Original Research

Kinematic Modeling of Pitch Velocity in High School and Professional Baseball Pitchers

Comparisons With the Literature

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Background: Kinematic parameters predictive of pitch velocity have been evaluated in adolescent and collegiate baseball pitchers; however, they have not been established for high school or professional pitchers.

Purpose: To create multiregression models using anthropometric and kinematics features most predictive for pitch velocity in high school and professional pitchers and compare them with prior multiregression models evaluating other playing levels.

Study Design: Descriptive laboratory study.

Methods: High school (n = 59) and professional (n = 337) baseball pitchers threw 8 to 12 fastballs while being evaluated with 3-dimensional motion capture (480 Hz). Using anthropometric and kinematic variables, multiregression models for pitch velocity were created for each group. A systematic review was conducted to determine previous studies that established kinematic models for ball velocity in youth, high school, and collegiate pitchers.

Results: Leg length was predictive of pitch velocity for high school and professional pitchers ($P < .001$ for both). When compared with previously established models for pitch velocity, almost all groups were distinct from one another when assessing age ($P_{maximum} < .001$), weight ($P_{max} = .0095$), and pitch velocity ($P_{max} < .001$). Stride length was a significant predictor for the youth/high school pitchers, as well as the current study's high school and professional pitchers ($P < .001$ for all). Maximal shoulder external rotation (collegiate: $P = .001$; professional: $P < .001$) and maximal elbow extension velocity (high school/collegiate: $P = .024$; collegiate: $P < .001$; professional: $P = .006$) were shared predictors for the collegiate and current study's professional group multiregression models. Trunk flexion at ball release was a commonly shared predictor in the youth/high school ($P = .04$), high school/collegiate ($P = .003$), collegiate ($P < .001$), and the current study's professional group ($P < .001$).

Conclusion: Youth, high school, collegiate, and professional pitchers had unique, predictive kinematic and anthropometric features predictive of pitch velocity. Leg length, stride length, trunk flexion at ball release, and maximal shoulder external rotation were predictive features that were shared between playing levels.

Clinical Relevance: Coaches, clinicians, scouts, and pitchers can consider both the unique and the shared predictive features at each playing level when attempting to maximize pitch velocity.

Keywords: ball speed; pitch speed; ball velocity; motion capture

Pitch velocity has been significantly popularized by the media and fans, as well as by coaching staff and players. Though desirable in terms of performance, pitch velocity has also been adversely associated with increased risk of elbow injury as well as incidence of ulnar collateral ligament (UCL) surgery in Major League Baseball.[7,45] In high school pitchers, pitch velocity has served as an independent correlate with injury at the shoulder and elbow.[5] Given both the performance benefits and the injury risks associated with pitch velocity, biomechanical assessments have been conducted in attempts to better characterize predictors of pitch velocity in professional pitchers.[22-24]

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Previous evaluations of pitch velocity have slightly varied in methodological approach, although several shared kinematic parameters have been identified. One fundamental variable that has been shown to affect pitch velocity in professional pitchers is the temporal sequence of core body segments and joint angular velocities during the pitching motion.[25,42] Temporal variations in the kinetic sequence of pelvis, to upper trunk, and to shoulder rotation affect upper extremity kinetics as well as ball velocity.[12] Because the lower extremities, pelvis, and trunk create the majority of the kinetic energy that is ultimately transferred to the baseball via the upper extremities, ensuring maximal energy transfer is essential to increasing pitch velocity by way of a proper, temporal sequence.[6,17,21,25,33,42]

Additional studies have identified other kinematics associated with faster pitch velocities, including increased maximal shoulder external rotation in pitchers from several playing levels.[25,26] Matsuo et al[25] suggested that increased shoulder external rotation benefits pitchers by way of an increased in-pitch range of motion, as well as increased generation of stored potential energy during the arm cocking phase. Other predictors evaluated include increased shoulder horizonal abduction at foot contact,[41] increased knee extension angular velocity at ball release,[25] greater trunk lateral flexion at maximal shoulder external rotation and at ball release,[40,26] and increased trunk flexion at ball release.[25,26,39,44] Beyond kinematic and temporal variables, anthropometric variables such as a pitcher's body weight, height, and age have also been associated with increased pitch velocity.[26,36,44] Though valuable in understanding the components to faster pitch velocity, these studies have predominantly been conducted in high school, collegiate, and mixed cohorts of pitchers with a dearth of investigation at the professional level.

