical plate location, while 23 kinematic variables directly affected the horizontal plate location (10 indirectly). Linear mixed models revealed that lateral trunk flexion at ball release (R^2 = 0.908, BIC = −598, ICC = 0.528) best explained vertical plate location. Trunk flexion at foot contact (R^2 = 0.944, BIC = −607, ICC = 0.776), mediolateral center of mass displacement at foot contact (R^2 = 0.974, BIC = −573, ICC = 0.918) and ball release (R^2 = 0.967, BIC = −593, ICC = 0.865), and pelvis rotation at ball release (R^2 = 0.965, BIC = −588, ICC = 0.895) models were identified for the horizontal plate location. Results indicate that the relationship between pitching kinematics, release conditions, and throw location is complex. Biomechanics can influence release parameters, which in turn impacts the throw location. This work may serve to understand better how biomechanics influence performance.

Introduction

It is well established that the overarching goal in baseball is to outscore your opponents. Though this is typically achieved by hitting a pitched ball into fair territory and advancing around the bases, it is not the only way to accumulate runs. Defensive errors also allow the batter to advance around the diamond, and in 2022 alone, approximately 21,079 occurred in Major League Baseball [1]. Among these errors, 18,506 (1,607 wild pitches; 2,046 batters hit by a pitch; and 14,853 walks) were attributable to arguably the most important defensive player on any given team, the pitcher. This is not surprising, however, when one considers the number of throws the pitcher makes compared to other defensive players. Barrett et al. reported that, on average, pitchers threw 71.4 % of "active" throws, with catchers contributing 17.2 %, and the remaining nine positions just 11.4 % [2]. Since the pitcher's main aim is to prevent runs from being scored [3], and with such a high proportion of throws made during a game, it is unsurprising why pitching has been the focus of countless research studies seeking to learn more about the nuances of the throwing skill.

Much of the pitching research has focused on pitch velocity, evidenced in a review of pitching performance where 30 out of the 34 studies included it as their primary focus [4]. Pitch velocity is commonly used because it is an easily measured metric in a game and in a research setting. But it is also a convenient way to approximate differences between two players when assessing their skill or ability [3]. Although it has proven valuable and factors related to throwing velocity are now well-understood in baseball, velocity is still only one component of throwing performance [3, 5]. Moreover, there is a lack of evidence proving that velocity alone indicates a pitcher's in-game effectiveness [6]. In fact, it has been suggested that higher ball velocities are potentially detrimental to pitching performance, with lower consistency pitchers exhibiting higher ball velocities than higher consistency pitchers [7]. Consequently, expanding pitching research into other areas associated with performance is warranted.

Accuracy (or throw location) is also a key component to throwing performance [8] and has received considerably less attention in the literature. Still, kinematic factors associated with the ability to locate the ball at the target have been identified, which may help us gain a better holistic understanding of throwing performance. Factors such as shoulder and trunk kinematics are strongly related to pitch location [9, 10], as are finger kinematics (more specifically, the controlled timing of finger extension) [11]. Although these findings demonstrate that kinematics are an important aspect of throwing accuracy, it has recently been argued that the conditions set at ball release have the biggest influence on the throw location at the target.

Whiteside et al. (2016) reported that release consistency and speed predicted performance, while release speed has independently been shown to have a quasi-inverse relationship with throwing accuracy [6, 8]. More recently, it has been contended that the projection angles in both vertical and horizontal planes have the most influence on where the ball ends up at its target [12, 13]. For every 1 SD, or a 1.09° change in vertical release angle, Nasu et al. (2021) observed an approximately 19.8 cm deviation in the vertical direction. Furthermore, a 1 SD or a 0.85° change in horizontal release angle led to an 18.2 cm deviation (half the width of the home plate) in the horizontal direction [13]. Similar findings have been reported in cricket, where Lozowski et al. (2021) established that, regardless of the approach angle to the target, the horizontal release angle accounted for between 76 and 82 % of the variance in horizontal displacement [14]. Moreover, for every 1° change in the horizontal release angle, 0.26–0.34 m of lateral displacement is expected.

When viewed holistically, the literature suggests that both pitching kinematics and release angles are fundamental to the throw location. The release angles may appear most important as they govern the ball's trajectory, which cannot be altered in flight (if one is to ignore external factors such as wind). However, since pitching kinematics also play a vital role in the throw location, their contributions cannot be discounted. Further exploration into the relationship between pitching kinematics, ball release angles, and throw locations is required, and a path analysis may be a suitable option. Path analyses allow for assessing the comparative significance of various pathways and mechanisms through which an exposure influences an outcome [15]. Although not commonly used in biomechanical research, it is a popular method in biomedical and social sciences where the interactions between variables and outcomes are complex. Using this approach, the relationships (direct or indirect) between predictors (kinematics) and an outcome (throw location) can be established. Therefore, the purpose of this study was to explore the relationships between kinematics, release angles and throw locations. Owing to previous research [13], ball release angles will be treated as mediators between biomechanical variables and throw locations within each path analysis.

Materials and Methods

Participants

Data for 77 male collegiate-level baseball pitchers from the National Collegiate Athletic Association (NCAA) were included in the present study (height: 1.88 ± 0.06 m and mass: 91.6 ± 9.2 kg). All data collection protocols were approved by the institutional review board of the university [16].

Materials

An 8-camera markerless motion capture system (Kinatrax Inc., FL, USA; 300 Hz) recorded in-game pitching biomechanics. The system was calibrated first extrinsically using a cube of known dimensions and then intrinsically for each camera by using observations of a binary checkerboard matrix covering the entire field of view. Static capture trials of the pitching rubber were also collected throughout the game to account for any error/drift that may have occurred. Ball metrics were collected using a TrackMan V3 Game Tracking stadium unit positioned behind home plate per the manufacturer's recommendations (TrackMan, Scottsdale, AZ).

