ORIGINAL INVESTIGATIONS

JOURNAL OF APPLIED BIOMECHANICS, 1998, **14**, 1-23

Kinematic Comparisons of Throwing Different Types of Baseball Pitches

Rafael F. Escamilla, Glenn S. Fleisig, Steven W. Barrentine, Naiquan Zheng, and James R. Andrews

The purpose of this study was to establish and compare kinematic data among four groups of collegiate pitchers who threw the fastball (FA), change-up (CH), curveball (CU), and slider (SL). Twenty-six kinematic parameters at lead foot contact, during the arm-cocking and arm acceleration phases, and at ball release were measured for 16 collegiate baseball pitchers. Approximately 60% of these parameters showed significant differences among the four pitch variations. The greatest number of differences (14 of 26) occurred between the FA and CH groups, while the fewest differences (2 of 26) occurred between the FA and SL groups. The CH group had the smallest knee and elbow flexion at lead foot contact and the greatest knee and elbow flexion at ball release. During the arm-cocking and arm acceleration phases, peak shoulder, elbow, and trunk angular velocities were generally greatest in the FA and SL groups and smallest in the CH group. At ball release the CH group had the most upright trunk and the greatest horizontal shoulder adduction, while the CU group had the most lateral trunk tilt. Understanding kinematic differences can help a pitcher select and learn different pitches and can help a batter learn how to identify different pitches.

Key Words: biomechanics, fastball, change-up, curveball, slider

Understanding how baseball pitching mechanics differ for various types of pitches is helpful to coaches, trainers, therapists, and physicians in recommending appropriate techniques, conditioning, and treatment. From a biomechanical perspective, pitches with faster velocities may correlate with faster arm and trunk angular velocities. However, kinematic differences between pitches may make learning new pitches difficult.

From a strategic perspective, a pitcher may want to produce similar kinematics among all pitch types in order to make pitch identification difficult for batters. If a pitcher exhibits a similar pitching motion regardless of the type of pitch thrown, a batter will only be able to determine the pitch type by observing the motion of the ball rather than body and arm motions. Consequently, the batter will have less time to prepare for the pitch. For college and professional pitchers, it typically takes less than 0.5 s for a pitched ball to travel from its release point to home plate. However, if a pitcher has a noticeably slower arm motion when throwing off-speed "breaking" pitches (e.g., change-up, curveball, and

At the time of the study, all authors were with the American Sports Medicine Institute, 1313 13th St. South, Birmingham, AL 35205. Direct correspondence to Glenn S. Fleisig. Rafael Escamilla is now with the Department of Physical Education & Kinesiology, California Polytechnic State University, San Luis Obispo, CA 93407.

slider) compared to the fastball, a batter may be able to detect the slower motion and have more time to anticipate and prepare for the off-speed pitch.

While several kinematic parameters have been measured for college and professional pitchers for the fastball pitch (Dillman, Fleisig, & Andrews, 1993; Feltner & Dapena, 1986, 1989a, 1989b; Hong & Roberts, 1992; Pappas, Zawacki, & Sullivan, 1985; Vaughn, 1985b; Werner, Fleisig, Dillman, & Andrews, 1993), fewer kinematic parameters have been quantified for the curveball pitch. Stevenson (1985) studied 9 college pitchers to determine thumb, index-finger, and middle-finger movements for the fastball and curveball pitches. Sakurai, Ikegami, Okamoto, Yabe, and Toyoshima (1993) compared joint angle kinematics of the pitching arm and ball velocity between the fastball and curveball of 6 Japanese university pitchers. Elliott, Grove, Gibson, and Thurston (1986) analyzed 6 pitchers from the Australian national team to compare stride length, elbow flexion, lower extremity angles, and ball velocity between the fastball and curveball. Kinematic data for the change-up and slider pitches have not yet been established. Although the fastball, curveball, slider, and change-up are four common pitches thrown by college and professional pitchers, we know of no studies comparing kinematic parameters among these four pitch variations. The purpose of this study was to establish and compare kinematic data for collegiate baseball pitchers who threw the fastball (FA), change-up (CH), curveball (CU), and slider (SL) pitches. Due to limitations in data collection techniques, the kinematics of the forearm and hand were omitted in this initial study. However, the forearm and hand will be the focus of a follow-up study involving pitch variations similar to those used in the current study.

Methods

Sixteen healthy college baseball pitchers, 14 right-handed and 2 left-handed, from two NCAA Division I colleges served as subjects. A pitcher was considered healthy if he met three criteria: He was not currently injured or recovering from an injury at the time of testing; he had not undergone surgery for at least 12 months prior to the study; and he felt that he was able to pitch with the same intensity (100%) as he would in a game environment. The subjects had a mean mass of 80.9 ± 10.2 kg, a mean height of 179.9 ± 10.0 cm, and a mean age of 19.9 ± 1.8 years.

Although most baseball pitchers throw the FA, the number and type of off-speed pitches thrown vary among pitchers. For example, many pitchers typically throw the FA, CU, and CH or the FA, SL, and CH. Some pitchers throw the SL in addition to the FA, CU, and CH. All 16 of the subjects tested threw the FA, CU, and CH, and 7 of these 16 also threw the SL. Each subject had at least 3 years experience in throwing each pitch variation in both practice and game environments.

Testing procedures were in accordance with previous work (Fleisig et al., 1996). Each subject reported for testing on one of his regularly scheduled pitching days. After providing history information and informed consent, the subject changed into a pair of spandex shorts, and body weight, body height, upper arm length, and forearm length were measured. Reflective markers (3.81 cm diameter) were attached bilaterally at the lateral malleoli, lateral femoral epicondyles, greater femoral trochanters, lateral superior tip of the acromions, and lateral humeral epicondyles. A reflective marker was also positioned on the ulnar styloid process of the nonpitching wrist, and a reflective band approximately 1 cm wide was placed around the pitching wrist. Once the markers were positioned on the body, the subject was given an unlimited amount of time for stretching, warm-up throwing, pitching off an ATEC (Athletic Training Equipment Company, Sparks, NV) indoor

Figure 1 — A baseball pitcher during testing. From "Kinetics of Baseball Pitching With Implications About Injury Mechanisms" by G.S. Fleisig, J.R. Andrews, C.J. Dillman, and R.F. Escamilla, 1995, *American Journal of Sports Medicine,* 23(2), p. 234.

pitching mound, and any other type of preparation he desired. Subjects were instructed to prepare just as if they were going to pitch in a game. Each subject threw toward a strike zone ribbon located over home plate at a regulation distance of 18.4 m from the pitching rubber. The testing setup is shown in Figure 1.

Once a subject was ready to pitch as in a game environment, data were collected from all pitch variations that each subject threw. These pitch variations were thrown in a randomized order for each subject. Each subject threw between five and eight pitches for each pitch variation, with approximately 30-60 s rest between each pitch. With this low pitch count, fatigue was assumed to be negligible. Although several previous studies used only one trial per subject (Elliott et al., 1986; Feltner & Dapena, 1986; Sakurai et al., 1993; Vaughn, 1985b; Werner et al., 1993), three trials per pitch variation were analyzed for each subject in the current study. Feltner and Dapena (1986) used only one trial per subject since they found little variability among the FA pitches of any given player. Although Pappas et al. (1985) analyzed 10 pitches per subject, they concluded that an individual pitcher is remarkably consistent in his delivery. With the methods used in the current study, Fleisig (1994) showed that deviations between trials were indeed small. However, Bates, Dufek, and Davis (1992) found that with group analyses on a sample of 20 subjects using similar performance strategies, a minimum of three trials were necessary.

A Motion Analysis (Motion Analysis Corporation, Santa Rosa, CA) three-dimensional automatic digitizing system was used to quantify each pitcher's motion. Four electronically synchronized, charged couple device cameras transmitted pixel images of the reflective markers directly into a video processor without being recorded onto video; each camera operated at 200 Hz. Three-dimensional marker locations were calculated with Motion Analysis Expertvision 3-D software utilizing the direct linear transformation method (Abdel-Aziz & Karara, 1971; Shapiro, 1978).

Camera coefficients were calibrated by recording the position of markers attached to four vertically suspended wires. Three reflective markers spaced at 61 cm intervals were attached to each wire. These wires, positioned so that the markers made a matrix approximately 1.5 m × 1.2 m × 1.2 m in size, were suspended approximately 0.3 m above the ground. The 1.5 m dimension of the matrix was aligned with the direction of the pitch. This matrix was designed to encompass as much of the testing area as possible while having each marker visible in the field of view of all four cameras. The root mean square error in calculation of three-dimensional marker location was less than 1.0 cm.

The position data were digitally filtered independently in the X, Y, and Z directions with a Butterworth low-pass filter (Winter, 1990). Qualitative evaluation of displacement, velocity, and acceleration data indicated that a sample frequency/cutoff frequency ratio of 12 was effective at rejecting noise and passing data. For 200 Hz sample frequency, this was equivalent to a second-order low-pass cutoff frequency of 16.7 Hz. The data were then passed through the filter a second time, in the reverse order, to eliminate phase distortion (Winter, Sidwall, & Hobson, 1974). This second passing created a fourth-order, zero-phase-shift, double-pass filter with a new cutoff frequency of 13.4 Hz, which was 80.2% of the original 16.7 Hz cutoff frequency (Winter, 1990).