To date, a relative deficiency exists in the evaluation of pitch velocity via multiregression models, in particular at the professional level.[28,36,44] Therefore, the first purpose of this study was to create multiregression models of kinematic and anthropometric features most predictive for pitch velocity in high school and professional pitchers. The second purpose was to qualitatively compare previously published kinematic models for pitch velocity at different playing levels with the current study's findings via a formal systematic review. We hypothesized that the kinematic variables most predictive of pitch velocity would vary among playing levels but that some variables, such as maximal shoulder external rotation and increased forward trunk flexion, would be retained between groups as predictive parameters for pitch velocity.

METHODS

Participants

The data sets of the participants selected for this study were from a database of baseball pitchers who had previously undergone a 3-dimensional biomechanical pitching assessment conducted by Motus Global. Players were asked to complete a consent document and a privacy waiver, permitting data from the assessment to be added to database. These data were deidentified before distribution, qualifying the study, which received institutional review board approval, for exempt review under federal guidelines. Included in this study were professional pitchers who were active on a roster spot on a major league or minor league (low A, high A, AA, and AAA) team and high school pitchers who were active on their high school or club team. Additionally, all included pitchers had to have no record of serious injury during the time of testing, defined as requiring >2 weeks of rest or rehabilitation within 6 months of testing.

Pitching Assessment

Pitching evaluations were performed as previously described.[8,19,20] Demographic data were reported by the pitcher, including age, preferred arm for throwing, and injury history. Researchers measured and recorded the pitchers' height and weight. Each pitcher was given unlimited time to warm up with his preferred routine of pitching at maximal effort (ie, arm bands, stretching, plyometric care, long toss, etc). Once the pitcher indicated that he was ready to pitch, 46 reflective markers were placed on anatomic landmarks as previously described.[20] An 8-

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Ethical approval for this study was obtained from the Hospital for Special Surgery (ref No. 2020-19-57).

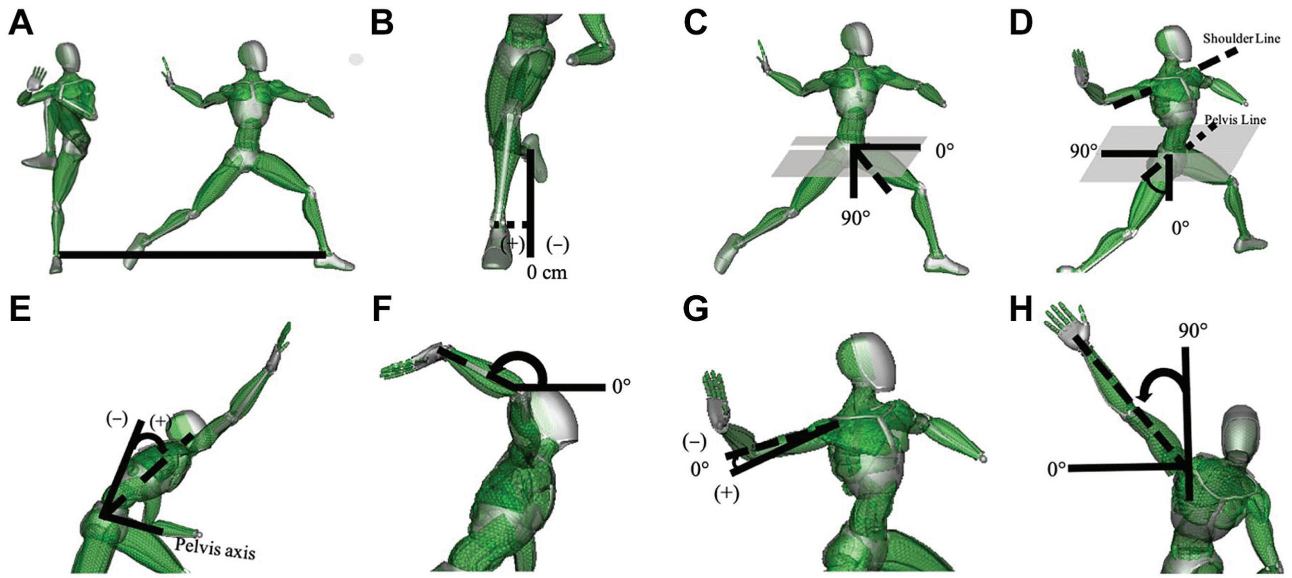

Figure 1. Definitions of position variables for (A) stride length, (B) stride width, (C) pelvic rotation, (D) trunk rotation, (E) trunk flexion, (F) shoulder external rotation, (G) shoulder horizontal abduction, and (H) arm slot.