Protocols

All pitching trials were recorded in-game during Division I (DI) NCAA baseball games. Pitchers each threw a variety of pitches as determined by their coach. No restrictions on the pitch count were enforced. All pitch types were recorded; however, for this study, only fastballs were included in the analysis owing to the novel nature of this work.

Data Analysis

Postgame, video data were processed, and 124 kinematic variables were extracted. All kinematic variables are defined per the Kinatrax documentation (see appendix). For clarity, "trunk lean", which refers to frontal plane flexion, will hereon be referred to as "lateral trunk flexion" for the remainder of this manuscript. Key events included foot contact (FC), maximum shoulder external rotation (MER), and ball release (BR). FC was defined as the first contact of the lead foot with the ground. The angle of MER was recorded when the shoulder reached its maximal external rotation, and the BR was defined as three frames after the maximal linear (rubber to home plate) velocity of the distal point of the throwing hand (see appendix). Eight ball release metrics were acquired using TrackMan: release speed, vertical release angle, horizontal release angle, spin rate, spin axis, tilt, release height, release side, and extension (see appendix for definitions). Ball data were paired with the corresponding biomechanical data using timecode synchronization. Three ball variables (the horizontal location at the target, the horizontal release angle, and the release side) and one kinematic variable (center of mass [COM] displacement in the mediolateral direction) required data to be inverted for left-handed players. A total of 699 fastballs for 77 pitchers were selected for analysis (a maximum of 10 trials per pitcher). All analyses were performed using version 2.3 of the Jamovi data analysis software [17]. Two initial correlation analyses were performed between each location at the target variable (×2 dependent variables [DVs]), the 8 release parameters collected via TrackMan (potential mediating variables; see Nasu and Kashino 2021 [13]), and 124 kinematic variables obtained using the Kinatrax system.

Path Analysis

The correlation analyses revealed that vertical and horizontal release angles had the strongest relationship with the location at target variables (▶ **Table 1**). Consequently, these were used as mediating variables in each path analysis. Kinematic variables exhibiting a statistically significant relationship ($p<0.05$) with each of the locations at target variables were included in a mediation analysis [18, 19]. In addition, variables previously identified as having a predictive relationship with location at the target were also included in the path analysis [8, 9]. In each of the path analyses, location at the target was set as the DV, release angle as the mediator (MED), and the kinematic variable as the independent variable (IV). A total of 58 mediation analyses were conducted. Standardized β values were obtained for each path (see ▶ **Fig. 1** for a generalized illustration), allowing direct and indirect effects of the IV on the DV to be determined. When the c′ path β was greater than the $a \times b$ path β, the IV had a direct effect on the DV; when the reverse was true, the IV had an indirect effect.

Following the path analyses, linear mixed models were used to determine the relationships between IVs and the MED (R^2_{MED}), the MED and the DV, and each IV + MED and the DV (R^2_{DV}). Since pitchers threw multiple pitches, linear mixed models were chosen to account for the repeated measures nature of the data. It is important to note that the predicted variance across linear mixed models is not cumulative. It is, therefore, more pragmatic to interpret the results by establishing the model(s) with the smallest Bayesian information criterion (BIC) values [20]. From here, it is then possible to infer those with the greatest influence on a specific outcome variable (i.e., the location at the target). For further interpretability, each model was also assessed on conditional R^2 values and their intraclass correlation coefficient (ICC). A larger ICC indicates that a greater portion of variability within the data can be explained by the clustering (player).

Results

Descriptives for DVs, MED, and IVs are presented in ▶ **Table 2**.

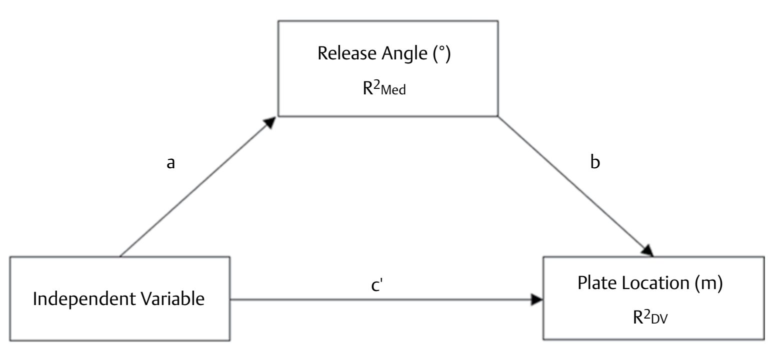
Vertical Location at the Target

A summary of the 24 path and linear mixed model analyses for vertical location at the target is presented in ▶ **Table 3**. Eleven kinematic variables had a direct relationship with the DV ($\beta_{c'} > \beta_{a\times b}$),

▶ **Table 1** Correlation statistics for release parameters and location(s) at the target.

	Vertical location		Horizontal location	
	r	***p***	***r***	***p***
Release speed (m/s)	−0.010	0.787	−0.070	0.064
Vertical release (°)	**0.616**	**<0.001*****	0.222	<0.001***
Horizontal release (°)	0.240	<0.001***	**0.524**	**<0.001*****
Spin rate (rpm)	−0.081	0.033*	−0.056	0.139
Spin axis (°)	0.090	0.018*	−0.079	0.038*
Release height (m)	0.030	0.422	0.000	0.993
Release side (m)	−0.081	0.033*	0.040	0.290
Extension (m)	−0.095	0.012*	−0.042	0.262

Note: the release parameter with the strongest relationship with the dependent variable is bolded. *$p<0.05$, **$p<0.01$, ***$p<0.001$.



▶ **Fig. 1** Example path model diagram. Note: path "a" represents the relationship between the IV and the mediator (Med), path "b" represents the relationship between the Med and the DV, and path c′ as the direct path between the IV and the DV. R^2_{Med} is the variance in the mediator as predicted by the IV, and R^2_{DV} is the variance in the DV as predicted by the IV + Med. When $\beta_{a\times b}$ (indirect path) is greater than $\beta_{c'}$ (direct path), a mediating effect has taken place. When $\beta_{c'}$ (direct path) is greater than $\beta_{a\times b}$ (indirect path), no mediating effect is present. DV, dependent variable; IV, independent variable.

