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BASIC SCIENCE

Predictors of throwing velocity in youth and adolescent pitchers

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Background: Shoulder and elbow injuries are a common cause of pain, dysfunction, and inability to play in overhead throwers. Pitch velocity plays an integral part in the etiology of these injuries; however, the demographic and biomechanical correlates with throwing velocity remain poorly understood. We hypothesized that pitchers with higher velocity would have shared demographic and kinematic characteristics.
Methods: Normal preseason youth and adolescent pitchers underwent dual-orthogonal high-speed video analysis while pitch velocity was collected with a radar gun. Demographic and pitching history data were also collected. Kinematic data and observational mechanics were recorded. Multivariate regression analysis was performed.
Results: A total of 420 pitchers were included, with a mean pitching velocity of 64 ± 10 mph. After multivariate logistic regression analysis, the most important correlates with pitch velocity were age ($P < .001$; $R^2 = 0.658$), height ($P < .001$; $R^2 = 0.076$), separation of the hips and shoulders ($P < .001$; $R^2 = 0.027$), and stride length ($P < .001$; $R^2 = 0.016$); in combination, these 4 variables explained 78% of the variance in pitch velocity. Each year of age was associated with a mean 1.5 mph increase in velocity; each inch in height, with 1.2 mph; separation of the hips and shoulders, with 2.6 mph; and a 10% increase in stride length, with 1.9 mph.
Conclusion: Pitch velocity is most strongly correlated with age, height, separation of the hips and shoulders, and stride length.
Level of evidence: Basic Science Study, Kinesiology.

Keywords: Baseball; injury prevention; pitching; overhand throwing; motion analysis; ulnar collateral ligament tear; superior labral anterior-posterior tear

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Overhead throwing places substantial forces and torques on the shoulder and elbow, with forces regularly exceeding 390 N and torques regularly exceeding 1000 Nm in professional pitchers.[13] These forces have been implicated in the pathogenesis of shoulder and elbow injuries,[5] which are common in baseball pitchers.[24,25] For example, superior

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labral anterior-posterior tears are a common cause of shoulder discomfort in pitchers and remain an unsolved problem, with rates of return to a preinjury level of play of 22% to 60%.[8,15,19,22]

The neuromuscular and biomechanical factors that correlate with injury during overhead pitching have been previously studied,[24,25,28] and velocity has been identified as a primary factor.[6,28] However, the demographic and kinematic factors that correlate with velocity remain only partially understood. Multiple prior kinematic and electromyographic analyses have been performed examining normal youth, collegiate, and professional pitchers.[1,2,6,10,12-14,17,21,32,36-39] These studies have focused on correlations between kinematic and kinetic factors.[1,2,10,13,14,32,36-39] Very few studies have identified kinematic and demographic correlates with velocity. Those studies that have been performed were conducted on small groups of pitchers and did not incorporate demographic factors, which limits their generalizability.[4,11,14,26,27,34,35,40] A better understanding of the demographic and kinematic factors that correlate with velocity could provide therapists and pitching coaches with areas on which to focus in training and pitcher development.

Our overarching goal was to perform a demographic and biomechanical analysis of the correlates with velocity in overhead youth and adolescent pitchers. Our primary aim with this study was to determine the demographic and biomechanical factors that predict throwing velocity. We hypothesized that pitchers with higher velocity would have shared demographic and kinematic characteristics.

Methods

This is a single-episode cross-sectional study. As many youth and adolescent overhand baseball pitchers as possible within our geographic area were recruited, and no a priori power analysis was conducted. All subjects were currently in preseason training and underwent a standardized evaluation. Exclusion criteria included age <9 years; sidearm or ‘‘submarine’’ style pitching motion, as the kinematic data obtained were thought to be incomparable to the rest of the cohort; those who were not planning to pitch for their team that year; and those pitchers who did not think they would be able to throw because of excess discomfort at the time of the evaluation. Pitchers who thought they were able to throw and who had been throwing in practice were included even if they had a history of injury or current discomfort within their arm. Participants were unaware of the study hypothesis. In all cases, the dominant extremity was measured.

