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Relationship of Pelvis and Upper Torso Kinematics to Pitched Baseball Velocity

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Generating consistent maximum ball velocity is an important factor for a baseball pitcher's success. While previous investigations have focused on the role of the upper and lower extremities, little attention has been given to the trunk. In this study it was hypothesized that variations in pelvis and upper torso kinematics within individual pitchers would be significantly associated with variations in pitched ball velocity. Nineteen elite baseball pitchers were analyzed using 3-D high-speed motion analysis. For inclusion in this study, each pitcher demonstrated a variation in ball velocity of at least 1.8 m/s (range: 1.8–3.5 m/s) during his 10 fastball pitch trials. A mixed-model analysis was used to determine the relationship between 12 pelvis and upper torso kinematic variables and pitched ball velocity. Results indicated that five variables were associated with variations in ball velocity within individual pitchers: pelvis orientation at maximum external rotation of the throwing shoulder ($p = .026$), pelvis orientation at ball release ($p = .044$), upper torso orientation at maximum external rotation of the throwing shoulder ($p = .007$), average pelvis velocity during arm cocking ($p = .024$), and average upper torso velocity during arm acceleration ($p = .035$). As ball velocity increased, pitchers showed an increase in pelvis orientation and upper torso orientation at the instant of maximal external rotation of the throwing shoulder. In addition, average pelvis velocity during arm cocking and average upper torso velocity during arm acceleration increased as ball velocity increased. From a practical perspective, the athlete should be coached to strive for proper trunk rotation during arm cocking as well as strength and flexibility in order to generate angular velocity within the trunk for maximum ball velocity.

Key Words: throw, biomechanics, trunk, pelvis orientation

Introduction

The majority of studies that have analyzed baseball pitching mechanics have focused on upper extremity kinematics and kinetics, and injuries caused by improper mechanics (Atwater, 1970, 1979; Barrentine, Matsuo, Escamilla, Fleisig, & Andrews, 1998;

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Braatz & Gogia, 1987; Dillman, Fleisig, & Andrews, 1993; Escamilla, Fleisig, Barrentine, Zheng, & Andrews, 1998; Feltner & Dapena, 1986; Fleisig, 1994; Fleisig, Andrews, Dillman, & Escamilla, 1995; Tippett, 1986). The importance of timing of lower body movements has been noted in several studies (Dillman et al., 1993; Elliott, Grove, & Gibson, 1988; Fleisig, 1994; Pappas, Zawacki, & Sullivan, 1985; Tippett, 1986). Yet studies that have examined lower extremity and trunk contributions to pitched ball velocity have dealt primarily with strength, range of motion, and ground reaction forces while ignoring positioning and timing (Elliott, Grove, Gibson, & Thurston, 1985; Hong & Roberts, 1993; MacWilliams, Choi, Perezous, Chao, & McFarland, 1998; Tippett, 1986; Toyoshima, Hoshikawa, & Miyashita, 1973). Additionally, the main focus of previous research on pitching has been to define and explain pitching mechanics in a global sense by comparing mechanics between pitchers.

The importance of within-pitcher differences in relation to performance has not been addressed. The ability to consistently achieve maximal pitched ball velocity requires a pitcher to consistently generate appropriate movement patterns. Therefore, the purpose of this study was to investigate the relationship between 12 pelvis and upper torso kinematic variables and pitched ball velocity. It was hypothesized that variations in pelvis and upper torso kinematics within individual pitchers would be significantly associated with variations in pitched ball velocity.

Methods

Nineteen healthy male baseball pitchers (7 professional, 9 college, 3 high school) were tested at the American Sports Medicine Institute for this study. Healthy participants were classified as individuals performing at 100% capability. Two pitchers had a history of surgery to the throwing shoulder or the throwing elbow, but were fully recovered. The 19 participants in this study had an average age of 20.9 ± 2.1 years, height of 185.4 ± 5.1 cm, and mass of 83.0 ± 6.8 kg. Pitchers were required to throw a fastball pitch 33.0 m/s (75 mph) or faster during testing to be considered for the study. In addition, they were required to have at least 1.8 m/s (4 mph) of variation in ball velocity in their maximal-effort pitch trials.