▶ **Table 2** Descriptives for dependent, mediating, and independent variables included in the path analysis.

	Mean ± SD	Range
Dependent Variables		
Vertical plate location (m)	0.76 ± 0.29	− 0.34 to 1.89
Horizontal plate location (m)	− 0.01 ± 0.28	− 0.87 to 0.88
Mediating variables		
Vertical release angle (°)	− 2.0 ± 1.5	− 5.6 to 3.5
Horizontal release angle (°)	− 0.01 ± 0.28	− 0.87 to 0.88
Kinematics at Foot Contact		
Lead ankle eversion/inversion (°)	− 3.8 ± 12.5	− 47.3 to 36.4
Trail ankle eversion/inversion (°)	− 36.4 ± 11.5	− 56.4 to 14.9
Trail ankle flexion (°)	30.5 ± 12.9	4.4 to 71.5
Lead foot angle (°)	− 10.9 ± 13.5	− 49.8 to 37.0
Lead hip abduction (°)	− 26.8 ± 9.1	− 52.3 to 1.0
Lead hip rotation (°)	− 8.7 ± 15.7	− 47.9 to 23.7
COM M/L zeroed (m)	0.0 ± 0.2	− 0.4 to 0.9
COM A/P zeroed (m)	0.3 ± 0.7	− 1.0 to 1.1
Lateral trunk flexion (°)	2.4 ± 5.7	− 16.1 to 22.7
Lateral trunk flexion (relative to pelvis) (°)	7.6 ± 8.5	− 14.1 to 30.4
Trunk flexion (°)	− 11.9 ± 10.7	− 48.8 to 13.8
Trunk flexion (relative to pelvis) (°)	− 0.5 ± 3.9	− 18.6 to 17.0
Shoulder rotation (°)	36.1 ± 22.1	− 20.3 to 89.9
Shoulder abduction (°)	85.1 ± 11.3	57.6 to 115.4
Shoulder horizontal abduction (°)[a]	− 33.5 ± 13.7	− 65.4 to − 1.9
Kinematics at Maximal Shoulder External Rotation		
Lead ankle flexion (°)	55.9 ± 7.7	21.7 to 86.9
Lead ankle eversion/inversion (°)	12.0 ± 13.7	− 27.5 to 51.2
Lead knee flexion (°)	51.5 ± 12.5	12.8 to 90.4
Lead knee extension velocity (°/s)	− 210.5 ± 155.9	− 682.9 to 192.9
Lead hip abduction/adduction (°)	8.8 ± 7.2	− 12.6 to 32.1
Lead hip rotation (°)	− 5.2 ± 16.2	− 56.8 to 40.8
Lateral trunk flexion (relative to pelvis) (°)	− 20.7 ± 6.9	− 39.8 to − 3.5
Trunk flexion (°)	− 14.3 ± 7.2	− 32.6 to 13.2
Trunk rotation (°)	− 0.3 ± 5.8	− 15.3 to 14.4
Shoulder rotation (°)[a]	181.0 ± 10.0	130.8 to 204.7
Shoulder horizontal abduction (°)[a]	− 2.7 ± 6.9	− 29.1 to 18.1
Elbow flexion (°)	79.5 ± 9.7	38.1 to 112.5
Elbow pronation/supination (°)	86.7 ± 13.7	53.0 to 132.3
Kinematics at Ball Release		
Lead ankle flexion (°)	53.4 ± 9.0	21.9 to 87.2
Lead ankle eversion/inversion (°)	13.6 ± 13.8	− 24.1 to 48.9
Lead knee flexion (°)	43.7 ± 16.0	2.5 to 89.7
Lead hip rotation (°)	− 5.6 ± 17.8	− 59.3 to 41.7
Pelvis rotation (°)	13.3 ± 8.7	− 17.9 to 32.8
COM M/L zeroed (m)	0.2 ± 0.2	− 0.4 to 1.0
COM A/P velocity (m/s)	1.2 ± 0.2	0.5 to 1.7
Lateral trunk flexion (°)	− 16.9 ± 11.1	− 38.7 to 26.1
Trunk flexion (°)[a]	− 36.6 ± 7.9	− 63.7 to − 9.7
Shoulder rotation (°)	106.9 ± 17.6	40.0 to 163.1
Shoulder abduction (°)	97.4 ± 7.5	77.3 to 121.7
Ball velocity (m s^{-1})[a]	40.5 ± 1.3	35.5 to 44.0
Timing parameters		
FC to max hip rotation (ms)	− 36.7 ± 63.3	− 280.0 to 150.0
FC to max trail hip Rotation (ms)	− 36.7 ± 63.3	− 280.0 to 150.0
Max pelvis to max trunk velocity (ms)	38.3 ± 26.9	− 20.0 to 183.3
BR to max knee extension velocity (ms)	43.4 ± 68.9	− 166.7 to 216.7

▶ **Table 2** Continued.

Note: all kinematic variables exhibited a significant relationship with a dependent variable ($p < 0.05$) in an initial correlation analysis.

[a]Variables that did not exhibit a significant relationship but have been shown to contribute to the plate location in the previous literature. For variable definitions, see the KinaTrax documentation in the appendix.

and 13 kinematic variables showed an indirect relationship ($\beta_{c'} < \beta_{a \times b}$). Correlation coefficients between vertical location at the target and IVs ranged from $r = -0.295$ to 0.310. A linear mixed model (MED → DV) accounting for players revealed that vertical release angle accounted for 91.8 % of the variance in vertical location at the target ($R^2 = 0.918$, BIC = − 528, ICC = 0.729; ▶ **Table 3**). Additionally, with every 1° change in the vertical release angle, a displacement of approximately 0.23 m was observed (unstandardized $\beta = 0.229$). For mixed models that included both the IV and MED, BIC values ranged from − 611 to − 485, and R^2_{DV} values ranged from 0.906 to 0.928. Based on their BIC values [20], one standout model was identified as fitting the data best (▶ **Fig. 2a** and ▶ **Table 4**): lateral trunk flexion at BR ($R^2 = 0.908$, BIC = − 598, ICC = 0.528).