The pitching motion was divided into several phases as previously defined (Dillman et al., 1993; Werner et al., 1993) (Figure 2). Twenty-six kinematic parameters and 10 temporal parameters were measured at foot contact (Figure 2F), during the arm-cocking (Figures 2F-2H) and arm acceleration (Figures 2H-2I) phases, and at ball release (Figure 2I). No parameters were statistically analyzed during the windup, stride, arm deceleration, and follow-through phases. Kinematic parameters were calculated using methods previously described (Dillman et al., 1993; Fleisig et al., 1996). In each pitching phase, local reference frames were established for the trunk and elbow. The trunk's reference frame was established using a vector between the two shoulders and a vector from the midhip to the midshoulder. The elbow reference frame used a vector from the throwing elbow to the throwing wrist and the plane formed by the wrist, elbow, and shoulder markers. The location of the shoulder was translated from the shoulder marker location to an estimated joint center (Fleisig et al., 1996). The direction of this translation was fixed in the trunk reference frame, and the distance was proportional to the length of the subject's upper arm. Similarly, the elbow location was translated from the elbow marker to the estimated joint center (Fleisig et al., 1996), with a direction fixed in the elbow's reference frame and a distance proportional to the length of the forearm.

The global X direction was defined as a vector from the center of the pitching rubber to the center of home plate. The global Z direction was defined as a vector pointing vertically. The cross-product of the Z and X vectors defined the global Y directional vector.

Elbow flexion of the throwing arm was defined as the angle between the distal directions of the upper arm and forearm (Figure 3A). Since external rotation of the upper arm about its long axis could not be directly measured, external rotation was calculated as the angle between the anterior direction of the trunk and the distal direction of the forearm, in a plane perpendicular to the upper arm (Feltner & Dapena, 1986; Fleisig, 1994; Fleisig et al., 1996; Vaughn, 1985a) (Figure 3B). Abduction was the angle between the distal direction of the upper arm and the inferior direction of the trunk in the trunk frontal plane (Figure 3C). Horizontal adduction was defined as the angle between the distal direction of the upper arm and the upper torso vector in the transverse plane (Figure 3D). Knee flexion of the lead leg was defined as the angle between the distal directions of the thigh and leg (Figure 3E). Forward trunk tilt was the angle between the superior direction of the trunk and the global Z direction in the global XZ plane (Figure 3F). Therefore, forward

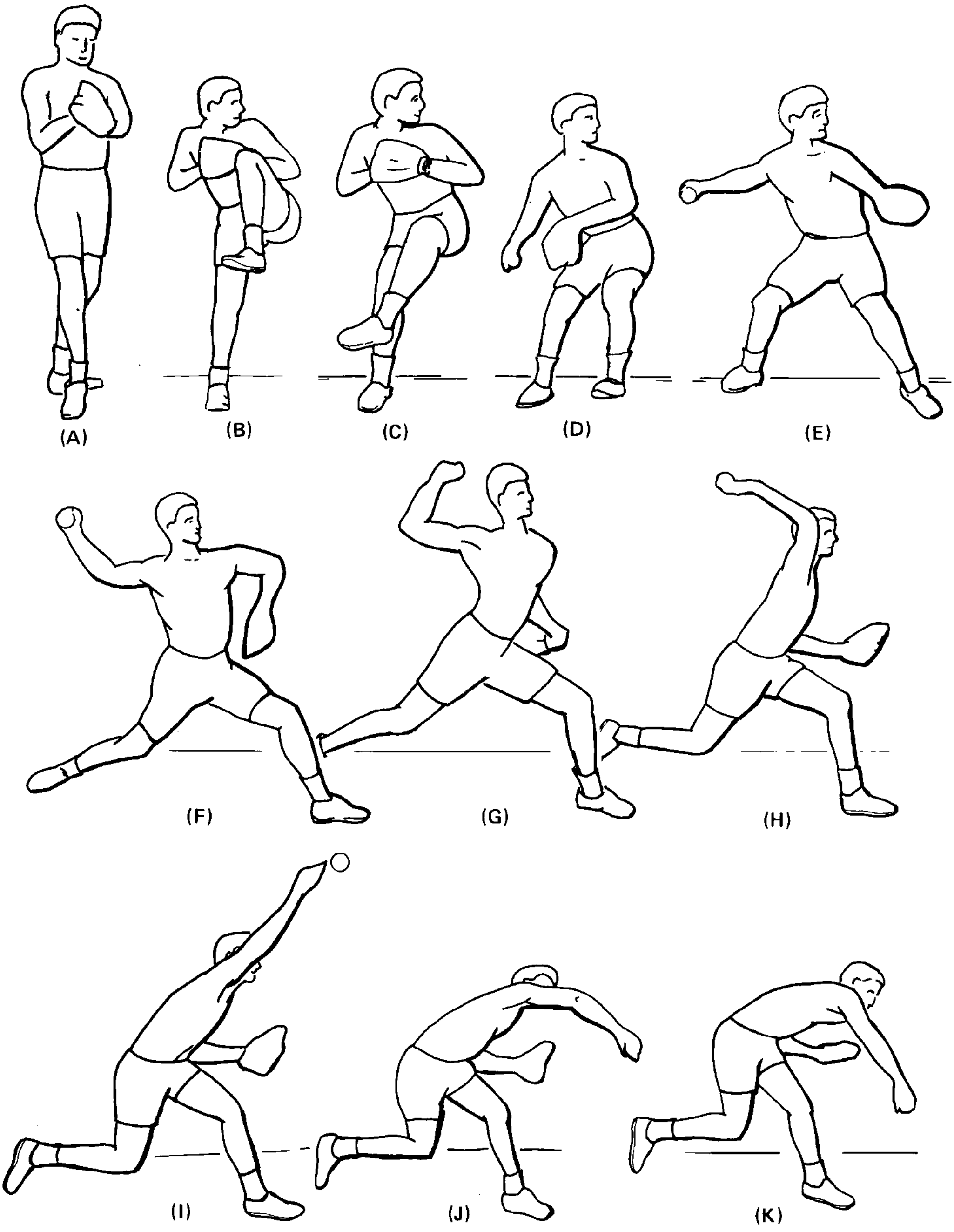

Figure 2 — Sequence of motion in pitching: (A-B) windup, (C-F) stride, (F-H) arm cocking, (H-I) arm acceleration, (I-J) arm deceleration, and (J-K) follow-through. From "Biomechanics of the Elbow During Baseball Pitching" by S.L. Werner, G.S. Fleisig, C.J. Dillman, and J.R. Andrews, 1993, *Journal of Orthopaedic and Sports Physical Therapy,* 17(6), p. 276.