Data collection

All pitchers completed a demographic survey, with the assistance of their parents when possible. Data collected included age, height, and weight. Height and weight were used to calculate body mass index (BMI). Surveys were administered in paper format in a standardized fashion by 2 study authors and were reviewed for completeness with participants. A standardized physical examination was performed. Passive glenohumeral rotation was measured by a goniometer with the subject supine and the scapula stabilized at neutral shoulder flexion, 90° shoulder abduction, and 90° elbow flexion. Total arc of motion, glenohumeral internal rotation deficit, and glenohumeral external rotation excess were then calculated from these measurements. These measurements were performed in both upper extremities.

All subjects then underwent video motion analysis.[3,7,16,18,24,25,29-31,33,36-39] With use of high-definition orthogonal video cameras from the frontal and lateral views, subjects were filmed at 210 Hz while pitching from a regulation practice mound appropriate for the subject’s level of play. Throwing velocity was measured with a radar gun (JUGS Sports, Tualatin, OR, USA), which per the manufacturer has an accuracy of ±0.5 mph. Filming took place after a full warm-up and once subjects felt ready to pitch at 100% velocity. All subjects pitched fastballs from the wind-up position over a regulation distance for their age at a strike zone target appropriately positioned and sized for their age. For each pitcher, the single pitch most representative of the pitcher’s best effort was recorded for analysis.

Data analysis

A standardized protocol was used to extract kinematic data from video footage using commercial software (Dartfish Inc., Alpharetta, GA, USA). Only those kinematic variables shown previously to correlate with kinetic variables, as identified a priori, were recorded (Table I). Observational mechanics were recorded once for each pitch, with 2 study authors performing the measurements. These were assigned a binary yes vs. no as previously described.[9] These included whether the subject (1) led with the hips, (2) had the hand on top of the ball during the stride phase, (3) had the arm in the throwing position at front foot contact, (4) had closed shoulders at the hand-set position, (5) had a closed foot orientation at front foot contact, (6) had separation of rotation in the hips and shoulders, and (7) was in the fielding position at follow-through.[9] Separation of rotation in the hips and shoulders was defined as a binary yes in those pitchers in whom, during the cocking phase, a period could be identified during which the pelvis rotated to face home plate while the shoulders continued to face third base (for a right-handed pitcher). Pitchers in whom no such period could be identified were recorded as having a binary no for separation of rotation of the hips and shoulders. All analyses were performed in Excel X (Microsoft, Redmond, WA, USA) and SPSS 21 (IBM Inc., Armonk, NY, USA). An independent observer who was not aware of the study hypothesis entered all data. Continuous data normality was evaluated with the Kolmogorov-Smirnov test. Velocity was compared between discrete groups by Student *t* test or Mann-Whitney *U* test as appropriate. Velocity was correlated with continuous variables by Pearson correlation coefficients. Because multiple comparisons were performed before regression, *P* values underwent Bonferroni correction, and values <.00147 were considered significant. Those variables that significantly correlated with velocity or those variables in which there was a significant difference in velocity between groups were then entered into a multivariate stepwise regression model to determine the most important correlates. Within this model, $P < .05$ were considered significant. From this model, correlation coefficients and R^2 values, as an estimation of percentage of variance in injury

Table I Demographic and kinematic correlates with throw velocity in miles per hour

Type	Variable	Univariate analysis		Multivariate analysis			
		Correlation	*P*	R^2	*P*	Coeff.	SE
Demographic	Age	0.816	**<.001**	**0.658**	**<.001**	1.47	0.139
	Height	0.792	**<.001**	**0.076**	**<.001**	1.191	0.227
	Weight	0.732	**<.001**				
	BMI	0.495	**<.001**	0.003	**.024**	−0.139	0.058
Physical examination	ER-Dom	0.204	**<.001**	0.004	**.006**	0.05	0.022
	IR-Dom	0.003	.949				
	Arc-Dom	0.183	**<.001**				
	GIRD	0.069	.166				
	GERE	0.013	.791				
Wind-up	Max. knee height (% Ht)	0.287	**<.001**	0.004	**.005**	0.089	0.031
Kinematics at front foot contact	Stride length (% Ht)	0.438	**<.001**	**0.016**	**<.001**	0.187	0.036
	Elbow flexion	−0.084	.09				
	Knee flexion	0.318	**<.001**	0.006	**.001**	0.083	0.022
	Shoulder abduction	0.07	.156				
	Foot angle	−0.196	**<.001**	0.004	**.003**	0.036	0.012
Kinematics at maximum shoulder ER	Max. shoulder ER	0.132	.008				
	Max. shoulder abduction	0.117	.017				
	Lateral trunk tilt	0.152	.002				
Kinematics at ball release	Elbow flexion	−0.107	.03				
	Forward trunk tilt	0.171	**.001**	0.002	**.04**	0.062	0.03
	Knee flexion	0.07	.16				
	Shoulder abduction	−0.086	.082				
	Lead hip flexion	0.266	**<.001**				
	Lateral trunk tilt	0.191	**<.001**				
Observed mechanics	Leads with hips	NA	.139				
	Hand on top of ball	NA	.002				
	Arm in throwing position at front foot contact	NA	.091				
	Closed shoulders at hand separation	NA	.001				
	Foot closed	NA	.03				
	Hip and shoulder separation	NA	**<.001**	0.027	<.001	2.621	0.511
	Fielding position at follow-through	NA	.411				