Lateral trunk flexion at BR had a direct effect on vertical location at the target, with a 1° increase in trunk lean at BR predicted to result in approximately 0.01 m of vertical deviation (unstandardized $\beta = -0.014$, $p < 0.001$). Despite the direct path being the strongest, it only reached practical significance ($\beta = -0.452$, $p > 0.05$). Further, both the lateral trunk flexion to release angle path ($\beta = 0.450$, $p < 0.001$) and release angle to location at the target path ($\beta = 0.819$, $p < 0.001$) achieved statistical and practical significance. This suggests that, although not identified explicitly in our analysis, lateral trunk flexion may also be influencing vertical location at the target via the MED instead of solely in a direct manner.

Horizontal Location at the Target

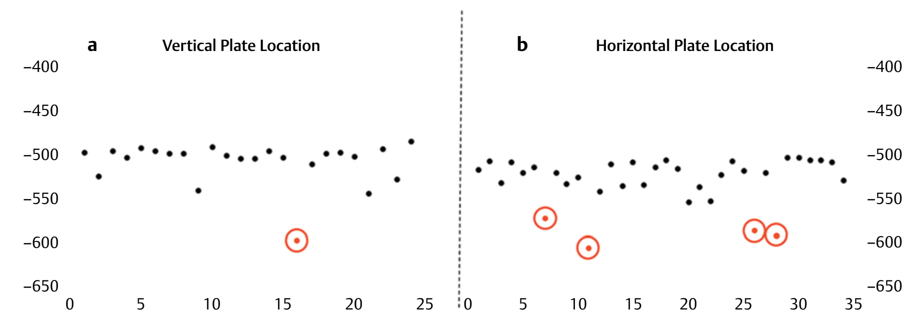
A summary of linear mixed model analyses and the 34 path for horizontal location at the target is presented in ▶ **Tables 5** and **6**. Twenty-three kinematic variables had a direct relationship with the DV ($\beta_{c'} > \beta_{a \times b}$), and 11 showed an indirect relationship ($\beta_{c'} < \beta_{a \times b}$). Correlation coefficients for IVs with horizontal location at the target ranged from $r = -0.277$ to 0.297. Like the vertical location at target analysis, a linear mixed model (MED → DV) accounting for players revealed that horizontal release angle accounted for 94 % of the variance in horizontal location at the target ($R^2 = 0.940$, BIC = − 546, ICC = 0.830; ▶ **Table 5**). Additionally, with every 1° change in the horizontal release angle, a displacement of approximately 0.24 m was observed (unstandardized $\beta = 0.243$, $p < 0.001$). For mixed models that included both the IV and MED, BIC values ranged from − 607 to − 504 and R^2_{DV} values ranged from 0.939 to 0.974. Based on their BIC values, four standout models were identified, which most closely fitted the data (▶ **Fig. 2b** and ▶ **Table 6**): Trunk

▶ **Table 3** Linear mixed model summaries for vertical location at the target.

Model	R^2	*F*	Num df	Den df	*p*	BIC	ICC
Release angle (vertical)	0.918	483.0	1	85.7	<0.001	−528.236	0.729
Release angle + ball velocity	0.928	64.7	1	64.0	<0.001	−611.058	0.731
Release angle + lateral trunk flexion at BR	0.908	50.9	1	53.2	<0.001	−598.051	0.528
Estimates							

			95 % confidence interval			
Predictor	Estimate	SE	Lower	Upper	t	*p*
Vertical release angle	0.229	0.010	0.209	0.250	22.00	<0.001
Ball velocity	0.087	0.011	0.066	0.657	8.04	<0.001
Lateral trunk flexion at BR	−0.014	0.002	−0.018	−0.010	−7.13	<0.001

Abbreviation: BIC, Bayesian information criterion; BR, ball release; Den df, denominator degrees of freedom; ICC, intraclass correlation coefficient (model); Num df, numerator degrees of freedom; SE, standard error.



▶ **Fig. 2** BIC values by models for vertical (left) and horizontal (right) plate locations. Note: The left panel represents BIC values (vertical axis) for each individual model (horizontal axis) in the vertical plate location analysis, whereas the right panel represents BIC values for individual models in the horizontal plate location analysis. BIC, Bayesian information criterion.

flexion at FC ($R^2 = 0.944$, BIC = −607, ICC = 0.776), COM displacement in the mediolateral direction between the start of the pitching cycle and FC ($R^2 = 0.974$, BIC = −573, ICC = 0.918), COM displacement in the mediolateral direction between the start of the pitching cycle and BR ($R^2 = 0.967$, BIC = −593, ICC = 0.865), and pelvis rotation at BR ($R^2 = 0.965$, BIC = −588, ICC = 0.895).

Trunk flexion at FC had a direct effect on horizontal location at the target, with a 1° change predicted to result in 0.01 m horizontal deviation (unstandardized $\beta = -0.010$, $p < 0.001$). As forward trunk flexion increases, the horizontal displacement of the ball tends toward the non-throwing side of the strike zone ($r = -0.117$). Although the direct path (trunk flexion → location at target) was stronger compared to the indirect path (trunk flexion → release angle → location at target), all individual paths reached statistical significance ($p < 0.001$). Furthermore, large effect sizes were observed for all but the indirect path ($\beta_{a\times b} = 0.247$). Since individual paths had large effect sizes, and the trunk flexion to ball release angle path was the strongest, it can be inferred that trunk flexion at FC has an influence on release angle, which then affects vertical displacement.