camera Raptor-E motion analysis system (Motion Analysis Corp) collected data at 480 Hz. The global coordination system was established on the basis of the International Society of Biomechanics standards: Y was vertically upward, X was perpendicular to Y (positive to home plate), and Z was the cross-product of X and Y.

Pitchers were instructed to pitch between 8 and 12 fastballs with gamelike effort to a catcher behind home plate at regulation distance (18.4 m). Pitchers threw from a regulation dirt mound and were allowed to pitch at their own set rate. They were given the option to pitch from either the stretch or the wind-up, as previous research has shown that no difference in mechanics exists between the 2 types.[9] Pitch velocity was collected with a radar gun located behind the pitcher (Stalker Sports Radar). Pitch location was charted by the team's pitching coach.

Data Processing

All data processing for kinematics and throwing arm kinetics was performed using custom-built MATLAB scripts (The Mathworks Inc).[20] Data from the markers were filtered by a low-pass filter (fourth-order, zero-lag Butterworth filter, 13.4-Hz cutoff frequency).[19] The pitch was divided into 4 time points: foot contact, maximal shoulder external rotation, ball release, and maximal shoulder internal rotation. Pitch timing was calculated as a percentage, where foot contact was considered 0% and ball release was 100%. Foot contact was identified as the first frame where either the lead toe or the heel reached minimal Y. Maximal external rotation of the shoulder was established as the frame in which the throwing arm achieved maximal external rotation. Ball release was calculated as the frame 0.01 seconds after the wrist passed the elbow in the X direction (toward home plate). Maximal internal rotation was defined as the frame where the throwing arm reached maximal internal rotation angle after ball release.

Stride length was calculated as the distance between the back ankle when the pitcher was bringing his knee up to start the pitch and the front ankle at foot contact and represented as a percentage of leg length (Figure 1A).[38] Leg length was measured as the distance from the greater trochanter of the femur to the lateral malleolus of the ankle. Stride width was calculated as the mediolateral displacement between the lead and stance medial malleolus at foot contact (Figure 1B). Pelvic rotation was defined as the angle between the anteriorly facing vector of the pelvic segment relative to the global X vector, where 0° corresponded to the pelvis facing home plate and 90° corresponded to the pelvis perpendicular to home plate (Figure 1C). Trunk rotation was calculated as the angle in the transverse plane from the shoulder line relative to the pelvic line; 0° was no rotation, a positive angle was considered rotation toward the throwing arm, and a negative angle was defined as rotation toward the glove hand (Figure 1D). Shoulder external rotation was calculated as the longitudinal rotation of the upper throwing arm relative to the trunk's sagittal plane (Figure 1F). Shoulder horizontal adduction was defined as the angle between the upper throwing arm and the upper trunk vector in the transverse plane of the upper trunk, so that a negative value was considered abduction and positive was adduction (Figure 1G). Trunk flexion was defined as the angle in the sagittal plane between the midpoint of both shoulders (shoulder line) and the midpoint of both anterior superior iliac spines (pelvic line); a negative value indicated trunk extension (Figure 1E). Arm slot was calculated as the angle between a vertical vector and a vector connecting the throwing shoulder joint center to the hand, when viewed from home plate in a global reference frame (Figure 1H).[10] Peak joint and segment velocities were calculated by taking the first derivative of the joint and segment center of mass and orientation using the 5-point central differences approximations.[20]