After completing informed consent and history forms, each participant was tested with a procedure previously described (Fleisig, Escamilla, Andrews, et al., 1996). Each participant completed his warm-up and stretching routine according to his preference and was then asked to complete 10 maximal-effort throws from a pitching mound. Pitchers threw in an indoor laboratory from a portable pitching mound (Athletic Training Equipment Co., Santa Cruz, CA) toward a partitioned strike zone area 18.4 m (60.6 ft) from the pitching rubber. Ball velocity was recorded with a Jugs Tribar Sport Radar Gun (Jugs Pitching Machines Co., Tualatin, OR) from behind home plate.

The participants wore spandex shorts but no shirt, in order to locate correct anatomical markers for digitizing and to limit the movement of the markers from their anatomical landmarks during the pitching motion. An automated high-speed digitizing system (Motion Analysis, Corp., Santa Rosa, CA) was used to record the 3-D throwing patterns of motion. Each pitcher was marked with retro-reflective, 2.2-cm diameter balls bilaterally on the distal end of the third metatarsal, lateral malleolus, lateral femoral epicondyle, greater trochanter of the femur, lateral tip of the acromion, and lateral humeral epicondyle. A reflective band wrapped around the wrist of the throwing arm was used to indicate the joint center of the wrist. A reflective ball was also placed on the glove-hand’s ulnar styloid.

The reflections of these markers were tracked individually by four electronically synchronized, 200-Hz charged-coupled device (CCD) cameras. The reflections from the markers were transmitted directly to the video processor, and the centroid of each reference point was automatically digitized. Three-dimensional marker locations were calculated with Motion Analysis ExpertVision 3D software, utilizing the direct linear transformation method (Abdel-Aziz & Karara, 1971).

Camera coefficients were calibrated by recording the surveyed position of 12 markers attached to four vertically suspended wires. The wires were positioned so that the markers created a matrix approximately 1.5 m (X) × 1.2 m (Y) × 1.2 m (Z) in size suspended approximately 0.3 m above the ground. The X dimension was aligned with the direction of throwing, Z was vertical, and Y was defined as the cross-product of Z and X. The matrix was aligned to encompass as much of the testing area as possible while leaving each marker within the field of view of all four cameras. A Topcon DT-30 digital transit (Topcon Instrument Corp. of America, Paramus, NJ) was used to measure the angles between the markers, and an algorithm provided by Peak Performance Technologies, Inc. (Englewood, CO) transferred the transit's readings into cartesian coordinates using the principle of similar triangles. Root mean square error in calculating the 3-D location of markers randomly placed within the calibration space was 1.0 cm (Fleisig et al., 1996).

Position data were digitally filtered independently in the X, Y, Z directions with a 13.4-Hz Butterworth low-pass filter (Fleisig et al., 1996). Each pitch was digitized from approximately 30 ms before the stride leg knee reached maximal height to approximately 30 ms after ball release. Twelve kinematic variables were analyzed from three phases previously described by Werner et al. (Werner, Fleisig, Dillman, & Andrews, 1993) (see Figure 1). The first phase studied, the stride, was defined between the instant of stride leg maximum knee height and front foot contact. Dillman et al. (1993) suggested that this was the phase in which the upper and lower bodies began to move in synchrony. The second phase, arm cocking, was defined from the instant of front foot contact to the instant of maximum shoulder external rotation. Proper execution of this phase allowed the pelvis to rotate first, followed by rotation of the upper torso. The third phase, arm acceleration, was defined as from maximum shoulder external rotation to ball release. Feltner and Dapena (1986) described the torso and pelvic motions during this phase as primary contributors to elbow extension, and thus ball speed.