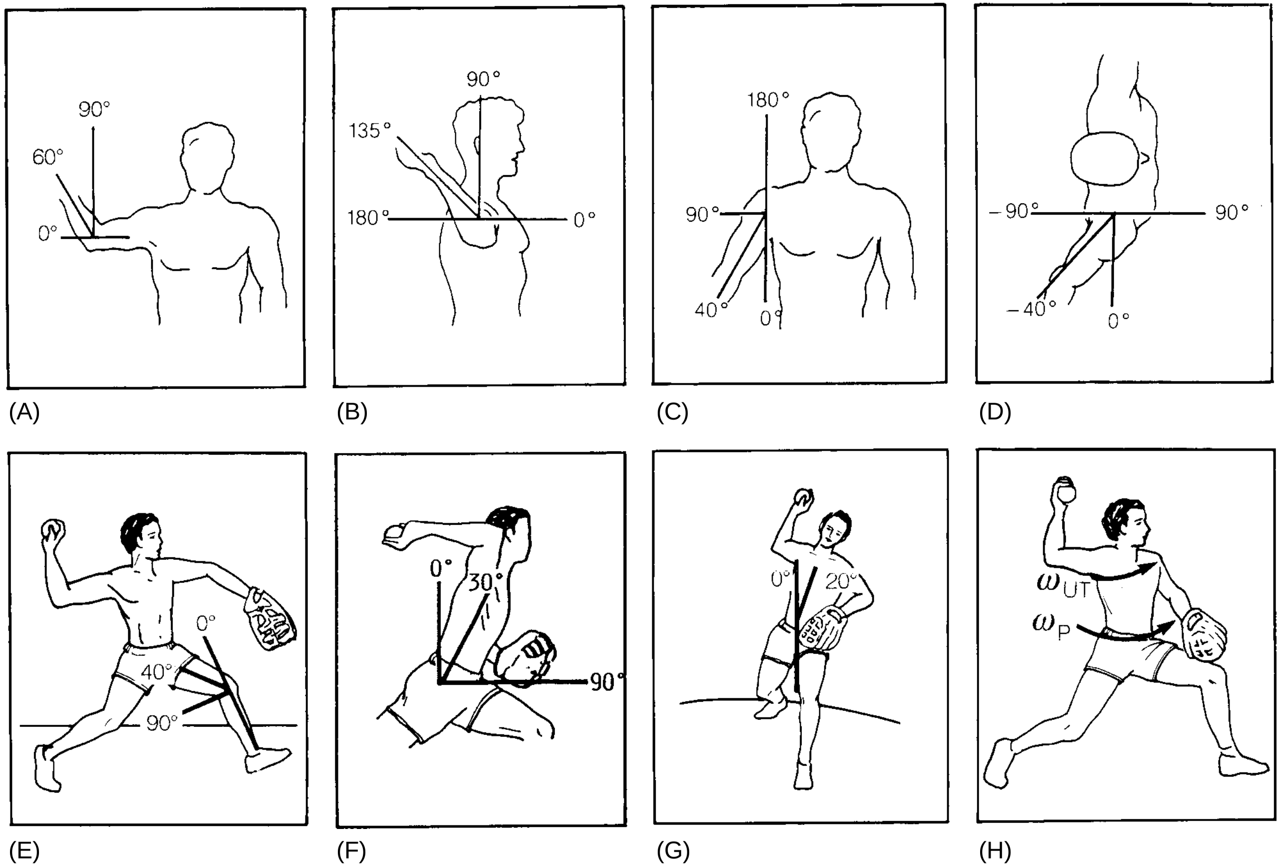

Figure 3 — Definition of kinematic parameters: (A) elbow flexion, (B) shoulder external/internal rotation, (C) shoulder abduction, (D) shoulder horizontal adduction, (E) lead knee flexion, (F) forward trunk tilt, (G) lateral trunk tilt, and (H) pelvis angular velocity (ω_p) and upper torso angular velocity (ω_{UT}).

trunk tilt was 0° when the trunk was vertical and 90° when the trunk was horizontal toward the target. Lateral trunk tilt was the angle between the superior direction of the trunk and the global Z direction in the global YZ plane (Figure 3G). Lateral trunk tilt was 0° when the trunk was vertical and 90° when the trunk was horizontal toward the glove side. For each angular displacement measurement, the corresponding velocity was calculated using the 5-point central difference method (Miller & Nelson, 1973).

Angular velocities of the pelvis and upper torso (Figure 3H) were calculated with a method published by Feltner and Dapena (1989a). Angular velocity of the pelvis was the cross-product of a vector joining the two hip markers and the derivative of this vector. Angular velocity of the upper torso was the cross-product of a vector joining the two shoulder markers and the derivative of this vector.

The arm-cocking phase began when the lead foot contacted the pitching mound. Lead foot contact was automatically determined as the time when velocity of the lead ankle marker decreased to less than 1.5 m/s (Fleisig, 1994). At lead foot contact, eight kinematic parameters were measured on the pitching arm and lead leg: stride length, foot placement, foot angle, shoulder abduction, shoulder horizontal adduction, shoulder external rotation, knee flexion, and elbow flexion. Stride length was the length from the pitching rubber to the lead ankle marker, and foot placement was the displacement between the lead ankle marker and the stance ankle marker in the global mediolateral Y direction. Neutral foot placement was defined as parallel alignment of a vector from the stance ankle marker to the lead ankle marker with the global X direction. From a right-handed pitcher's perspective, an open foot placement occurred when his lead ankle marker was to the left of his stance ankle marker, and a closed foot placement occurred when his lead ankle marker was to the right of his stance ankle marker (opposite for a left handed pitcher). Foot angle was measured as the angle between the global X direction and the longitudinal axis of the foot. Neutral position occurred when the longitudinal axis of the foot was in the global X direction. From a right- or left-handed pitcher's perspective, an open foot angle occurred when his lead foot pointed out, and a closed foot angle occurred when his lead foot pointed in.

Seven kinematic parameters were measured during the arm-cocking phase, which occurred from lead foot contact to maximum shoulder external rotation of the pitching arm: maximum pelvis angular velocity, maximum upper torso angular velocity, maximum forward trunk angular velocity, maximum shoulder horizontal adduction angular velocity, maximum elbow flexion, maximum shoulder horizontal adduction, and maximum shoulder external rotation.

The arm acceleration phase began at the instant of shoulder maximum external rotation and ended when the ball was released. Three kinematic parameters were measured during the arm acceleration phase: maximum elbow extension angular velocity, maximum shoulder internal rotation angular velocity, and average shoulder abduction. Maximum shoulder internal rotation angular velocity was included in the arm acceleration phase even though its maximum value occurred 3–4 ms after ball release.

At ball release, six kinematic parameters were measured: knee flexion, forward trunk tilt, lateral trunk tilt, elbow flexion, shoulder horizontal adduction, and ball velocity. Ball velocity was recorded from a Jugs Tribar Sport radar gun (Jugs Pitching Machine Company, Tualatin, OR) as the ball left the pitcher's hand.

An automated method for determining ball release for the FA was demonstrated using manual and automatic digitizing techniques with high-speed video on pitchers who threw between 30 and 38 m/s (Fleisig, 1994). Based on these techniques, ball release (REL) for the FA pitch was automatically quantified as the second video frame after the wrist passed the elbow in the global X direction ($Wrist_{Pass}$), where each video frame was 0.005 s. Therefore, REL during the FA was defined to have occurred somewhere between 0.010 s and 0.015 s after $Wrist_{Pass}$. Although this method has been used previously for FA pitches (Fleisig et al., 1996), there are no data that quantitatively determine the time from $Wrist_{Pass}$ to REL for the CU, SL, and CH. Consequently, for each subject a Kodak Ektapro 1000 (Eastman Kodak Company, San Diego, CA) video camera was used to collect 500 Hz of video data in the sagittal plane of the pitcher's motion. This high-speed video recording was used to quantify the time from $Wrist_{Pass}$ to REL for each pitch variation. Mean times from $Wrist_{Pass}$ to REL for the FA, CU, SL, and CH were 0.010 ± 0.001 s, 0.010 ± 0.001 s, 0.010 ± 0.002 s, and 0.012 ± 0.002 s, respectively. Since all these times were within the accuracy (i.e., between 0.010 s and 0.015 s) of the automated method described for the FA, the automated method was used for all four pitch variations. Hence, REL for the FA, CU, SL, and CH was automatically quantified as the second video frame after the wrist passed the elbow in the global X direction. The final two kinematic parameters were knee and elbow range of motion parameters: (a) difference between knee flexion at lead foot contact and knee flexion at ball release, where a positive difference implied that knee flexion at lead foot contact was larger than knee flexion at ball release; and (b) difference between maximum elbow flexion and elbow flexion at ball release, where a positive difference implied that maximum elbow flexion was larger than elbow flexion at ball release.

Ten temporal parameters were measured: (a) time from lead foot contact to ball release (FC-REL), (b) time of maximum pelvis angular velocity, (c) time of maximum upper torso angular velocity, (d) time of maximum forward trunk angular velocity, (e) time of maximum shoulder horizontal adduction angular velocity, (f) time of maximum elbow flexion, (g) time of maximum shoulder horizontal adduction, (h) time of maximum shoulder external rotation, (i) time of maximum elbow extension angular velocity, and (j) time of maximum shoulder internal rotation angular velocity. Each of the nine temporal parameters listed in (b) through (j) occurred during the arm-cocking or arm acceleration phases. These temporal parameters were defined as the time interval from lead foot contact to maximum measurement of the parameter and were normalized as a percentage of FC-REL. For example, time of maximum elbow flexion was defined as the time interval from foot contact to maximum elbow flexion.

Although greater ball velocity does not always result in better pitching mechanics or a more effective pitch (especially when pitchers throw off-speed pitches), ball velocity was remarkably consistent for each subject when throwing each pitch variation (typically less than 3% variation among same type pitches). This type of consistency is expected as one's pitching level and specialization skills increase. Similar consistencies among the same pitching trials have been observed in both college and professional pitchers (Feltner & Dapena, 1986, Pappas et al., 1985). For each pitch variation, kinematic and temporal data were calculated and averaged from the three fastest pitches by each subject that were thrown for strikes. Analysis of variance (ANOVA) methods were used on all kinematic and temporal data to assess the significance of differences among the FA, CH, and CU thrown by the 16 pitchers. The analysis was blocked on subject to control for differences among pitchers. ANOVA methods, including the block on subject, also were conducted on all kinematic and temporal data for the 7 pitchers who threw the FA, CH, CU, and SL. To help control the overall Type I error resulting from multiple comparisons, only p values <.01 were considered significant. Both $p < .01$ and $p < .001$ are reported. Pair-wise comparisons using Tukey's least significant difference (LSD) method were conducted to assess the post hoc differences among the pitch variations. The pair-wise overall p value for the Tukey LSD comparisons was set at $p < .05$.

The statistical package SAS (Statistical Analysis System) was used to analyze the data, utilizing the general linear model procedure (PROC GLM).