Statistical Analysis

Pitchers were grouped based on playing level: professional or high school. All statistical analyses were performed separately for the 2 groups to avoid confounding. The mean and standard deviation of demographic variables of the pitchers, including age, height, weight, and pitch velocity, were calculated, with analysis of variance tests performed between populations in this study as well as 2 previously characterized populations for comparison.[36,44] High school and professional pitchers threw a mean ± SD 7 ± 5 pitches each. All pitches with an outlier ball velocity (defined as >3 or <3 scaled median absolute deviation away from the median in its respective population) were removed from the data set. All anthropometric and kinematic variables were assessed and an optimal set of independent, nonduplicate, continuous variables (n > 200) were chosen for regression analysis. A multivariate linear regression model was then used to assess the effects of the chosen set of variables on ball velocity. A regression coefficient (B) and standardized regression coefficient (β) were then calculated. When comparing the current study's demographics with prior literature with multiregression analyses for pitch velocity,[36,44] an analysis of variance with post hoc Tukey honestly significant difference was performed. Alpha was set at .01 for all statistical analysis. Statistical analyses were performed using MATLAB scripts.

Literature Review

A systematic review was conducted to determine previously published studies in English that established kinematic models for ball velocity in youth, high school, and collegiate pitchers. Only studies that created multiregression models using kinematic variables as input data with ball velocity as the primary outcome were considered for inclusion. Studies that focused on ball trajectory kinematics, studies on softball, and studies with sample sizes of <5 pitchers were not included. Studies that were included were ones with evidence levels from 1 to 3 that directly compared cases and controls, as well as level 4 studies that carried out a subanalysis that made available the data required to produce metaregressions. Case reports, technical notes, conference abstracts, narrative or systematic reviews, and letters to editors were excluded.

Article Search Process. The 2009 PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines were followed while extracting the articles.[27] Using the Boolean search term "(((pitch velocity) OR (pitch speed)) OR (ball velocity)) AND (baseball)," a study search was conducted in November 2023 for literature relating to kinematic predictors of ball velocity in high school, collegiate, and professional baseball pitchers.

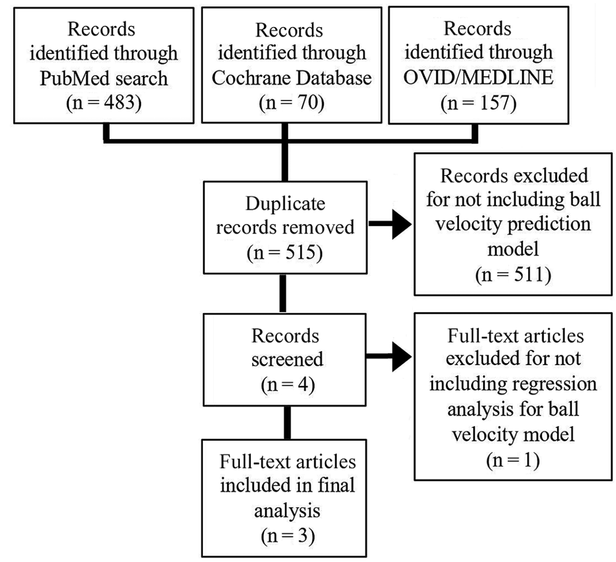

Figure 2. Flowchart showing inclusion process of studies.

The Cochrane Central Register of Controlled Trials, the Cochrane Database of Systematic Reviews, PubMed (2008-2019), and OVID/MEDLINE (2008-2019) databases were used to conduct the inquiry.

Search Results. A total of 515 studies were identified from the initial search with publication dates ranging between 1999 and 2023 (Figure 2). After a review of the reference sections, no additional studies were added. One article predicted ball velocity in youth pitchers from the Netherlands utilizing anthropometric characteristics as well as angular velocities of the pelvis and trunk via a Bayesian model.[14] This was excluded from the Results section due to its methodological incomparability but is examined in the Discussion section. Three articles were ultimately deemed appropriate for analysis in the present study: Sgroi et al,[36] Nicholson et al,[28] and Werner et al.[44] The lack of consistent study design or outcome variables precluded meta-analysis. A MINORS (methodological index for non-randomized studies) score was calculated for each study included, with all 3 studies scoring 12 out of 16, suggesting good quality.