COM displacement from the start of the pitch to FC had an indirect effect, with a 1 m change predicted to result in approximately 0.61 m in horizontal location at target deviation (unstandardized $\beta = -0.606$, $p < 0.001$). Though the indirect path reached statistical significance, the effect size was small ($\beta = 0.090$, $p < 0.001$). The strongest path was the ball release angle to location at the target (MED → DV; $\beta = 0.523$ and $p < 0.001$); however, the second strongest was COM displacement to release angle (IV → MED; $\beta = 0.173$, $p < 0.001$), suggesting that COM displacement influences release angle, which gives rise to greater horizontal displacement. The COM displacement also showed an indirect relationship with horizontal location at the target between the start of the pitch and BR. A 1 m change over this timeframe would theoretically lead to 0.29 m of horizontal displacement, although this was not statistically significant (unstandardized $\beta = 0.285$, $p = 0.140$). Again, the effect size for the indirect path was small ($\beta = 0.069$), and the strongest path was release angle to the location at the target (MED → DV; $\beta = 0.516$, $p < 0.001$). Additionally, the COM displacement to release angle (IV → MED; $\beta = 0.133$, $p < 0.001$) path had the second largest effect size ($\beta = 0.133$). Collectively, these findings indicate that the displacement of the pitcher's COM influences their horizontal release angle, which in turn leads to a change in the ball's horizontal location at the target.

The final model of interest was pelvis rotation at BR, which had a direct relationship with the ball's horizontal location at the target. Results revealed that every 1° that the pelvis is closed relative to the target (rotated more towards the glove side) at BR, approx-

▶ **Table 4** Path and linear mixed model analyses of variables exhibiting a significant relationship with vertical location at the target (DV), with the inclusion of vertical release angle (mediator).

	Path estimates (β)								
	r	a	b	c′	a×b	R^2_{MED}	R^2_{DV}	BIC	Effect
Kinematic parameters at FC									
COM A/P zeroed (m)	0.267	0.037	0.613***	0.091**	0.023	0.514	0.918	−498.438	Direct
Lateral trunk flexion (°)	0.052	−0.244***	0.675***	0.241***	−0.165***	0.484	0.915	−525.467	Direct
Shoulder abduction (°)	0.310	0.119**	0.615***	0.009	0.073**	0.479	0.920	−496.010	Indirect
Shoulder horizontal abduction (°)[a]	0.021	−0.003	0.616***	0.020	−0.002	0.517	0.926	−504.687	Direct
Kinematic parameters at MER									
Lead knee flexion (°)	0.212	0.172***	0.621***	−0.028	0.107***	0.510	0.918	−493.965	Indirect
Lead knee extension velocity (°/s)	0.228	0.166***	0.620***	−0.022	0.103***	0.474	0.919	−496.686	Indirect
Lead hip abduction (°)	−0.185	0.033	0.619***	−0.096**	0.021	0.530	0.921	−499.308	Direct
Trunk flexion (°)	0.103	0.159***	0.617***	−0.009	0.098***	0.488	0.923	−499.223	Indirect
Lateral trunk flexion (relative to pelvis) (°)	−.058	0.394***	0.767***	−0.383***	0.302***	0.446	0.906	−542.944	Direct
Trunk rotation (°)	−0.074	−0.104**	0.615**	−0.011	−0.064**	0.507	0.918	−491.654	Indirect
Shoulder rotation (°)[a]	−0.024	−0.207***	0.636***	0.098**	−0.132***	0.509	0.923	−501.293	Indirect
Shoulder horizontal abduction (°)[a]	−0.088	0.023	0.616***	0.009	0.014	0.507	0.928	−505.633	Indirect
Elbow flexion (°)	0.213	−0.125***	0.635***	0.157***	−0.079***	0.503	0.919	−505.270	Direct
Kinematic parameters at BR									
Lead knee flexion (°)	0.206	0.174***	0.621***	−0.030	0.108***	0.501	0.918	−496.161	Indirect
COM M/L zeroed (m)	−0.295	−0.124***	0.614***	−0.018	−0.076***	0.508	0.919	−503.337	Indirect
Lateral trunk flexion (°)	−0.108	0.450***	0.819***	−0.452	0.369***	0.433	0.908	−598.051	Direct
Trunk flexion (°)[a]	0.033	0.335***	0.677***	−0.182***	0.227***	0.483	0.915	−511.731	Indirect
Shoulder rotation (°)	−0.199	−0.233***	0.630***	0.059	−0.146***	0.511	0.925	−499.006	Indirect
Shoulder abduction (°)	−0.108	−0.154***	0.619***	0.018	−0.095***	0.526	0.917	−498.370	Indirect
Timing parameters									
BR to max knee extension velocity (ms)	0.204	0.264***	0.634***	−0.067**	0.167***	0.473	0.922	−502.766	Indirect
Nonevent specific kinematic parameters									
Max lead hip flexion velocity (°/s)	0.160	−0.373***	0.758***	0.382***	−0.283***	0.433	0.918	−545.066	Direct
Max hip−shoulder separation (°)	0.137	−0.060	0.623***	0.115***	−0.038	0.506	0.917	−494.486	Direct
Max lateral trunk flexion (relative to pelvis) (°)	−0.037	0.390***	0.762***	−0.375***	0.298***	0.446	0.906	−528.441	Direct
Max shoulder rotation velocity (°/s)	0.190	0.041	0.613***	0.084**	0.025	0.672	0.914	−485.579	Direct

Abbreviation: A/P, displacement in the anterior-posterior direction; BIC, Bayesian information criterion; BR, ball release; COM, center of mass; DV, dependent variable; FC, foot contact; MER, maximum shoulder external rotation; M/L, displacement in the mediolateral direction; R^2_{DV}, predicted variance in dependent variable (predictor + mediator); R^2_{MED}, predicted variance in mediator (predictor); zeroed, data zeroed to setup position.