Results and Discussion

Of the 26 kinematic parameters statistically analyzed (Table 1), 18 showed significant differences among the FA, CH, and CU groups (i.e., three-pitch comparison with 16 subjects) and 16 showed significant differences among the FA, CH, CU, and SL groups (i.e., four-pitch comparison with 7 subjects). At lead foot contact, three of the eight kinematic parameters showed significant differences among pitch variations, while four of the seven kinematic parameters during arm cocking showed significant differences. All nine kinematic parameters measured during the arm acceleration phase and at ball release showed significant differences among the pitch variations. Both knee and elbow range of motion parameters displayed significant differences among the pitch variations.

Ball velocity was the only parameter that showed a significant difference for all pitch comparisons. The FA group threw approximately 10% faster than the SL group, approximately 15% faster than the CH group, and approximately 25% faster than the CU group. Although ball velocity was most different between the FA and CU groups, kinematic parameters were most different between the FA and CH groups. As expected, since ball velocity was most similar between the FA and SL groups, kinematic parameters were most similar between these two groups.

One limitation in the current study was the omission of kinematic data for forearm and hand motions. Although these motions can significantly affect ball velocity, it was not possible to zoom out the cameras enough to capture the kinematics of the entire body and at the same time accurately digitize the medial and lateral wrist as well as adjacent landmarks on the hand. The reflective markers on these structures would blend together, and individual markers would be indistinguishable from each other. In a follow-up study involving college pitchers who will throw similar pitch variations, the cameras will be zoomed in on the upper extremities and trunk. This will allow adequate hand and forearm data to be collected while sacrificing lower extremity kinematic data. However, lower extremity kinematic data were collected in the current study.

Mean angular displacement and angular velocity graphs for the 16 pitchers who threw the FA, CU, and CH are shown in Figures 4–7. Since only 7 of these 16 pitchers also threw the SL, mean SL data were not included on these graphs. Similar patterns were observed among the FA, CU, and CH groups throughout the arm-cocking, arm acceleration, and arm deceleration phases of the pitch, where the arm deceleration phase was defined from ball release to maximum shoulder internal rotation. Magnitudes from these figures were most similar between the FA and CU groups, while greater differences in magnitudes were observed between the FA and CH groups and between the CU and CH groups.

Temporal measurements (i.e., timing of maximum kinematic measurements) during the arm-cocking, arm acceleration, and arm deceleration phases were previously reported for collegiate pitchers who threw the FA (Fleisig et al., 1996). Of the temporal parameters measured in the current study during the arm-cocking and arm acceleration phases, only time of maximum upper torso angular velocity between the CH and CU groups showed a significant temporal difference ($p < .001$) among the four pitch variations. The mean time of maximum upper torso angular velocity occurred approximately 10% later for the CH group (0.089 ± 0.011 s after foot contact) relative to the CU group (0.080 ± 0.014 s after foot contact). It was not surprising that only one significant timing

Table 1 Kinematic Differences Among the Fastball (FA), Change-Up (CH), Curveball (CU), and Slider (SL)

Parameter	FA (*n* = 16)		CH (*n* = 16)		CU (*n* = 16)		SL (*n* = 7)		Significant differences among FA, CH, CU (*n* = 16)	Significant differences among FA, CH, CU, SL (*n* = 7)
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*		
Lead foot contact										
Stride length (% height)	84	5	84	5	82	4	87	3	*(b,c)	*(b,c,e)
Foot placement (cm) (closed –; open +)	0	10	–3	9	–7	9	0	9	**(b,c)	*(b,c)
Foot angle (°) (closed –; open +)	–8	12	–7	11	–14	14	–10	11		
Shoulder abduction (°)	98	12	97	12	95	11	93	13		
Shoulder horizontal adduction (°)	–20	10	–18	10	–18	10	–22	9		
Shoulder external rotation (°)	52	33	50	33	49	38	50	48		
Knee flexion (°)	48	11	42	11	47	10	47	11	**(a,c)	
Elbow flexion (°)	84	17	79	19	80	19	86	15		
Arm-cocking phase										
Maximum pelvis angular velocity (°/s)	640	80	570	70	590	70	600	70	**(a,b)	*(a,b,d)
Maximum upper torso angular velocity (°/s)	1,220	100	1,120	100	1,160	80	1,220	90	**(a,b)	*(a,d)
Maximum forward trunk angular velocity (°/s)	350	70	310	80	340	70	340	80		
Maximum shoulder horizontal adduction angular velocity (°/s)	600	180	610	190	620	200	570	180		
Maximum elbow flexion (°)	104	12	101	11	104	14	105	13		
Maximum shoulder horizontal adduction (°)	20	7	24	7	22	6	19	6	**(a,b)	*(a,d)

Maximum shoulder external rotation (°)	171	6	169	8	172	7	167	6	*(c)	*(c,d)
Arm acceleration phase										
Maximum elbow external angular velocity (°/s)	2,440	240	2,170	260	2,360	280	2,490	280	**(a,c)	*(a,d)
Maximum shoulder internal rotation angular velocity (°/s)	7,550	1,110	6,680	1,050	7,120	1,170	7,920	1,440	**(a,c)	*(d,e)
Average shoulder abduction (°)	95	13	99	13	98	13	92	9	**(a,b)	**(a,b,d,e)
Instant at ball release										
Knee flexion (°)	46	13	55	11	53	14	53	12	**(a,b)	**(a,b,e)
Forward trunk tilt (°)	28	5	26	6	29	6	28	6	*(c)	*(b,c,d,f)
Lateral trunk tilt (°)	28	9	24	10	31	10	26	10	**(a,c)	**(b,c,e)
Elbow flexion (°)	24	5	28	5	24	5	24	5	**(a,c)	
Shoulder horizontal adduction (°)	10	9	16	8	13	8	10	7	**(a,b,c)	*(a,b)
Ball velocity (m/s)	35	2	30	2	28	2	31	1	**(a,b,c)	**(a,b,c,d,e,f)
Elbow and knee range of motion										
Difference between knee flexion at lead foot contact and knee flexion at ball release (°)	2	13	–13	11	–6	11	–6	11	**(a,b,c)	**(a,b,d)
Difference between maximum elbow flexion and elbow flexion at ball release (°)	80	15	73	15	80	17	81	13	*(a,c)	**(a,c,d)

Note. Significant difference ($p < .05$) between (a) FA and CH, (b) FA and CU, (c) CH and CU, (d) SL and CH, (e) SL and CU, and (f) SL and FA.
*$p < .01$. ** $p < .001$.

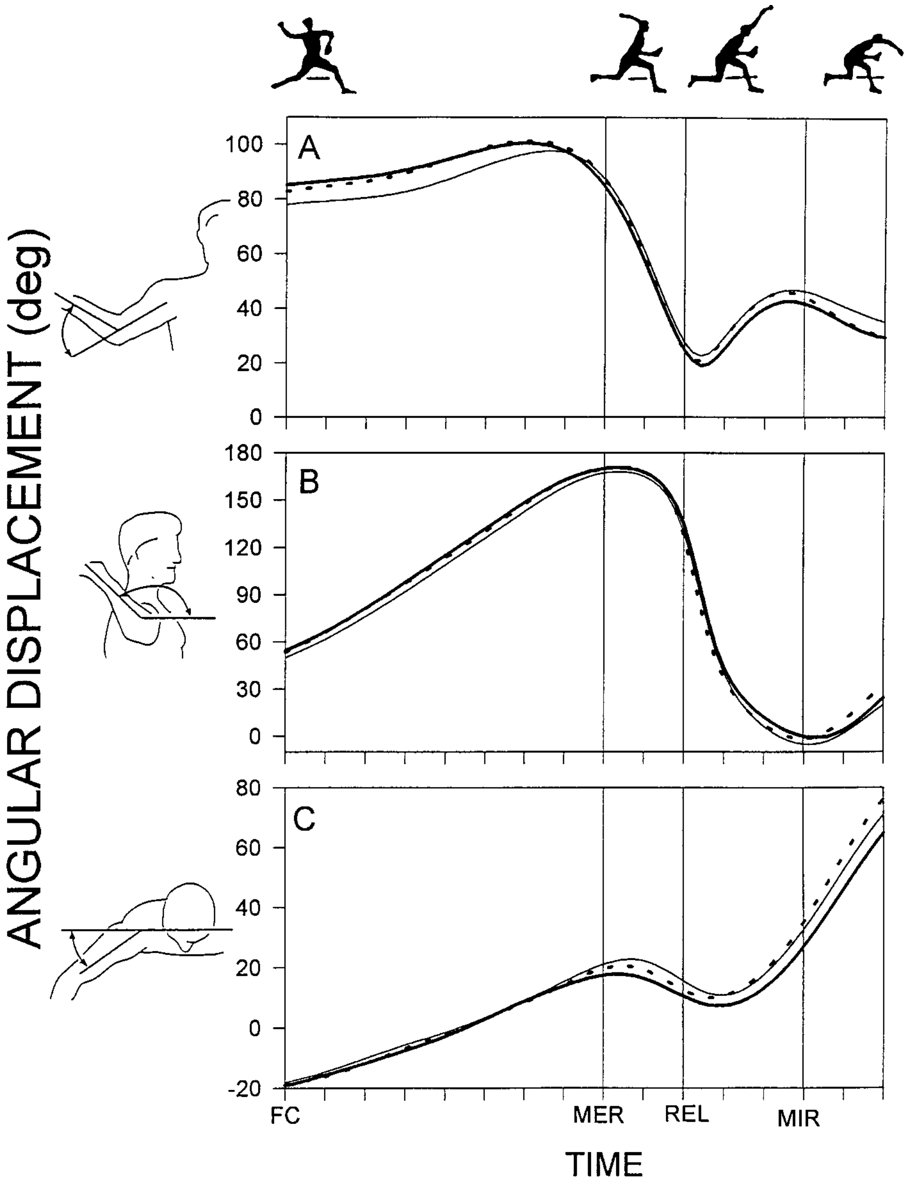

Figure 4 —Angular displacement for (A) elbow flexion, (B) shoulder external rotation, and (C) shoulder horizontal adduction (+)/abduction (–). Mean graphs are from the 16 pitchers who threw the fastball (thick line), curveball (dashed line), and change-up (thin line) combinations. The times of lead foot contact (FC), maximum shoulder external rotation (MER), ball release (REL), and maximum shoulder internal rotation (MIR) are shown.