RESULTS

Results of Multiregression Models

For the regression models created, 59 high school pitchers with a total of 538 fastball pitches and 337 professional pitchers with a total of 3627 pitches were included. Top parameters predictive for ball velocity in high school pitchers are included in Table 1. Leg length (B = 26.406; β = 0.440; $P < .001$), stride length (B = 0.414; β = 1.415; $P < .001$), forearm pronation at maximal shoulder external rotation (B = 0.099; β = 0.835; $P < .001$), and the timing of maximal trunk rotational velocity (typically occurring

TABLE 1
Predictive Parameters for Ball Velocity in High School Pitchers[a]

Parameter	B	β	SE	*t*	*P*
Anthropometric					
Leg length	26.406	0.440	7.180	3.678	<.001
Foot contact					
Stride length	0.414	1.415	0.070	5.887	<.001
Stride width	3.864	0.242	0.986	3.919	<.001
Maximal shoulder external rotation					
Forearm pronation	0.099	0.835	0.022	4.572	<.001
Ball release					
Back hip flexion	–0.227	–0.726	0.086	–2.629	.009
Shoulder horizontal adduction	0.198	0.677	0.056	3.538	<.001
Forearm pronation	–0.073	–0.653	0.019	–3.788	<.001
Shoulder external rotation	–0.048	–0.325	0.018	–2.720	.007
Peak segmental and joint velocities/kinetic energy					
Pelvic rotational kinetic energy	0.063	0.236	0.021	3.074	.002
Temporal					
Peak trunk rotational velocity	0.038	0.133	0.013	2.979	.003
Peak shoulder external rotation	0.326	0.653	0.118	2.769	.006

[a]Predictors listed here reached the minimal threshold ($P < .01$) and achieved the highest standardized regression coefficient (β). Total predictive capacity for the model (adjusted R^2) = 0.925. B, regression coefficient.

immediately after maximal shoulder external rotation; B = 0.038; β = 0.133; *P* = .003) were significant predictors for high school pitchers. For every 12.7-cm (5-in) increase in leg length for high school pitchers, pitch velocity increased by 3.35 m/s (7.5 mph). For every 10° increase in forearm pronation at maximal shoulder external rotation, pitch velocity increased by 1.0 m/s (2.2 mph). For every 1 SD in delay of maximal trunk rotational velocity timing, ball velocity increased by 0.3 m/s (0.65 mph).

Predictive features for the multiregression model in professional pitchers are shown in Table 2. Leg length (B = 13.706; β = 0.292; *P* < .001), stride length (B = 0.060; β = 0.334; *P* < .001), trunk rotation at foot contact (B = 0.059; β = 0.289; *P* = .005), maximal shoulder external rotation (B = 0.688; β = 0.333; *P* < .001), and maximal elbow extension velocity (B = 0.001; β = 0.176; *P* = .006) were all predictive parameters, in addition to trunk flexion at maximal shoulder external rotation (B = −0.366; β = −1.741; *P* < .001), at ball release (B = 0.371; β = 1.829; *P* < .001), and at maximal shoulder internal rotation (B = −0.111; β = −0.601; *P* < .001). For every 12.7-cm increase in leg length for professional pitchers, pitch velocity increased by 1.74 m/s (3.9 mph). For every 10° increase in trunk flexion at ball release, pitch velocity increased by 3.71 m/s (8.3 mph).

Results of Literature Review

When compared with previously established models for pitch velocity, demographic data were first compared and analyzed among groups (Table 3). All groups were distinct from one another when assessing age ($P_{maximum} < .001$), weight (P_{max} = .0095), and pitch velocity ($P_{max} < .001$), except for Nicholson et al,[28] which showed comparable ball velocity to Werner et al[43] and comparable age to our high school cohort. There was no difference in height between the high school group in the current study and the collegiate group in Werner et al[44] (*P* = .871).