BMI, body mass index; *ER*, glenohumeral external rotation; *Dom*, dominant extremity; *IR*, glenohumeral internal rotation; *Arc*, glenohumeral rotational arc; *GIRD*, glenohumeral internal rotation deficit; *GERE*, glenohumeral external rotation excess; *Max*, maximum; *% Ht*, values expressed as a percentage of subject height; *Coeff*, coefficient of correlation; *SE*, standard error; *NA*, not applicable.
For univariate analyses, because multiple comparisons were made, Bonferroni correction was performed and *P* values < .00147 were considered significant. For multivariate analyses, only those variables found to be significant in univariate analyses were included, and thus the traditional *P* value of .05 was used. *P* values identified as significant are marked in bold. R^2 values > 0.01 are also marked in bold as these variables explained >1% of the variance in velocity.

status explained by each variable, were determined. Only those variables with R^2 values > 0.01 are discussed.

Results

Of the 429 pitchers recruited, 9 were excluded because they were no longer planning to pitch (3), threw with a sidearm or submarine style (2), had too much pain to pitch (1), or did not complete the demographic survey (3). A total of 420 subjects were included for a 98% inclusion rate. Our cohort had a mean ± standard deviation age of 14.7 ± 2.6 years, mean height of 67.5 ± 5.3 inches, mean weight of 145.4 ± 39.2 pounds, and mean BMI of 22.0 ± 3.9. Mean pitch velocity for the cohort was 64 ± 10 mph.

On univariate correlation analyses, pitch velocity significantly correlated with the subject's age, height, weight, BMI, glenohumeral external rotation in the dominant extremity, glenohumeral rotational arc in the dominant extremity, glenohumeral external rotation in the nondominant extremity, and glenohumeral rotation arc in the nondominant extremity (*P* < .001 in all cases; Table I). On univariate analyses of the kinematic analyses, pitch velocity significantly correlated with 7 of the 15 measured variables: maximal knee height during the wind-up as a percentage of subject height, stride length as a percentage of subject height at front foot

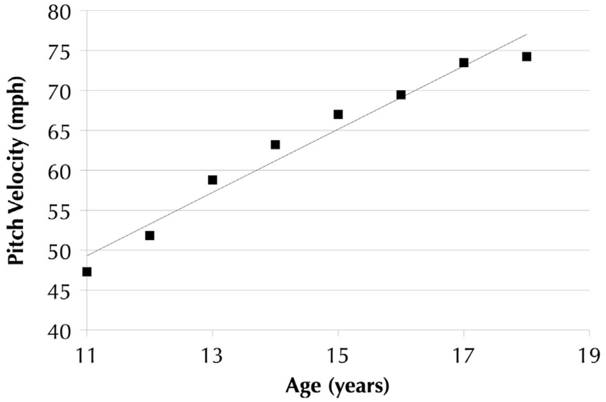

Figure 1 Pitcher age significantly correlates with pitch velocity ($P < .001$; multivariate $R^2 = 0.658$). To simplify, mean velocity for each year of age is shown.