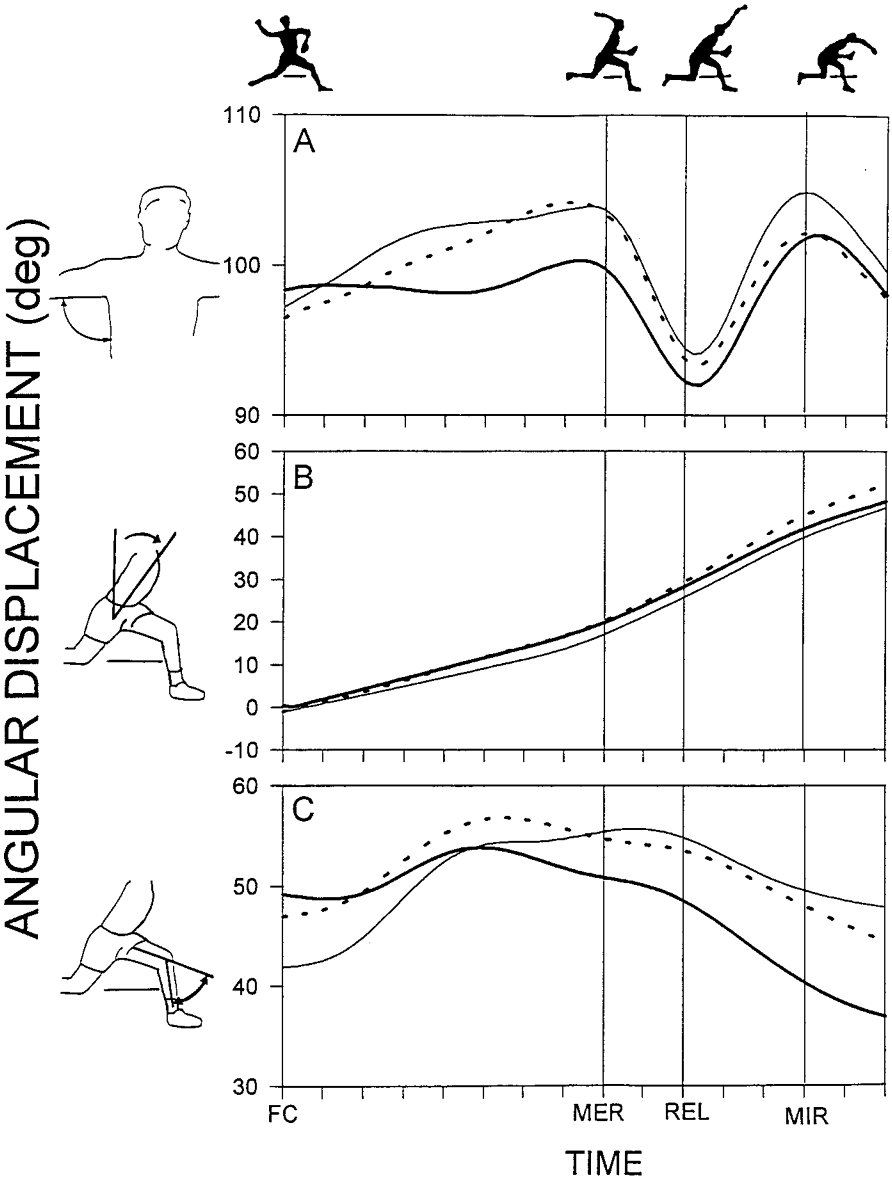

Figure 5 — Angular displacement for (A) shoulder abduction, (B) forward trunk tilt, and (C) knee flexion. Mean graphs are from the 16 pitchers who threw the fastball (thick line), curveball (dashed line), and change-up (thin line) combinations. The times of lead foot contact (FC), maximum shoulder external rotation (MER), ball release (REL), and maximum shoulder internal rotation (MIR) are shown.

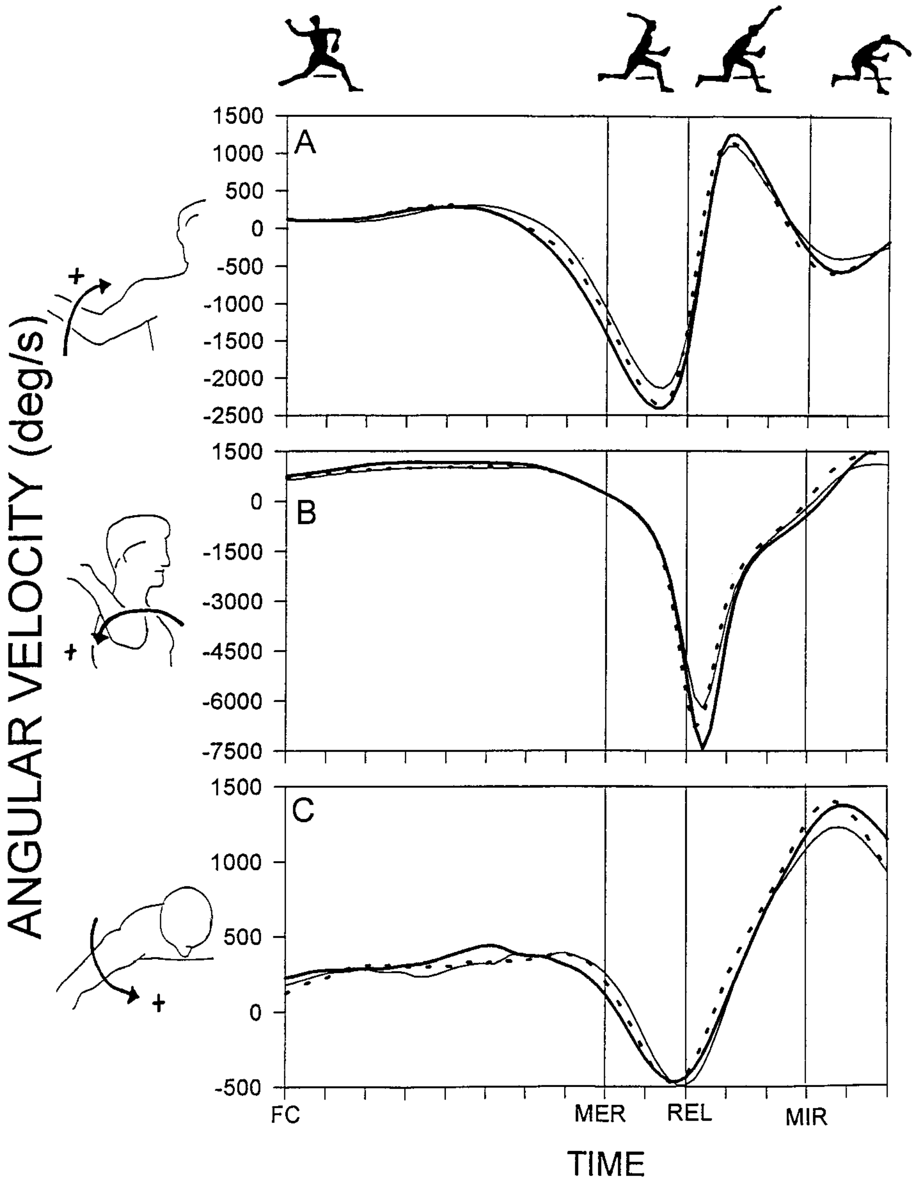

Figure 6 — Angular velocity for (A) elbow flexion (+)/extension (–), (B) shoulder external (+)/ internal (–) rotation, and (C) shoulder horizontal adduction (+)/abduction (–). Mean graphs are from the 16 pitchers who threw the fastball (thick line), curveball (dashed line), and change-up (thin line) combinations. The times of lead foot contact (FC), maximum shoulder external rotation (MER), ball release (REL), and maximum shoulder internal rotation (MIR) are shown.