Comparisons of the multiregression models for pitch velocity among the different playing levels are in Supplemental Table S1. The Sgroi et al[36] cohort involving youth/high school pitchers included several anthropometric features as predictive, including age (B = 1.47; *P* < .001), height (B = 1.19; *P* < .001), and body mass index (B = 0.05; *P* = .006). Leg length, not assessed by Sgroi et al[36] or Werner et al,[44] was a predictive feature for the current study's high school (B = 26.41; β = 0.44; *P* < .001) and professional pitchers (B = 13.71; β = 0.29; *P* < .001). Normalized stride length was a significant feature for youth/high school pitchers in Sgroi et al[36] (B = 0.19; *P* < .001) as well as the current study's high school (B = 0.41; β = 1.41; *P* < .001) and professional pitchers (B = 0.06; β = 0.33; *P* < .001). Knee flexion at foot contact was commonly shared by the youth/high school[36] (B = 0.08; *P* = .001) and collegiate[44] (B = 0.10; β = 0.23; *P* = .044) models. In collegiate[44] and professional pitchers, maximal shoulder external rotation (collegiate: B = 0.27, β = 0.41, *P* = .001; professional: B = 0.07, β = 0.33, *P* < .001) and maximal elbow extension velocity (collegiate: B = 0.01, β = 0.46, *P* < .001; professional: B = 0.001, β = 0.18, *P* = .006) were common features in the multiregression models. Maximal elbow extension velocity derived significance for the high school/collegiate cohort (β = 0.00; SE = 0.00; *P* = .024). Last, trunk flexion at ball release was a commonly shared positive feature in all of the groups except for the current study's high school pitchers.

TABLE 2
Predictive Parameters for Ball Velocity in Professional Pitchers[a]

Parameter	B	β	SE	*t*	*P*
Anthropometric					
Leg length	13.706	0.292	1.413	9.703	<.001
Foot contact					
Stride length	0.060	0.334	0.012	4.851	<.001
Trunk rotation	0.059	0.289	0.021	2.822	.005
Maximal shoulder external rotation					
Back hip flexion	–0.096	–0.411	0.021	–4.512	<.001
Pelvic tilt	0.171	0.584	0.052	3.309	<.001
Trunk flexion	–0.366	–1.741	0.046	–7.987	<.001
Trunk lateral flexion	–0.222	–0.964	0.049	–4.578	<.001
Shoulder external rotation	0.068	0.333	0.008	8.594	<.001
Ball release					
Back hip flexion	0.063	0.308	0.024	2.648	.008
Trunk flexion	0.371	1.829	0.059	6.244	<.001
Lateral trunk flexion	0.197	0.887	0.060	3.273	.001
Shoulder external rotation	–0.030	–0.210	0.006	–4.613	<.001
Maximal shoulder internal rotation					
Trunk lateral flexion	–0.117	–0.608	0.033	–3.585	<.001
Trunk flexion	–0.111	–0.601	0.031	–3.539	<.001
Peak segmental and joint velocities					
Elbow extension velocity	0.001	0.176	<0.001	2.768	.006
Temporal					
Peak shoulder internal rotation velocity	0.196	0.381	0.050	3.947	<.001

[a]Predictors listed here reached the minimal threshold ($P < .01$) and achieved the highest standardized regression coefficient (β). Total predictive capacity for the model (adjusted R^2) = 0.536. B, regression coefficient.

TABLE 3
Comparison of Demographic Data Between Pitch Velocity Modeling Studies[a]

Variable	Sgroi et al[36] (Youth/HS)	Current Study HS	Nicholson et al[28] (HS/Collegiate)	Werner et al[44] (Collegiate)	Current Study PRO	Significance[b]
Sample size, N	420	59	227	54	337	—
Age, y	14.7 ± 2.6	16.4 ± 1.4	16.9 ± 3.1	20.0 ± 2.0	21.9 ± 2.1	A,B,C,D,E,F,G,I,J
Height, cm	171.5 ± 13.5	180.5 ± 7.8	NA	182.0 ± 8.0	189.7 ± 5.7	A,C,D,F,G,J
Weight, kg	66.0 ± 17.8	74.6 ± 11.6	NA	83.0 ± 9.0	94.8 ± 9.5	A,C,D,F,G,J
Pitch velocity, m/s	28.6 ± 4.5	31.3 ± 2.9	36.1 ± 3.4	35.0 ± 3.0	38.3 ± 2.1	A,B,C,D,F,G,I,J

[a]Data are presented as mean ± SD, unless otherwise indicated. HS, high school; NA, not available; PRO, professional.
[b]Statistically significant differences between cohorts ($P < .01$) as follows: (A) Sgroi et al vs current study HS; (B) Sgroi et al vs Nicholson et al; (C) Sgroi et al vs Werner et al; (D) Sgroi et al vs current study PRO; (E) current study HS vs Nicholson et al; (F) current study HS vs Werner et al; (G) current study HS vs current study PRO; (H) Nicholson et al vs Werner et al; (I) Nicholson et al vs current study PRO; and (J) Werner et al vs current study PRO.