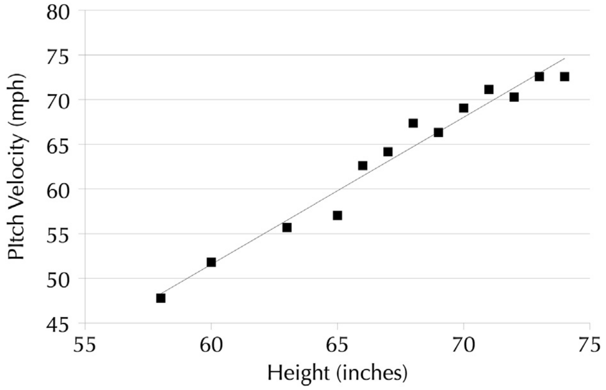

Figure 2 Pitcher height significantly correlates with pitch velocity ($P < .001$; multivariate $R^2 = 0.076$). To simplify, the full range of heights was divided into equally sized segments, and mean velocity for each of these groups is displayed.

Figure 3 Clinical photograph demonstrating separation of rotation within the hips and shoulders; while the pelvis has rotated to face home plate (*arrow*), the shoulders still face third base. This observed mechanical factor was significantly correlated with pitch velocity on multivariate analysis ($R^2 = 0.027$; $P < .001$).

Figure 4 Clinical photograph demonstrating the measurement of stride length at the moment of front foot contact, which was then normalized to the subject's height. On multivariate analyses, stride length was significantly correlated with pitch velocity ($P < .001$; multivariate $R^2 = 0.016$).

contact, knee flexion at front foot contact, foot angle at front foot contact, forward trunk tilt at ball release, lead hip flexion at ball release, and lateral trunk tilt at ball release ($P < .001$ in all cases; Table I). Among the observed mechanics, subjects with a closed shoulder position at front foot strike had significantly higher velocity than those with an open shoulder position ($P < .001$; Table I). Those subjects with separation of the hips and shoulders had significantly higher pitch velocity than those without separation of the hips and shoulders ($P < .001$; Table I).

On multivariate regression analysis, those variables with R^2 values > 0.01 (i.e., those variables that explained $>1\%$ of the variance in pitch velocity) included age (Fig. 1), height (Fig. 2), hip and shoulder separation (Fig. 3), and stride length as a percentage of the patient's height ($P < .001$ in all cases; Table I, Fig. 4). In combination, these 4 variables explained 78% of the variance in pitch velocity within our group; in total, all 11 variables with significant correlations with velocity on multivariate analysis explained 81% of the variance. Age alone accounted for 66% of the variance in pitch velocity. In multivariate analyses, each year of age was associated with a 1.5 ± 0.1 mph increase in velocity (Fig. 1). Each inch in height was associated with a 1.2 ± 0.2 mph increase in velocity (Fig. 2). Separation of rotation within the hips and shoulders was associated with a 2.6 ± 0.5 mph increase in velocity. Each increase in stride length by 10% of the subject's height was associated with a 1.9 ± 0.4 mph increase in velocity.

Discussion

Shoulder and elbow injuries are common among baseball pitchers,[24,25] and operative treatment of these injuries does not predictably return players to painless pitching with preinjury velocity and control.[8,15,19,22] Whereas multiple prior kinematic analyses have been performed to understand the kinematic correlates with joint loads in pitchers,[1,2,6,10,12-14,17,21,32,36-39] fewer have analyzed correlates with pitch velocity and none have incorporated demographic data.[4,11,14,26,27,34,35,40] Our overarching goal with this project was to perform a demographic and biomechanical analysis of those factors that correlate with increased velocity in youth and adolescent pitchers using video motion analysis.

The 4 factors independently associated with an increase in velocity on multivariate regression analysis were age, height, hip and shoulder separation, and stride length as a percentage of the patient's height. In combination, these factors explained 78% of pitch velocity variance. The covariance of age and pitch velocity is likely due to multiple factors. Older pitchers are more likely to have learned proper pitching mechanics and are more likely to have the muscle development to allow higher velocity pitching. After correction for the remaining variables, each year of age was associated with a 1.5 ± 0.1 mph increase in velocity.

The correlation between the pitcher's height and pitch velocity is likely due to the longer lever arm this allows subjects to use to transfer force onto the ball. Each inch in height was associated with a 1.2 ± 0.2 mph increase in velocity. Previous biomechanical analyses have normalized force and torque for subject height, as taller subjects are known to be able to exert more force and torque through the upper extremity because of the longer lever arm.[1,9] Subsequent kinetic analyses of the pitching motion should normalize for subject height.