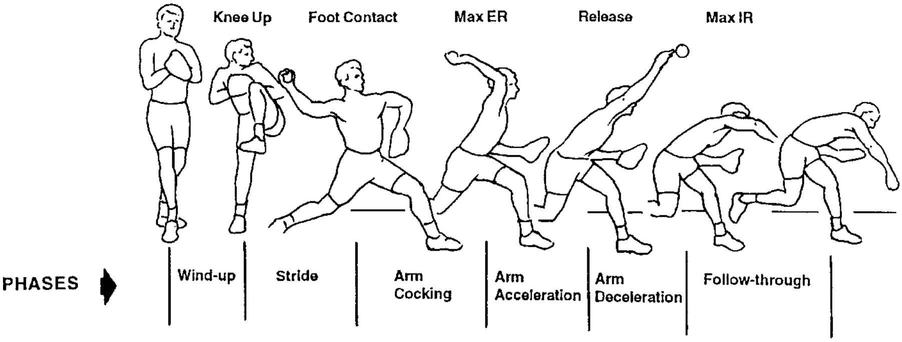

Figure 1 — The six phases of pitching: windup, stride, arm cocking, arm acceleration, arm deceleration, and follow-through. These phases are divided at the instants of maximum knee height (Knee Up), front foot contact (Foot Contact), maximum shoulder external rotation (Max ER), ball release (Release), and maximum shoulder internal rotation (Max IR). (Adapted from Fleisig et al., 1996)

Front foot contact was defined as the time when velocity of the lead ankle joint marker decreased to less than 1.5 m/s (Escamilla et al., 1998). This was based on the assumption that foot contact was the prominent deceleration factor at the end of the stride. Since external rotation of the humerus about its longitudinal axis could not be directly measured, the rotation of the forearm about the upper arm's longitudinal axis was used as defined by Fleisig et al. (1996). The wrist joint center was represented by the digitized center of the tape that wrapped completely around the wrist. Shoulder and elbow joint centers were calculated as previously described (Dillman et al., 1993). From these data, pelvis orientation and upper torso orientation were computed. The data were used to compute the average angular velocity of the pelvis and upper torso during the arm cocking and arm acceleration phases.

Pelvis orientation was defined as the angle between a line connecting the two hip markers and the X-axis in the XY plane (Figure 2A). Pelvis orientation angle was positive when the pelvis was "open" (i.e., anterior aspect of pelvis visible to batter) and negative when the pelvis was "closed" (posterior aspect of pelvis visible to batter). Pelvis orientation angles were measured at four instances: stride leg maximum knee height, front foot contact, maximum external rotation, and ball release.

The upper torso orientation was defined as the angle between a line connecting the shoulder markers and the X-axis in the XY plane (Figure 2B). Upper torso orientation angle was positive when the upper torso was "open" (i.e., anterior aspect of

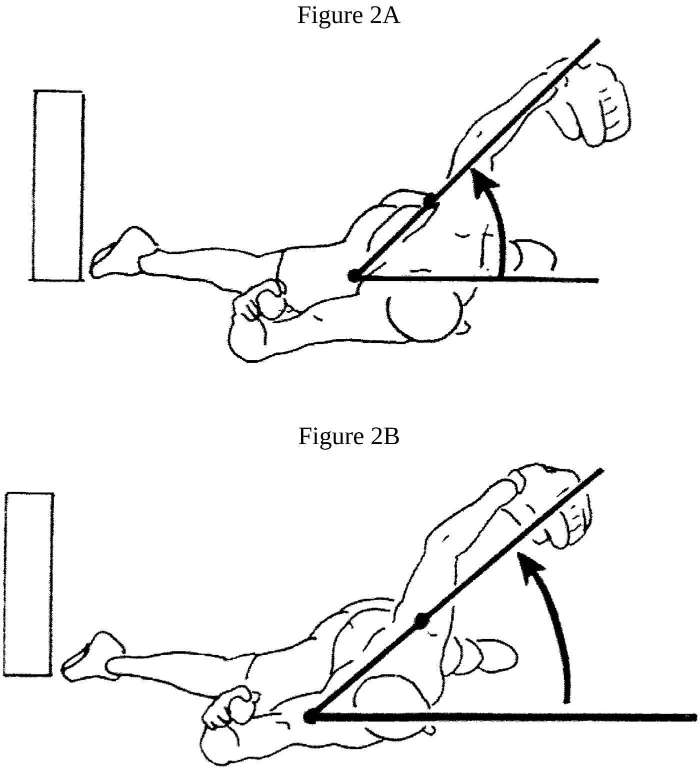

Figure 2 — Definition of kinematic parameters: A) pelvic orientation; B) upper torso orientation.

upper torso visible to batter) and negative when the upper torso was "closed" (posterior aspect of upper torso visible to batter). Upper torso orientation angles were measured at four instances: stride leg maximum knee height, front foot contact, maximum external rotation, and ball release. Upper torso orientations and pelvis orientations were measured in the XY plane because most of the rotation of the upper torso and pelvis occurs in this plane (Hong & Roberts, 1993).