DISCUSSION

By understanding the variables associated with increased pitch velocity, coaches and athletic trainers can better tailor training regimens by playing level to maximize pitch velocity. When comparing the overall coefficient of determination for each included study, the model's efficacy was highest for the high school cohort from the current study (R^2 = 0.925), followed by the youth/high school cohort from Sgroi et al[36] (R^2 = 0.78), with the least predictability in the professional cohort from the current study (R^2 = 0.536) and the high school/collegiate cohort from Nicholson et al[28] (R^2 = 0.45). This range of module applicability can be due to a myriad of factors including which variables were included in each model, kinematic parameter collection methodology, exclusion criteria, as well as respective analyses conducted. The major findings of this study were as follows: (1) normalized stride length was a predictive feature across youth, high school, and professional groups; (2) maximal shoulder external rotation and maximal elbow extension velocity were common features of the collegiate and current study's professional cohort multiregression models; and (3) trunk flexion at ball release was a commonly shared feature in the youth/high school, high school/collegiate, collegiate and current study's professional cohorts.

Anthropometric features including age, height, and body mass index were predictive features in the youngest playing group evaluated in Sgroi et al,[36] while leg length was critical in the high school and professional multiregression models. The rapid development and pubescent changes typical of youth and juvenile pitchers (age, 14.7 ± 2.6 years) likely explain the significant changes in pitch velocity experienced by pitchers who are older, heavier, and taller.[16] Gomaz et al[14] interestingly noted that in their Bayesian model the inclusion of pitcher height added value to the prediction of ball velocity based on body segment rotation. Werner et al[44] also observed weight as a predictive feature in collegiate pitchers, suggesting mass may continue to play an important role in pitch velocity as pitchers advance; heavier pitchers likely have greater strength, are able to generate increased power, and ultimately achieve faster pitch velocity as a result. It should be noted that this suggested weight benefit was not observed at the high school or professional level in the current study.

An anthropometric feature that may play a more important role in pitch velocity is leg length. For every 12.7-cm (5 in) increase in leg length for high school pitchers, pitch velocity increased by 3.35 m/s (7.5 mph). Similarly, for every 12.7-cm increase in leg length for professional pitchers, pitch velocity increased by 1.74 m/s (3.9 mph). Leg length, though closely associated with standing height, uniquely was only included in the analysis for the current study's populations but not in the studies included in the systematic review, a parameter that develops at a discrete and separate rate compared with torso length (ie, sitting height).[13] Stride length normalized by leg length or by body height was significantly predictive of pitch velocity in the youth/high school, high school, and professional groups. Ultimately, pitchers with longer strides have been found to better attenuate total body transverse momentum from foot contact onward and, thus, be capable of transferring momentum efficiently for optimal use at the distal limb for generation of faster pitch velocity.[22,32] Longer stride lengths increase regulation of transverse trunk momentum before acceleration.[32] When pitching with shorter strides, higher transverse trunk momentum before throwing arm acceleration may cause unwanted momentum exchanges between the trunk and throwing shoulder, adversely affecting the kinetic chain and lowering ball velocity. While leg length is not modifiable, pitchers at all playing levels can strive for increased stride length to achieve faster ball velocity, a finding previously corroborated in collegiate and professional pitchers.[22,46]

When attempting to determine parameters most predictive for pitch velocity at differing playing levels, maximal shoulder external rotation and maximal elbow extension velocity were common features of the collegiate and professional group multiregression models. Collegiate and professional pitchers have previously been noted to have positive ball velocity benefits with increased maximal shoulder external rotation.[23,25] Increased layback during the arm-cocking phase results in more stored elastic energy and stretch, which is then used to maximize the accelerating force applied to the ball for the longest distance during the ensuing acceleration phase.[30] Though a well-established benefit in higher playing levels for increased pitch velocity, increased shoulder external rotation has also been associated with increased elbow varus torque as well as increased shoulder distraction force in professional pitchers.[3,23] However, increased elbow varus torque has directly been implicated in risk of elbow injury,[1] while shoulder distraction has been implicated in risk of shoulder injury, including proximal humeral epiphysiolysis, labral tears, bicipital tendinitis, and rotator cuff lesions.[11,35]