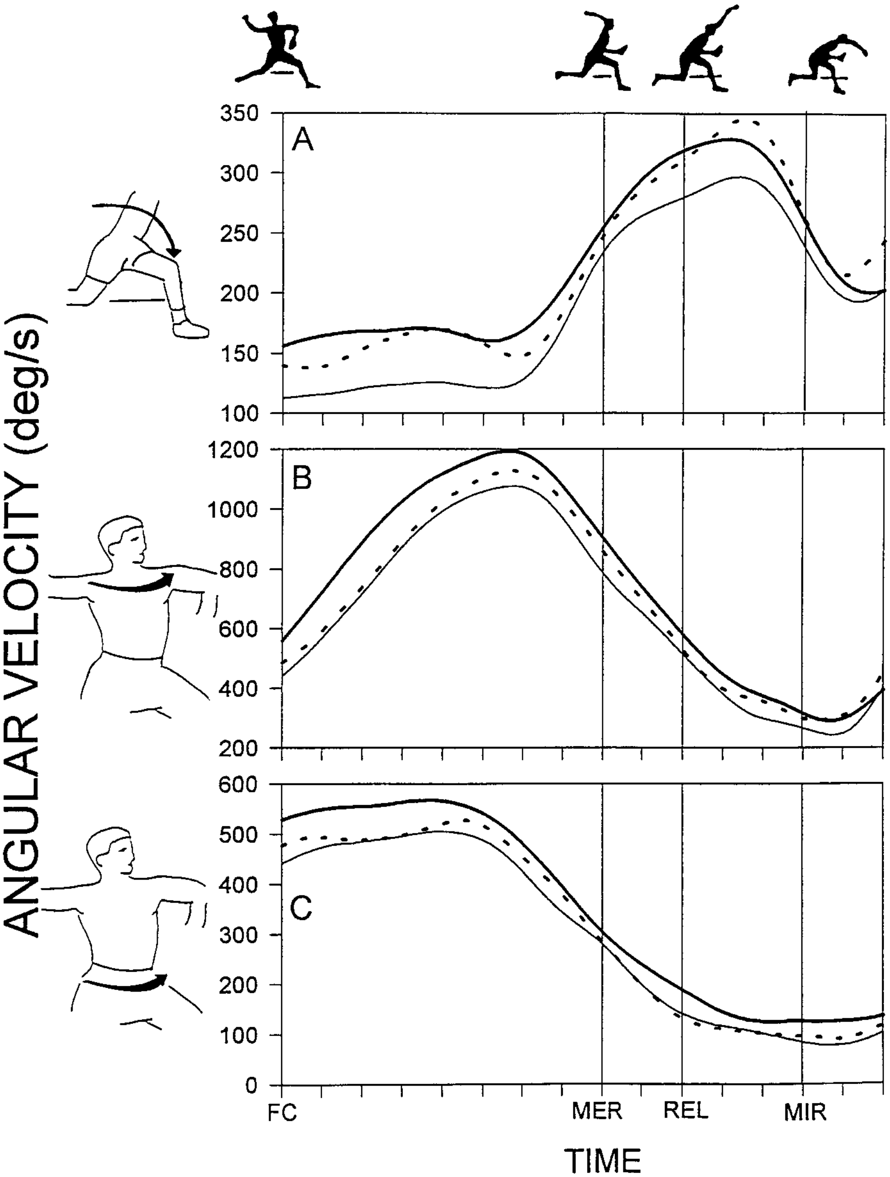

Figure 7 — Angular velocity for (A) forward trunk rotation, (B) upper torso rotation, and (C) pelvis rotation. Mean graphs are from the 16 pitchers who threw the fastball (thick line), curveball (dashed line), and change-up (thin line) combinations. The times of lead foot contact (FC), maximum shoulder external rotation (MER), ball release (REL), and maximum shoulder internal rotation (MIR) are shown.

difference was found, since Figures 4–7 show similar timing patterns among the FA, CU, and CH groups.

Fastball (FA) Versus Curveball (CU) Comparison

Of the 26 kinematic parameters quantified, 10 showed significant differences between the FA and CU groups. This suggests that the pitching motions between the FA and CU groups were similar for 16 kinematic parameters even though the CU group produced the lowest ball velocity (28 m/s, 63 mph) and the FA group produced the highest (35 m/s, 78 mph).

Of the significant differences at lead foot contact, stride length was greater in the FA group whereas foot placement was more closed (i.e., toes pointed in more) in the CU group. Of the significant differences during the arm-cocking phase, maximum pelvis and upper torso angular velocities were 5–10% greater in the FA group whereas maximum shoulder horizontal adduction was 10% greater in the CU group. The only significant difference during the arm acceleration phase was average shoulder abduction, which was approximately 5% greater in the CU group. Of the significant differences at ball release, knee flexion and shoulder horizontal adduction were 15–25% greater in the CU group, whereas ball velocity was 25% greater in the FA group.

For both the FA and CU groups, the knee continued flexing after lead foot contact throughout most of the arm-cocking phase (Figure 5). The knee then began to extend near the end of the arm-cocking phase and continued extending throughout the arm acceleration phase until ball release. It is interesting that the rate of knee extension during the arm acceleration phase was greater in the FA group, as seen from the steeper negative slope in the FA graph compared to the CU graph. Relative to knee flexion at lead foot contact, at ball release the knee was flexed 2° less in the FA group and 6° more in the CU group. This range of motion difference between knee flexion at lead foot contact and knee flexion at ball release was significantly greater in the CU group (Table 1).

Kinematic comparisons between FA and CU data are similar to two other studies (Elliott et al., 1986; Sakurai et al., 1993) that included similar kinematic parameters. Comparison of kinematic parameters between the FA and CU groups (Table 2) revealed no significant differences except ball velocity (all three studies), stride length (the current study), and average shoulder abduction during the arm acceleration phase (the current study). Ball velocities in the current study were nearly identical to the ball velocities reported in Sakurai et al. (1993) and Elliott et al. (1986). Data in the current study show that a pitcher had a slightly shorter stride (<5%) when throwing a CU. For years coaches have advocated that pitchers shorten their stride when throwing a CU to keep the pitch down in the strike zone (McFarland, 1990). However, other coaches feel that to consciously alter pitching mechanics among different pitches may be deleterious to the pitcher and may also tip off the batter as to the type of pitch being thrown (McFarland, 1990). The significantly shorter stride (approximately 3.5 cm) in the CU group (82 ± 4% height) compared to the FA group (84 ± 5% height) is probably not a large enough difference to be noticeable to the batter.

Sakurai et al. (1993) compared temporal events between the FA and CU groups. The time from lead foot contact to ball release (FC-REL) was approximately 5% greater in the FA group (0.130 ± 0.020 s) than the CU group (0.123 ± 0.022 s). In contrast, FC-REL in the current study was significantly less (8%) in the FA group (0.149 ± 0.016 s) compared to the CU group (0.164 ± 0.020 s). Furthermore, in the current study, FC-REL in the FA group was significantly less (5–10%) than FC-REL in the CH group (0.166 ± 0.017 s) and FC-REL in the SL group (0.162 ± 0.018 s). It seems reasonable that the FA

Table 2 Comparisons Between Mean (*SD*) Curveball and Fastball Kinematic and Temporal Data

	Curveball						Fastball					
	Current (*n* = 16)		Elliott[a] (*n* = 6)		Sakurai[b] (*n* = 6)		Current (*n* = 16)		Elliott[a] (*n* = 6)		Sakurai[b] (*n* = 6)	
Parameter	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Lead foot contact												
Knee flexion (°)	47	10	43				48	11	48			
Elbow flexion (°)	80	19			104	19	84	17			107	20
Stride length (% height)	82	4*	81	6			84	5*	82	2		
Shoulder abduction (°)	95	11			85	9	98	12			83	12
Shoulder horizontal adduction (°)	–18	10			–17	13	–20	10			–20	8
Arm cocking phase												
Maximum elbow flexion (°)	104	14	101		114	17	104	12	101		116	19
Time of maximum elbow flexion (% FC-REL)	63	11			37	27	57	17			39	23
Maximum shoulder external rotation (°)	172	7			181	6	171	6			181	7
Time of maximum shoulder ext. rot. (% FC-REL)	83	4			72	10	82	3			73	9
Maximum shoulder horizontal adduction (°)	22	6			14	13	20	7			11	12
Arm acceleration phase												
Maximum elbow extension angular velocity (°/s)	2,360	280	986				2,440	240	969			
Average shoulder abduction (°)	98	13*			82	10	95	13*			82	8
Instant at ball release												
Elbow flexion (°)	24	5	38	2	38	12	24	5	36	3	35	12
Shoulder horizontal adduction (°)	13	8			9	9	10	9			6	7
Ball velocity (m/s)	28	2*	28	1*	29	1*	35	2*	35	2*	35	2*

Note. FC-REL is the time interval from lead foot contact to ball release. [a]Data from Elliott et al. (1986). [b]Data from Sakurai et al. (1993).
*Significant differences between fastball and curveball.

group would generate an FC-REL interval smaller than those for the three off-speed pitch groups (CU, CH, and SL), since peak angular velocities during FC-REL were greatest in the FA group.