Note: all β-values are standardized. *r* = correlation coefficient between the variable and the vertical location at the target. a = predictor to the mediator path, b = mediator to the dependent variable path, c′ = predictor to the dependent variable path (when the mediator is included in the model), *a* × *b* = indirect path. All R^2 values are "conditional". [a]Variables exhibiting non-significant correlation coefficients with the DV but included in the mediation analysis owing to previously being identified in the literature as important components of the DV. $^*p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$.

▶ **Table 5** Linear mixed model summaries for the horizontal location at the target.

Model	R^2	*F*	Num df	Den df	*P*	BIC	ICC
Release angle (horizontal)	0.940	466.0	1	83.9	<0.001	−546.311	0.830
Release angle + trunk flexion at FC	0.944	24.1	1	77.9	<0.001	−607.478	0.776
Release angle + COM (ML) at FC	0.974	9.1	1	29.2	0.005	−573.791	0.918
Release angle + COM (ML) at BR	0.967	2.3	1	42.7	0.140	−593.664	0.865
Release angle + pelvis angle at BR	0.965	7.3	1	55.7	0.009	−588.083	0.895

Estimates

			95 % Confidence interval			
Predictor	Estimate	SE	Lower	Upper	t	p
Horizontal release angle	0.243	0.011	0.221	0.265	21.58	<0.001
Trunk flexion at FC	−0.010	0.002	−0.015	−0.006	−4.91	<0.001
COM (ML) at FC	−0.606	0.201	−1.000	−0.211	−3.01	0.005
COM (ML) at BR	0.285	0.189	−0.086	0.655	1.51	0.140
Pelvis angle at BR	−0.009	0.003	−0.015	−0.002	−2.71	0.009

Abbreviation: BIC, Bayesian information criterion; BR, ball release; COM, center of mass; Den df, denominator degrees of freedom; FC, foot contact; ICC, intraclass correlation coefficient (model); Num df, numerator degrees of freedom; SE, standard error.

imately 0.01 m in horizontal displacement will be observed towards the pitcher's non-throwing side ($r = -0.088$, unstandardized $\beta = -0.01$; $p = 0.009$). The direct path was statistically significant ($p < 0.01$), although the effect size was relatively small ($\beta = -0.102$). Like all models identified across the two DVs, the release angle to location at the target (MED → DV) path was the strongest ($\beta = 0.529$, $p < 0.001$); however, unlike other models, only the direct path and mediating path reached statistical significance. This suggests that pelvis rotation has no real influence on release angle. As a more proximal segment, it could be that segments further up the kinematic chain are able to compensate in some way to maintain a similar release angle, though this was not explicitly observed here.

Discussion

This paper set out to establish the relationship between in-game pitching kinematics, ball release angles, and throw location using in-game baseball pitching data and path analyses. Thirty-four (~60 %) kinematic variables had a direct effect on location at the target, and 23 (~40 %) had an indirect effect. To the authors' knowledge, this is the first attempt to quantify the relationships of multiple biomechanical variables using a path analysis. The decision to explore our data this way was based on two main factors. Firstly, path analysis is better able to explain complex interactions between variables [15, 21], and since the skill of pitching is a highly complex movement pattern consisting of multiple linked segments, there is a need to account for this. Secondly, it has best been described by Koike et al. (2019) that the equation of motion for a multiple linked-segment system includes a cause-and-effect relationship, indicating that one variable is not always directly influencing another [22]. Instead, there are intermediate, or mediating, variables that help to explain this. Thus, due to the inherent variation both within and between individuals, simply determining variables that are most strongly associated with a performance outcome does not explain the whole picture sufficiently.

In accordance with the previous literature, the current study confirmed that release angles (both vertical and horizontal) have the strongest relationship with the throw location at the target (▶ **Table 1**) [12–14]. Since horizontal and vertical release angles were both shown to have the strongest relationship with horizontal and vertical locations at the target, each was subsequently used as a mediating variable between kinematics and their respective DV (see ▶ **Fig. 1**). The two linear mixed models used to better determine the relationship between release angles (MED) and locations at the target (DV) confirmed the above assumption, with 91.8 % of the variance in vertical location at the target being accounted for by vertical release angle, and approximately 94 % of the variance in horizontal location at the target accounted for by horizontal release angle. From these two models, it was determined that for every 1° change in the vertical release angle, approximately 0.23 m of vertical deviation can be expected, and for every 1° change in the horizontal release angle, approximately 0.24 m of horizontal deviation would be observed.

Path Analysis – the Vertical Location at the Target

One model was a standout in the vertical location analysis: lateral trunk flexion at BR (direct). Lateral trunk flexion is a variable that has been identified in the literature previously as playing an important role in throw location. Manzi et al. (2021) observed that higher consistency pitchers had a more upright trunk at both MER and BR compared to lower consistency pitchers [7]. Interestingly, and maybe intuitively, less lateral trunk flexion in the higher consistency group was also coupled with a greater arm slot angle (more sidearm), suggesting that by flexing their trunk laterally players are able to manipulate arm slot. Why less lateral trunk flexion and a more sidearm slot resulted in more consistency is unclear, but Dutton et al. (2020) provided a potential mechanism [23]. Commenting on the throwing biomechanics of cricketers, the authors proposed that players may use a more sidearm throwing technique to improve throw accuracy by exploiting the speed-accuracy tradeoff [23]. In the sidearm position, the arm is straighter, which increases the moment of inertia (from the midline of the trunk to the hand/ball). Subsequently, as trunk rotation slows, the player may

▶ **Table 6** Path and linear mixed model analyses for variables exhibiting a significant relationship with horizontal location at the target (DV), with the inclusion of horizontal release angle (mediator).