A mixed model was used to assess the independent effects of the 12 kinematic variables on pitched ball velocity since the data structure included multiple pitch trials for each pitcher. An initial model was examined with all variables. It was then reduced using a stepwise modeling procedure, which eliminated nonsignificant variables without reducing model fit. The stepwise regression was a combination backward and forward modeling procedure. The modeling procedure reduced the full model by the least significant variable (Var1). The model was then reevaluated and then the next least significant variable was removed (Var2). At this point Var1 was re-entered into the model to see if significance was then obtained. If not, it was dropped again. At each step, the overall model significance was then evaluated to see if a significant reduction in model fit had occurred. This continued until all remaining variables were significant and/or the removal of an additional variable significantly reduced model fit. Alpha level was set at 0.05 to determine statistical significance. SAS® Version 8.0 was used for all analyses.

Results

The 19 pitchers threw a total of 167 pitches for data collection. Mean values for the trunk kinematic variables and ball velocity are shown in Table 1. The average ball velocity in this study (35 m/s) was comparable to other studies involving elite pitchers (Dillman et al. [1993], 36 m/s; Feltner & Dapena [1986], 34 m/s; Pappas et al. [1995], 38 m/s). At maximal knee height, both upper torso orientation (–30 ± 13°) and pelvis orientation (–36 ± 13°) were negative in reference to the X direction, indicating a closed position.

Pitchers then rotated to a more open position throughout the proceeding stages of the pitch. Pelvis orientation at front foot contact was 27 ± 13°. Upper torso orientation remained in a more closed position at front foot contact (–19 ± 15°), which indicated a delay in upper torso rotation. The pitcher continued to rotate the pelvis and upper torso throughout the arm cocking phase. By the instant of maximal external rotation, upper torso orientation (88 ± 10°) had surpassed pelvis orientation (85 ± 7°), indicating momentum transfer from the pelvis to the upper torso. During the arm acceleration phase, the upper torso continued rotating (111 ± 9° at release), while pelvis orientation remained stable (89 ± 8° at release). Pelvis velocities (490 ± 80°/s, 150 ± 100°/s) and upper torso velocities (920 ± 120°/s, 810 ± 230°/s) during the arm cocking and arm acceleration phases were consistent with previous results (Hong & Roberts, 1993).

Results from the reduced mixed model indicated a very strong model fit ($\chi^2 = 193.09$, $p < .0001$), with five variables significantly associated with variations in pitched ball velocity (Table 2). As velocity increased, pitchers showed an increase in pelvis orientation angle and upper torso orientation angle at the instant of maximal external rotation of the throwing shoulder (MER). In addition, pelvis orientation angle increased at ball release (Rel) as velocity increased. Average pelvis velocity from front foot contact (FFC) to MER increased as velocity increased, and average upper torso velocity from MER to Rel also increased as velocity increased.

Table 1 Mean (± *SD*) for Pelvis and Upper Torso Kinematic Variables and Ball Velocity (N = 167)

Variable	Mean	*SD*
Instant of maximum knee height		
Upper torso orientation (º)	–30	±13
Pelvis orientation (º)	–36	±13
Instant of front foot contact		
Upper torso orientation (º)	–19	±15
Pelvis orientation (º)	27	±13
Arm cocking phase		
Upper torso velocity (º/s)	920	±120
Pelvis velocity (º/s)	490	±80
Instant of maximum shoulder external rotation		
Upper torso orientation (º)	88	±10
Pelvis orientation (º)	85	±7
Arm acceleration phase		
Upper torso velocity (º/s)	810	±230
Pelvis velocity (º/s)	150	±100
Instant of ball release		
Upper torso orientation (º)	111	±9
Pelvis orientation (º)	89	±8
Ball velocity (m/s)	35	±2

Table 2 Variables Significantly Associated With Ball Velocity

	F	*p*
Pelvis orientation at MER	5.06	.026
Pelcvis orientation at ball release	4.14	.044
Upper torso orientation at MER	7.50	.007
Average pelvis velocity, FFC to MER	5.24	.024
Average upper torso velocity, MER to Rel	4.53	.035

Discussion

In this study it was hypothesized that variations in trunk kinematics in a given pitcher would be significantly associated with pitched ball velocity. In baseball pitching, rapid changes in ball speed (from 0 m/s to over 33 m/s in less than 0.5 sec) are achieved by transferring momentum from proximal (base) segments to distal segments, and finally to the ball. In accordance with the kinetic link theory, force generated by the trunk must be correctly transferred in the proper sequence to the throwing arm, and finally to the ball, to produce maximum velocity. When combined, variations in kinematic characteristics of an individual's mechanics led to inconsistencies in the pitching motion and to decreased velocity.