Compared to FC-REL from Sakurai et al. (1993), FC-REL in the current study was approximately 15% longer in the FA group and approximately 35% longer in the CU group. However, these disparities were primarily due to differences between the studies in how lead foot contact and ball release were defined. Although ball release was easy to define as when the ball leaves contact with the hand, lead foot contact was more ambiguous. Lead foot contact could be defined as when the toe, heel, or any part of the foot first contacts the pitching mound, or it could be defined as when the lead foot is flat on the pitching mound. From high-speed video observations, the time interval from first contact of the lead foot with the pitching mound to the point when the lead foot is flat on the mound is typically between 0.02 and 0.05 s, which is 15–30% of the entire FC-REL interval. The automated process used in the current study calculated lead foot contact approximately halfway between initial foot contact with the pitching mound and when the lead foot was flat on the mound (Fleisig, 1994). Sakurai et al. (1993) did not specify their definition of lead foot contact. However, their smaller FC-REL suggests that they defined lead foot contact closer to when the lead foot was flat on the mound.

Of the maximum kinematic parameters reported both in the current study and by Sakurai et al. (1993), the time of maximum elbow flexion and the time of maximum shoulder external rotation during the arm-cocking phase were the only two temporal parameters mutually reported (Table 2). These temporal parameters were normalized by the appropriate FC-REL interval in each study and expressed as a percentage. Both studies showed no significant differences between the CU and FA groups for both temporal parameters. That the time of maximum elbow flexion and the time of maximum shoulder external rotation in the current study occurred later in the arm-cocking phase compared to the findings of Sakurai et al. (1993) is not surprising, since FC-REL was probably defined differently between studies. Temporal parameters can only be compared accurately if they are similarly defined.

The kinematic parameter that showed the greatest difference between studies was maximum elbow extension angular velocity during the arm acceleration phase (Table 2), which was reported for the FA and CU groups in the current study and by Elliott et al. (1986). For both the FA and CU groups, the current study showed 140–150% greater maximum elbow extension angular velocity than that reported by Elliott et al. (1986). Since the pitchers from Elliott et al. (1986) had almost identical ball velocities as the pitchers in the current study, it is difficult to understand the discrepancy between our results. Several other authors who calculated maximum elbow extension angular velocities for the FA during pitching and throwing found results similar to the 2,440°/s from the current study. Using college pitchers whose FA group velocity was nearly identical to the current study (35 ± 2 m/s), Feltner and Dapena (1986) calculated a maximum elbow extension angular velocity of 2,200 ± 400°/s. Using primarily college pitchers, Vaughn (1985a) calculated a maximum elbow extension angular velocity of approximately 2,000°/s. Having adult subjects (nonpitchers) throw balls (100 g) that weighed approximately the same as regulation baseballs (140 g), Toyoshima, Hoshikawa, Miyashita, and Oguri (1974) calculated a maximum elbow extension angular velocity of 1,785°/s and a ball velocity of 27 m/s during normal throwing. Interestingly, a second group of subjects threw the same 100 g ball using only the forearm to extend the elbow (forearm throw) instead of the entire body (normal throwing). During the forearm throw, a maximum elbow extension angular velocity of 893°/s was calculated, which is similar to the 969°/s calculated by Elliott et al.

(1986) for the FA group. However, ball velocity during the forearm throw was only 11 m/s, which is approximately one third the ball velocity calculated by Elliott et al. (1986). Toyoshima et al. (1974) concluded that the increase in maximum elbow extension angular velocity and ball velocity during normal throwing compared to forearm throwing was due to the forearm being swung open like a whip by the rotary actions of other parts of the body, such as the pelvis, upper torso, and shoulder.

Fastball (FA) Versus Change-Up (CH) Comparison

The FA versus CH group comparison was the most different among the six pitch comparisons, with 14 of the 26 kinematic parameters showing significant differences. The only significant difference at lead foot contact was knee flexion, which was approximately 15% greater in the FA group. Of the significant differences during the arm-cocking phase, maximum pelvis and upper torso angular velocities were approximately 10% greater in the FA group, while the CH group had 20% greater shoulder horizontal adduction. Several significant differences occurred at ball release. The CH group had 15–20% more knee and elbow flexion and 60% more shoulder horizontal adduction. Lateral trunk tilt and ball velocity were approximately 15% greater in the FA group.

In contrast to the FA group, in which the knee flexed throughout most of the arm-cocking phase and extended throughout the arm acceleration phase, the CH group continued flexing the knee after lead foot contact throughout all of the arm-cocking phase and during the first half of the arm acceleration phase (Figure 5). Relative to knee flexion at lead foot contact, at ball release the knee was flexed 2° less in the FA group and 13° more in the CH group. This range of motion difference between knee flexion at lead foot contact and knee flexion at ball release was significantly greater in the CH group (Table 1).

The elbow range of motion from maximum elbow flexion to elbow flexion at ball release was significantly greater (10%) in the FA group, with the FA group extending the elbow 80° during this range of motion and the CH group extending the elbow 73° (Table 1). It is clear from Figure 4 that maximum elbow flexion occurred during the arm-cocking phase and that the elbow extended continuously from maximum elbow flexion to elbow flexion at ball release.

The numerous differences in segmental angular velocities and joint angles between the FA and CH groups may tip off a batter concerning which type of pitch is being thrown. Consequently, it may behoove a pitcher to learn how to minimize differences in pitching kinematics in order to disguise these two pitches, which could necessitate changes in the pitcher's training methodologies and pitching mechanics. However, this may not be practical for higher level pitchers (e.g., college or professional), since it could be difficult to deviate from movement patterns that have been ingrained in their neuromuscular systems for many years. However, it may be appropriate and practical for younger pitchers, who have not yet established a particular pattern of pitching, to learn to minimize differences in pitching kinematics.

Change-Up (CH) Versus Curveball (CU) Comparison

Thirteen of the 26 kinematic parameters showed significant differences between the CH and CU groups. Of the significant differences at lead foot contact, the CH group had a slightly longer stride (<5%), whereas the CU group had approximately 5% greater knee flexion and a foot placement that was 4 cm more closed. The only significant difference during the arm-cocking phase was maximum shoulder external rotation, which was slightly greater (<5%) in the CU group. Significant differences during the arm acceleration phase included maximum elbow extension angular velocity and maximum shoulder internal rotation angular velocity, which were 5–10% greater in the CU group. Several significant differences occurred at ball release. The CH group had 15–25% greater elbow flexion and shoulder horizontal adduction and approximately 5% more ball velocity. The CU group had approximately 10% greater forward trunk tilt and approximately 30% more lateral trunk tilt.

In contrast to the CU group, in which the knee flexed throughout most of the arm-cocking phase and extended throughout the arm acceleration phase, the CH group continued flexing the knee after lead foot contact throughout all of the arm-cocking phase and during the first half of the arm acceleration phase (Figure 5). Relative to knee flexion at lead foot contact, at ball release the knee was flexed 6° more in the CU group and 13° more in the CH group. This range of motion difference between knee flexion at lead foot contact and knee flexion at ball release was significantly greater in the CH group (Table 1). Some coaches believe that knee extension during the arm acceleration phase is important in stabilizing the lead leg, allowing the trunk to rotate forward over the lead hip; in effect, forward trunk tilt and forward trunk angular velocity would increase. The significantly greater forward trunk tilt in the CU group may substantiate these qualitative observations by coaches. Although the CU group also displayed greater forward trunk angular velocities throughout the pitch (Figure 7), the maximum values statistically analyzed during the arm-cocking phase were not significantly different from each other (Table 1). The elbow range of motion from maximum elbow flexion to elbow flexion at ball release was significantly greater (10%) in the CU group. The CU group extended the elbow 80° during this range of motion, whereas the CH group extended the elbow 73° (Table 1).

Both the CH and CU are considered off-speed pitches, since they are typically thrown with 15–25% less ball velocity compared to the FA. To disguise these pitches to the batter, the pitcher attempts to make deliveries of these pitches indistinguishable from the FA. Between the CU and CH groups, the CU group kinematics were slightly more similar to the FA group kinematics. Therefore, the CU may be a more effective off-speed pitch for this group of pitchers (based only on pitching kinematics), especially since the CU group displayed a ball velocity that was most different from the FA group. However, the CH may be a more effective off-speed pitch in another group of subjects. Subsequent studies would be helpful to test kinematic similarities and differences on additional pitching levels (e.g., professional pitchers) as well as on pitchers who specialize in throwing a particular off-speed pitch, such as the CH or CU.

Slider (SL) Versus Fastball (FA) Comparison

The FA versus SL group comparison was the most similar of the six pitch comparisons. Ball velocity and forward trunk tilt at ball release were the only two kinematic parameters that showed significant differences. At ball release, forward trunk tilt was slightly less (<5%) in the FA group, while ball velocity was approximately 10% less in the SL group. However, only 7 pitchers threw both the SL and FA, and a greater sample size may show different statistical results. The similar peak shoulder, elbow, and trunk angular velocities between these two pitches may make it difficult for the batter to perceive which pitch is being thrown, especially since ball velocity in the SL group was similar to ball velocity in the FA group.