		Path estimates (*b*)							
	r	a	b	c′	a×b	R^2_{MED}	R^2_{DV}	BIC	Effect
Kinematic parameters at FC									
Lead ankle eversion/inversion (°)	−0.240	−0.066	0.535***	−0.163***	0.035	0.673	0.941	−518.675	Direct
Trail ankle eversion/inversion (°)	0.178	0.148***	0.525***	−0.003	0.078***	0.652	0.940	−508.970	Indirect
Trail ankle flexion (°)	−0.117	−0.189***	0.528***	0.022	−0.100***	0.667	0.948	−533.415	Indirect
Lead foot angle (°)	−0.277	0.040	0.531***	−0.161***	0.021	0.663	0.940	−509.337	Direct
Lead hip abduction (°)	0.227	0.006	0.524***	0.092**	0.003	0.690	0.945	−521.465	Direct
Lead hip rotation (°)	0.280	0.209***	0.519***	0.027	0.109***	0.661	0.939	−514.780	Indirect
COM M/L zeroed (m)	0.249	0.173***	0.523***	0.011	0.090***	0.737	0.974	−573.791	Indirect
COM A/P zeroed (m)	−0.262	0.017	0.527***	−0.159***	0.009	0.667	0.939	−521.276	Direct
Lateral trunk flexion (°)[a]	0.091	0.287***	0.554***	−0.103**	0.159***	0.664	0.948	−534.660	Indirect
Lateral trunk flexion (relative to pelvis) (°)	−0.150	−0.140***	0.549***	0.176***	−0.077***	0.669	0.936	−526.381	Direct
Trunk flexion (°)	−0.117	0.380***	0.649***	−0.328***	0.247***	0.646	0.944	−607.478	Direct
Trunk flexion (relative to pelvis) (°)	−0.225	0.023	0.527***	−0.120***	0.012	0.682	0.951	−543.189	Direct
Shoulder rotation (°)	0.255	0.132***	0.522***	0.018	0.069***	0.636	0.943	−511.878	Indirect
Shoulder abduction (°)[a]	0.054	0.006	0.514***	−0.008	0.003	0.671	0.951	−536.774	Direct
Shoulder horizontal adduction (°)	0.297	0.020	0.522***	0.135***	0.010	0.684	0.941	−509.292	Direct
Kinematic parameters at MER									
Lead ankle flexion (°)	−0.173	−0.157***	0.523***	−0.009	−0.082***	0.682	0.947	−535.722	Indirect
Lead ankle eversion/inversion (°)	−0.266	−0.020	0.521***	−0.156***	−0.011	0.683	0.939	−514.322	Direct
Lead knee extension velocity (m/s)	−0.133	0.030	0.528***	−0.107***	0.016	0.673	0.941	−507.220	Direct
Lead hip rotation (°)	0.190	0.126***	0.522***	0.017	0.066***	0.676	0.941	−517.536	Indirect
Shoulder rotation (°)	−0.207	0.027	0.528***	−0.128***	0.014	0.666	0.950	−554.087	Direct
Shoulder horizontal adduction (°)[a]	0.088	−0.070	0.532***	0.111***	−0.037	0.660	0.947	−537.906	Direct
Elbow pronation/supination (°)	0.171	−0.016	0.526***	0.113***	−0.009	0.674	0.951	−553.651	Direct
Kinematic parameters at BR									
Lead ankle flexion (°)	−0.198	−0.090*	0.519***	−0.058	−0.047*	0.672	0.941	−523.888	Direct
Lead ankle eversion/inversion (°)	−0.251	−0.041	0.519***	−0.135***	−0.021	0.678	0.939	−508.831	Direct
Lead hip rotation (°)	0.184	0.167***	0.526***	−0.011	0.088***	0.661	0.940	−519.404	Indirect
Pelvis rotation (°)	−0.088	0.044	0.529***	−0.102**	0.023	696	0.965	−588.083	Direct
COM A/P velocity (m/s)	−0.201	0.001	0.524***	−0.100**	0.001	0.668	0.940	−521.799	Direct
COM M/L zeroed (m)	0.177	0.133***	0.516***	0.061	0.069***	0.686	0.967	−593.664	Indirect
Timing parameters									
FC to max hip rotation (ms)	−0.110	0.150***	0.553***	−0.192***	0.083***	0.662	0.940	−504.889	Direct
FC to max trail hip rotation (ms)	−0.110	0.150***	0.553***	−0.193***	0.083***	0.662	0.940	−504.889	Direct
Max pelvis to max trunk velocity (ms)	0.153	0.159***	0.524***	0.003	0.083***	0.670	0.940	−507.865	Indirect
BR to max knee extension velocity (ms)	−0.162	−0.072	0.520***	−0.058	−0.038	0.664	0.941	−507.861	Direct

▶ **Table 6** Continued.

	r	Path estimates (b)				R^2_{MED}	R^2_{DV}	BIC	Effect
		a	b	c′	a × b				
Non-event specific kinematic parameters									
Max lateral trunk flexion (relative to pelvis) (°)	0.128	−0.249***	0.586***	0.250***	−0.146***	0.672	0.937	−509.847	Direct
Max shoulder horizontal adduction/abduction (°)	0.277	0.069	0.518***	0.086**	0.036	0.689	0.941	−529.289	Direct

Abbreviation: BIC, Bayesian information criterion; BR, ball release; COM, center of mass; DV, dependent variable; FC, foot contact; MER, maximum shoulder external rotation; R^2_{DV}, predicted variance in DV (predictor + mediator); R^2_{MED} = predicted variance in the mediator (predictor).

Note: all β-values are standardized. r = correlation coefficient between the variable and horizontal location at the target. a = predictor to the mediator path, b = mediator to the DV path, c′ = predictor to the DV path (when the mediator is included in the model), a × b = indirect path. All R^2 values are "conditional". [a]Variables exhibiting non-significant correlation coefficients with the DV but included in the mediation analysis owing to previously being identified in the literature as important components of the DV. *p<0.05, **p<0.01, ***p<0.001.

be afforded slightly more time to release the ball in a more optimal location.