Previous studies have indicated that an elite pitcher is "remarkably consistent in his delivery" (Pappas et al., 1985) and that there is "little variability among the fastball pitches of any given player" (Feltner & Dapena, 1986). In practical situations, however, variations in mechanics and velocities produced by individuals are noticed by coaches and sensed by performers. Since pitchers in this study demonstrated at least 1.8 m/s variation in ball velocity, kinematic deviations for each pitcher may be more noticeable. This study suggests that the variability within individual pitching mechanics is important to performance and should be addressed.

To maximize the potential contribution of the trunk, pitchers must be in a position to optimally rotate both the pelvis and upper torso during the arm cocking and acceleration phases. If the pitcher lands with the pelvis in a more closed position, then the pelvis may not be able to optimally rotate and the pitcher will end up throwing without much energy being contributed to the lower body. If the pitcher lands with the pelvis too open, then the energy from the rotation of the pelvis will be applied prematurely to the upper trunk (Dillman et al., 1993). The participants in this study were more open at MER, with respect to pelvic and upper torso orientations, as velocity increased.

Pitchers also showed an increase in average pelvic angular velocity during the arm cocking phase (FFC to MER) as velocity increased. In accordance with the kinetic link theory and the law of conservation of angular momentum, the increase in average pelvic velocity allows more energy to be transferred to the upper torso, which rotates after the pelvis. The increase in energy transfer to the upper torso was realized as average upper torso velocities increased during the arm acceleration phase (MER to Rel). Theoretically, the increased upper torso velocities allowed more energy to be transferred from the trunk to the throwing arm, and ultimately to the ball, to produce higher ball velocities.

To maximize the contribution of increased momentum generated at the trunk, the sequencing of pelvis rotation, upper torso rotation, and movement pattern of the throwing arm must be properly timed. Herring and Chapman (1992), using a three-segment model representing the throwing arm, showed there were many timings of torques which produced outputs close to maximum, but there was only one timing pattern that produced maximum velocity. In addition, an increase in momentum transfer caused by increased pelvis and upper torso velocities would suggest that an increase in the forces at the shoulder and elbow would be needed to accelerate the throwing arm. These two previously mentioned factors may help explain injury potential related to pitching, as well as define more completely the factors involved in achieving maximal ball velocities in a given pitcher.

One methodological limitation in this study was that pelvis and upper torso movement patterns were limited to the horizontal plane. Hong and Roberts (1993) indicated that pelvis and upper torso movement occurred primarily in the horizontal plane. Specifically, they found that the upper torso and pelvis rotated approximately 130° and 70°, respectively, in the transverse plane from FFC to Rel, but only 29° and 13°, respectively, in the frontal plane from FFC to Rel. However, their results were based on only one pitch. Three-dimensional movement patterns must be addressed to fully understand and describe the role of the trunk in pitching. Another limitation was that the current statistical model (mixed model) does not predict how much the five significant variables contributed to variations in pitched ball velocity within individual pitchers. Analyzing more pitches per pitcher would aid in determining other significant trends and percent contributions of specific variables to pitched ball velocity.

In summary, the kinematic data in this study suggest that when pitchers were in a position to optimally rotate the pelvis and upper torso, they were able to generate increased momentum. Theoretically, the increase in momentum would allow a pitcher to transfer more energy through the kinetic chain from the trunk, to the throwing arm, and finally to the ball to produce increased ball velocities. To consistently produce maximum velocities, pitchers should focus on consistent, optimal positioning to be able to maximize the potential contribution of the trunk. Increased trunk strength and flexibility may improve a pitcher's ability to generate pelvis and upper torso angular velocity, and consequently increased ball velocity. Hence, exercises that improve strength and flexibility of the trunk should be included in a pitcher's conditioning program. Further study of within-pitcher variation including kinetic, temporal, and other kinematic variables is warranted to address the factors involved in achieving maximal ball velocity within pitchers.

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