Two kinematic factors correlated with pitch velocity: hip and shoulder separation and stride length. In combination, these 2 factors explain 4.3% of the variance in pitch velocity, suggesting that a pitcher with a short stride length and without hip and shoulder separation would be able to add 4.3% to the velocity by improving these aspects of the mechanics (i.e., a 70 mph pitcher could increase to 73 mph). Adding separation of the hips and shoulders alone added an average 2.6 ± 0.5 mph. The importance of hip and shoulder separation to pitch velocity relates to the "summation of speed" principle,[1] that is, the greatest transfer of force occurs when the subsequent segment begins rotating at the moment at which the prior segment reaches maximal angular velocity; therefore, proximal trunk rotation ideally begins at the moment of maximal angular velocity of the pelvis, which explains the critical importance of the core musculature for high-velocity pitching. This factor has been previously associated with improved pitch efficiency (i.e., lower humeral rotational torque and elbow valgus torque per velocity[9]) and thus could represent an avenue by which pitching coaches could improve velocity by improving mechanics. This factor, dubbed the X-factor, has also been associated with increased club speed in golf.[20,23]

Stride length may play a similar role. Each increase in stride length by 10% of the subject's height was associated with a 1.9 ± 0.4 mph increase in velocity. Whereas multiple kinematic factors, such as elbow flexion angle at various points within the pitch and shoulder abduction angle within various points within the pitch, have been associated with increased elbow valgus torque and shoulder proximal force,[2,32,36-39] no previous studies have associated stride length with increased stress on the arm. However, stride length is associated with increased velocity. As a result, pitching coaches could focus on stride length to improve a pitcher's velocity.

Several previous studies have been conducted to correlate factors identified in pitching motion analysis with pitch velocity. Other studies performing similar analyses have correlated velocity with the kinematic variables shoulder external rotation,[11,34,40] shoulder abduction,[11,34] knee flexion,[34] trunk tilt,[34] elbow flexion,[34] trunk-pelvis separation,[26] pelvis orientation at maximal shoulder external rotation,[35] and stride length.[4] Several of these variables were measured by our study and did not significantly correlate with pitch velocity. Multiple potential explanations exist for the differences between our results and those of the previous studies,[4,11,14,26,27,34,35,40] including differences in the underlying population of patients (i.e., the evaluation of youth and adolescent pitchers in this study, whereas other studies have largely analyzed elite collegiate and professional pitchers), differences in the methods of data collection (i.e., the use of video motion analysis instead of a markered motion analysis), differences in sample size (i.e., the use of 420 pitchers instead of the much smaller sample sizes of previous studies), and differences in data analysis (i.e., the analysis of 1 pitch per subject instead of multiple pitches per subject as independent variables). One variable identified in our study and also identified in multiple prior studies is proper timing of pelvic and trunk rotation, allowing optimal summation of speed.[14,26,35]

Our study has several limitations. One limitation is the use of a video motion analysis system instead of a traditional markered motion analysis system. Video motion analysis has been widely used for this purpose and is a well-accepted method.[3,7,16,18,24,25,29-31,33,36-39] However, the authors have not performed any validation or reliability studies with this methodology and are not aware of any within the literature. An additional limitation is the use of a single-episode study design. As a result, whereas the factors identified in this study correlate with velocity, alteration of these factors would not necessarily improve velocity. Correlation does not imply causation. These factors, in particular stride length and hip and shoulder separation, could be the result of increased velocity instead of the cause. In addition, many other unmeasured factors, such as strength, could also influence velocity. Without a prospective longitudinal study to observe pitchers who experience improvements in velocity, this limitation will remain.

One additional limitation is the strong covariance of height and age. The multivariate regression model corrects for this limitation, and although the whole model remains valid, interpretation of these factors as independent correlates can be more difficult.

Conclusion

Pitch velocity is most strongly correlated with age, height, separation of the hips and shoulders, and stride length. These factors have implications with regard to the etiology of injury in youth pitchers, the rehabilitation of these injuries, and the improvement in pitching performance.

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