Slider (SL) Versus Change-Up (CH) Comparison

Although statistical power was decreased since only 7 pitchers threw both the SL and CH, 11 of the 26 kinematic parameters showed significant differences between these two pitch variations. Of the significant differences during the arm-cocking phase, the CH group had approximately 25% more maximum shoulder horizontal adduction and slightly more maximum shoulder external rotation (<5%). Peak angular velocities of the pelvis and upper torso were 5–10% greater in the SL group. Significant differences occurred for all parameters in the arm acceleration phase. Maximum elbow extension angular velocity and maximum shoulder internal rotation angular velocity were 15–20% greater in the SL group, while average shoulder abduction was 5–10% greater in the CH group. Of the significant differences at ball release, the SL group had 5–10% greater forward trunk tilt and approximately 5% more ball velocity.

Relative to knee flexion at lead foot contact, at ball release the knee was flexed 6° more in the SL group and 13° more in the CH group. This range of motion difference between knee flexion at lead foot contact and knee flexion at ball release was significantly greater in the CH group (Table 1).

The elbow range of motion from maximum elbow flexion to elbow flexion at ball release was significantly greater (10%) in the SL group. The SL group extended the elbow 81° during this range of motion, while the CH group extended the elbow 73° (Table 1). The differences in joint angles, ranges of motions, and segmental velocities between the CH and SL groups may be perceived by a keen batter.

Curveball (CU) Versus Slider (SL) Comparison

Only 6 of the 26 kinematic parameters were significantly different between the CU and SL groups. Therefore, the kinematics of these pitches were quite similar and may be difficult for a batter to discern. A significantly greater stride length at lead foot contact was measured in the SL group. Of the significant differences during the arm acceleration phase, peak shoulder internal rotation angular velocity was 15–20% greater in the SL group, while average shoulder abduction was approximately 5% more in the CU group. Of the significant differences at ball release, the CU group had approximately 20% greater lateral trunk tilt and slightly more knee flexion (<5%). Ball velocity was 10–15% greater in the SL group.

Conclusions

Qualitative analyses using high-speed video have long been helpful to researchers, coaches, trainers, and others in assessing kinematic similarities and dissimilarities among different types of pitches; however, until now kinematic parameters have not been quantified for pitches other than the CU and FA. Collegiate kinematic data reported in the current study for the FA, CU, CH, and SL pitches can be useful for assessing kinematic parameters for other collegiate pitchers. The FA kinematic data presented in the current study are similar to previously reported FA kinematic data for college and professional pitchers (Dillman et al., 1993; Werner et al., 1993) and college and high school pitchers (Fleisig et al., 1996). Therefore, kinematic parameters among high school, college, and professional pitchers may not be significantly different. Ideally, a pitcher would want minimal kinematic differences between pitches in order to make visual identification of a pitcher's motion difficult for batters. However, since results from the current study showed that approximately 60% of the kinematic parameters were significantly different among the four pitch variations, a college batter may be able to identify a pitch by observing a pitcher's pitching motion. The CH group was the most different from the FA group, implying that disguising the CH may be most challenging. The SL group was most similar to the FA group. Both the FA and SL groups generated similar peak shoulder, elbow, and trunk angular velocities, which were significantly greater than those generated in the CH group. Although it may be difficult and impractical for higher level pitchers (e.g., college and professional pitchers) to change pitching mechanics that have been ingrained in their neuromuscular systems for years, it may be feasible for younger pitchers to learn how to throw different pitches with similar pitching mechanics (i.e., kinematics).

A follow-up study in which pitchers of different levels (e.g., high school, professional) throw different pitch variations may be helpful to determine if homogeneity within pitch variations differs among different level pitchers. It may also be beneficial to compare the kinematic data reported in this study using collegiate pitchers with kinematic data derived from lower or higher pitching levels. A follow-up study should be broadened to quantify kinematic and kinetic parameters involving the hand and forearm.

References

Abdel-Aziz, Y.I., & Karara, H.M. (1971). Direct linear transformation from comparator coordinates into object–space coordinates in close-range photogrammetry. In *ASP Symposium on Close-Range Photogrammetry* (pp. 1-19). Falls Church, VA: American Society of Photogrammetry.

Bates, B.T., Dufek, J.S., & Davis, H.P. (1992). The effect of trial size on statistical power. *Medicine and Science in Sports and Exercise*, **24**(9), 1059-1068.

Dillman, C.J., Fleisig, G.S., & Andrews, J.R. (1993). Biomechanics of pitching with emphasis upon shoulder kinematics. *Journal of Orthopaedic and Sports Physical Therapy*, **18**(2), 402-408.

Elliott, B., Grove, J.R., Gibson, B., & Thurston, B. (1986). Three-dimensional cinematographic analysis of the fastball and curveball pitches in baseball. *International Journal of Sport Biomechanics*, **2**, 20-28.

Feltner, M., & Dapena, J. (1986). Dynamics of the shoulder and elbow joints of the throwing arm during a baseball pitch. *International Journal of Sport Biomechanics*, **2**(4), 235-259.

Feltner, M.E., & Dapena, J. (1989a). Three-dimensional interactions in a two-segment kinetic chain: Part I. General model. *International Journal of Sport Biomechanics*, **5**(4), 403-419.

Feltner, M.E., & Dapena, J. (1989b). Three-dimensional interactions in a two-segment kinetic chain: Part II. Application to the throwing arm in baseball pitching. *International Journal of Sport Biomechanics*, **5**(4), 420-450.

Fleisig, G.S. (1994) *The biomechanics of baseball pitching*. Unpublished doctoral dissertation, University of Alabama at Birmingham.

Fleisig, G.S., Andrews, J.R., Dillman, C.J., & Escamilla, R.F. (1995). Kinetics of baseball pitching with implications about injury mechanisms. *American Journal of Sports Medicine*, **23**(2), 233-239.

Fleisig, G.S., Escamilla, R.., Andrews, J.R., Matsuo, T., Satterwhite, Y., & Barrentine, S.W. (1996). Kinematic and kinetic comparison between baseball pitching and football passing. *Journal of Applied Biomechanics*, **12**(2), 207-224.

Hong, D., & Roberts, E.M. (1992). A three-dimensional, six segment chain analysis of forceful overarm throwing. In L. Draganich, R. Wells, & J. Bechtold (Eds.), *The 16th Annual Conference of The American Society of Biomechanics* (pp. 55-56). Chicago: Organizing Committee.

McFarland, J. (1990). *Coaching pitchers* (2nd ed.). Champaign, IL: Leisure Press.

Miller, D.I., & Nelson, R.C. (1973). *Biomechanics of sport—A research approach*. Philadelphia: Lee & Febiger.

Pappas, A.M., Zawacki, R.M., & Sullivan, T.J. (1985). Biomechanics of baseball pitching: A preliminary report. *American Journal of Sports Medicine*, **13**(4), 216-222.

Sakurai, S., Ikegami, Y., Okamoto, A., Yabe, K., & Toyoshima, S. (1993). A three-dimensional cinematographic analysis of upper limb movement during fastball and curveball baseball pitches. *Journal of Applied Biomechanics*, **9**(1), 47-65.

Shapiro, R. (1978). Direct linear transformation method for three-dimensional cinematography. *Research Quarterly*, **49**, 197-205.

Stevenson, J.M. (1985). Finger release sequence for fastball and curveball pitches. *Canadian Journal of Applied Sports Science*, **10**(1), 21-25.
Toyoshima, S., Hoshikawa, T., Miyashita, M., & Oguri, T. (1974). Contributions of the body parts of throwing performance. In R.C. Nelson & C.A. Morehouse (Eds.), *Biomechanics IV* (pp. 169-174). Baltimore: University Park Press.
Vaughn, R.E. (1985a). An algorithm for determining arm action during overarm baseball pitches. In D.A. Winter (Ed.), *Biomechanics IX-B* (pp. 510-515). Champaign, IL: Human Kinetics.
Vaughn, R.E. (1985b). Three dimensional kinematics of the baseball pitch. In J. Terauds & J.N. Barham (Eds.), *Biomechanics in sports II* (pp. 72-78). Del Mar, CA: Academic.
Werner, S.L., Fleisig, G.S., Dillman, C.J., & Andrews, J.R. (1993). Biomechanics of the elbow during baseball pitching. *Journal of Orthopaedic and Sports Physical Therapy*, **17**(6), 274-278.
Winter, D.A. (1990). *Biomechanics and motor control of human movement*. New York: Wiley.
Winter, D.A., Sidwall, H.G., & Hobson, D.A. (1974). Measurement and reduction of noise in kinematics of locomotion. *Journal of Biomechanics*, **7**, 157-159.

Acknowledgments

Special thanks to our biostatistician, Gary Cutter, PhD, for his assistance with our statistical analyses; Andy Demonia and Phillip Sutton for their assistance in collecting and tracking the data; David Downs for his assistance in preparing our tables; and Heather Conn for secretarial assistance.