Trunk flexion at ball release was a commonly shared feature in the youth/high school, high school/collegiate, and collegiate, as well as the current study's professional, multiregression models for pitch velocity, a finding substantiated by several previous biomechanical evaluations in adult pitchers.[25,39] Smoother transference of kinetic energy by way of accentuated forward trunk flexion may help pitchers more efficiently utilize the kinetic chain and capitalize on the segmental velocities generated by the core segments and lower extremities.[25,26,39] While positively associated with pitch velocity, forward trunk flexion at ball release has also been noted to have elbow varus torque associations that may not necessarily warrant the pitch velocity benefit.[39] Werner et al[44] noted that for every 10° increase in trunk flexion at ball release, pitch velocity increased by 3.8 m/s (8.5 mph) in collegiate pitchers, a regression value similarly observed for our professional group. However, Solomito et al[39] noted a much less pronounced relationship in collegiate pitchers, reporting for every 10° of trunk flexion at ball release, there was a 0.7 m/s (1.5 mph, or 2% average) increase in ball velocity, while elbow varus torque increased by 2.9 N·m (or 4% average), suggesting a modest increase in joint torque with a limited increase in pitch velocity. Increased trunk flexion at ball release appears to play a significant role in the generation of pitch velocity, with mixed results when it comes to the quantification of this relationship, even within the same playing level. The theoretical increase in elbow joint torque suggests that additional evaluation of trunk flexion and its relationship with throwing arm kinetics is merited. Pitchers and coaching staff should consider this potential trade-off.

Strengths and Limitations

The current work includes 2 new subgroups for multiregression model prediction for pitch velocity and also the first direct comparison of demographically distinct cohorts including youth, high school, collegiate, and professional pitchers. We incorporated 8 motion capture cameras at a 480-Hz capture rate, double that of most prior evaluations.

Our study is not without limitations. While we attempted to incorporate as much as possible of the surrounding literature associating kinematic variables with pitch velocity in a formal systematic review, the primary objective for comparison was studies featuring multiregression models, suggesting other evaluations assessing distinct variables may have been overlooked. Additionally, variability existed in methodology between studies assessed, including the use of marker motion analysis as opposed to video motion analysis, differential means by which metrics were defined, and mixed playing level analyses in some studies, as well as the inclusion criteria for variables incorporated into multiregression analysis.

Unmeasured variables, including strength and passive range of motion parameters, have been implicated in faster pitch velocity[34,36] yet were not directly assessed in the current study. Faster ball velocity has also been implicated, with increased throwing arm kinetics in high school,[15,29] collegiate,[29,31] and professional pitchers,[24,37] as a surrogate for injury risk, which in some sense gives indirect clinical relevance to the study findings. More pertinently, numerous studies have demonstrated in both youth and professional pitchers an increased risk of injury overall,[5] elbow injury,[2] UCL injury,[18] and UCL reconstruction[4] with faster pitch velocity, suggesting there is a good deal of clinical interest in parameters that influence ball velocity as a potential risk factor for injury among various playing levels.

Lastly, selection bias was introduced to the methodology, given that not all parameters that derived significance from each study were included in Supplemental Table S1 due to a lack of feasibility in listing this plethora of variables together. We attempted to identify significant variables shared among studies rather than the occasional unique kinematic that was analyzed in a single analysis. While we attempted to characterize several playing levels and age groups in this study, Little League pitchers (age, <12 years) were not evaluated independently and, therefore, the applicability of this study's results to that group are unclear.

CONCLUSION

Youth, high school, collegiate, and professional pitchers have unique, predictive kinematic, and anthropometric features predictive for pitch velocity. In addition, several predictive features are also shared between playing levels including leg length, stride length, trunk flexion at ball release, and maximal shoulder external rotation. Coaches, athletic trainers, and pitchers can consider these unique and shared predictive features for distinctive playing levels when attempting to maximize pitch velocity, a frequently sought-after performance metric in baseball.

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