Path Analysis – the Horizontal Location at the Target

Four models were standouts in the horizontal location analysis: trunk flexion at FC (direct), mediolateral displacement of the COM up until FC (indirect), pelvis rotation at BR (direct), and COM displacement in the mediolateral direction between the start of the pitching cycle and BR (indirect). Trunk flexion is a variable well established in the baseball pitching literature as being linked to performance, with numerous studies having observed that greater trunk flexion at BR is linked to increased ball velocity [4, 24–26]. However, the relationship with throwing accuracy is less well understood, and to the authors' knowledge, the current study is the first to observe a relationship. Although our results identified that trunk flexion had a direct effect on horizontal location at the target, components of the indirect pathway were also statistically significant with large effect sizes. In fact, the effect that trunk flexion had on the release angle was greater than that which it had on location at the target, suggesting that it may also influence the horizontal release angle.

A potential explanation for the trunk flexion's impact on horizontal throw location is the association between trunk angle at BR and ball velocity. During the early stages of the pitching motion (up to FC), a more extended trunk position is advocated for [27] as it allows for a greater acceleration path up to ball release [14]. As a consequence, it may be that trunk flexion is prioritized when the trunk is more extended early on in the pitching cycle (like at FC). Since it has been documented that biomechanical compensations are utilized in order to maintain ball velocities [28], when the trunk is more flexed early on in the pitch, rotation may be the only movement that can be employed to accomplish this. If this is the case, the arm will likely move in a path more around the body, impacting the horizontal release angle and leading to greater horizontal displacement.

COM displacement and its relationship with throwing performance has yet to be reported in the literature. Nevertheless, the transfer of linear momentum may help to explain why COM displacement between the start of the pitch and two time points (FC and BR) indirectly affects horizontal location at the target. When the COM shifts laterally, it reduces the momentum directed toward the target, necessitating adjustments in the overall movement sequence. Pitchers must be cautious not to allow excessive lateral movement of their COM as this can compromise stability. Should COM displacement be too great at FC, it may not be possible for them to regain a stable platform to throw from. However, if they are to shift their COM back towards the center of their base of support by BR, horizontal ball displacement will be impacted less. A notion that is evident in the estimates of the linear mixed models, where for the same displacement in COM (1 m) at each time point, twice the horizontal displacement of the ball is observed at FC (0.61 m) compared to BR (0.29 m).

When COM is displaced laterally, distal segments like the arm and the hand may need to adjust to bring it back inside the base of the support. However, since the arm is now actively involved in positioning the hand in space, achieving an optimal release position becomes challenging. It is known that compensations at the more distal end of the kinematic chain (segments closer to the hand) become necessary to account for inefficiencies in the more proximal segments [28]; thus, if a pitcher allows their COM to move laterally and still aims to maintain ball velocity, their distal segments must compensate accordingly. These compensations can lead to alterations in ball release conditions, potentially resulting in an inability to hit an intended target. One of the most affected release parameters is the horizontal release angle, which was observed to be directly influenced by COM displacement at two time points (FC and BR). This suggests that the COM not only influences momentum transfer through the body towards the target, but also impacts the release angle, leading to greater horizontal ball displacement over home plate.

Pelvis rotation was the last variable of prominence in our analysis and had a direct effect on horizontal location. Similar to trunk flexion, pelvis rotation has also been linked to measures of pitching performance; however, literature typically observes rotational velocities as being the key kinematic parameter [29, 30]. Pelvis rotation angle, however, is not a variable frequently reported on, especially at BR. This might be explained by the findings in the present study, which suggest that it is less important to throwing performance overall. A weak negative correlation and small path *βs* suggest that pelvis rotation at BR has a little impact on horizontal displacement, which may simply be a function of the requirements of the baseball pitch. Since the target (strike zone) is directly in front of the pitcher at ball release, pelvis rotation may only really be required in the early stages of the pitch to get the pitcher facing the batter. Differences in pelvis angle have been observed in the early stages of the pitching cycle; yet, by MER, these were negligible [31]. Wight et al. (2004) also note that despite differing early pelvis kinematics, performance outcomes were the same [31]. As the pelvis is a proximal segment in the kinematic sequence, it could be that there is some intrinsic redundancy, which allows for a wider range of pelvis kinematics early in the pitching cycle. Couple this with the potential prioritization of trunk flexion during the pitching motion, and it appears that pelvis kinematics in the latter portion (i.e., from MER onwards) of the pitch are much less important than those of the trunk. This may go some way to explain why for pelvis kinematics, only the direct path was significant, and the effect size was small.

Limitations

A few limitations of the present study must be considered. First is that there is currently no peer-reviewed research validating KinaTrax, making it challenging to fully interpret the current findings. However, it is understood that at the time of writing a number of articles are being prepared to overcome this, and preliminary indications suggest that KinaTrax values are comparable to those obtained from validated motion capture systems. Nevertheless, there is a need to confirm this. Second, a mixture of right- and left-handed batters were faced by pitchers. While this should not impact pitching kinematics extensively, pitchers may have adjusted, which could have been reflected in the data. Finally, finger kinematics were not included despite research identifying that the fingers play an integral role in controlling ball release. Unfortunately, the KinaTrax system is currently unable to track these, so whether or not the current work would have also reached similar conclusions is therefore unknown.

Conclusions

The present study has demonstrated the complex relationship between throwing kinematics, release angles, and throw location. Many of the key variables identified here have previously been reported in the literature (trunk kinematics and pelvis rotation); however, our results also indicated that COM plays a considerable role in the horizontal displacement of the ball. This work has provided key insights into how kinematic variables might influence horizontal and vertical displacement of the ball at the target during pitching; yet, there is still a need to better understand how kinematics influence release parameters. Since release angles were shown to influence throw location at the target most, more research is needed on this topic. It should then be possible to determine which variables might be manipulated in order to "correct" or "improve" release conditions so that a pitcher may be more effective in-game.

Disclosure statement

The authors report there are no competing or conflicts of interest to declare.

Conflict of Interest

The authors declare that they have no conflict of interest.

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