Kinematic Analysis of the Wrist and Forearm During Baseball Pitching

Steven W. Barrentine, Tomoyuki Matsuo, Rafael F. Escamilla, Glenn S. Fleisig, and James R. Andrews

Previous researchers studying baseball pitching have compared kinematic and kinetic parameters among different types of pitches, focusing on the trunk, shoulder, and elbow. The lack of data on the wrist and forearm limits the understanding of clinicians, coaches, and researchers regarding the mechanics of baseball pitching and the differences among types of pitches. The purpose of this study was to expand existing knowledge of baseball pitching by quantifying and comparing kinematic data of the wrist and forearm for the fastball (FA), curveball (CU) and change-up (CH) pitches. Kinematic and temporal parameters were determined from 8 collegiate pitchers recorded with a four-camera system (200 Hz). Although significant differences were observed for all pitch comparisons, the least number of differences occurred between the FA and CH. During arm cocking, peak wrist extension for the FA and CH pitches was greater than for the CU, while forearm supination was greater for the CU. In contrast to the current study, previous comparisons of kinematic data for trunk, shoulder, and elbow revealed similarities between the FA and CU pitches and differences between the FA and CH pitches. Kinematic differences among pitches depend on the segment of the body studied.

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

Throwing a baseball is one of the most dynamic skills in all sports. To understand this skill, information about the shoulder, elbow, forearm, and wrist of the throwing arm is essential. While the kinematics and kinetics of the shoulder and elbow are well documented (Dillman, Fleisig, & Andrews, 1993; Elliott, Grove, Gibson, & Thurston, 1986; Feltner & Dapena, 1986; Fleisig et al., 1996; Pappas, Morgan, Schulz, & Diana, 1995; Sakurai, Ikegami, Okamoto, Yabe, & Toyoshima, 1993; Werner, Fleisig, Dillman, & Andrews, 1993), minimal data for the forearm and wrist are available (Elliott et al., 1986; Pappas et al., 1995; Sakurai et al., 1993; Vaughn, 1985). Researchers have compared kinematics and kinetics of throwing different types of baseball pitches (Elliott et al., 1986; Escamilla, Fleisig, Barrentine, Zheng, & Andrews, 1998; Fleisig, Escamilla, Barrentine, & Andrews, 1998; Sakurai et al., 1993): however, only two of these studies included the motions of the wrist and forearm (Elliott et al., 1986; Sakurai et al., 1993), and in each case only the fastball and curveball pitches were analyzed. Elliott et al. (1986) filmed 6 pitchers from the Australian national team throwing fastball and curveball pitches and

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reported differences for wrist and forearm motion, although differences were not quantified. Sakurai et al. (1993) analyzed 6 Japanese university pitchers throwing fastball and curveball pitches and observed significant differences for forearm supination and wrist extension during the late cocking and acceleration phases. Kinematic analyses of wrist and forearm motion for other types of pitches have not been reported.

Some of the data reported for wrist motion do not appear to be consistent. Elliott et al. (1986) found the wrist to be slightly extended 2° at ball release, whereas Sakurai et al. (1993) found the wrist to be extended 19°. Vaughn (1985) filmed 4 high school and 8 collegiate pitchers and determined wrist flexion to be slightly flexed at 4° at ball release. Pappas et al. (1995) used a glove equipped with strain gauge goniometers to analyze 5 professional pitchers and determined that the wrist was in a position of 27° flexion at ball release. Earlier, Pappas et al. (1985) used high-speed cameras to film 15 professional pitchers and reported that the wrist was in a neutral position at ball release and did not flex beyond the neutral position.

The lack of wrist and forearm data has limited the understanding of upper extremity mechanics during baseball pitching. The purpose of this study was to expand existing knowledge of baseball pitching by quantifying and comparing the kinematic data of the wrist and forearm during fastball, curveball, and change-up pitches. This information will provide clinicians, coaches, and researchers with a more complete understanding of the mechanics of baseball pitching and the differences between throwing different types of pitches.

**Methods**

Eight healthy male collegiate baseball pitchers volunteered to participate in the study. A subject was considered healthy if he was not injured or recovering from an injury at the time of testing and had not been injured within the previous 12 months. The subject group had a mean age of 20 ± 0.6 years, a mean mass of 83.4 ± 7.1 kg, and a mean height of 186.0 ± 5.0 cm. All subjects were tested 1 week prior to initiation of the competitive season. Two subjects were retested at the conclusion of the competitive season due to problems encountered during the first testing session that prevented a complete data collection. Preseason and postseason data for each retested subject were compared to ensure consistency of the data collected at the end of the season. Each subject signed an informed consent after being instructed about the study and given the opportunity to ask questions. Each subject was also given the opportunity to warm up sufficiently prior to testing.

Data collection and analyses consisted of a procedure similar to that used in previous work (Fleisig, Dillman, Escamilla, & Andrews, 1995; Fleisig et al., 1996), with modifications to obtain the motions of the wrist and forearm. Eight spherical (3.8 cm in diameter) reflective markers were used to identify anatomical landmarks for digitization. Markers were placed on the following locations: (a) lower extremity at the greater trochanter bilaterally; (b) lateral tip of the acromion bilaterally; (c) lateral epicondyle of the throwing arm; (d) both ends of a 24 cm rigid stick placed on the dorsal aspect of the throwing wrist with the midpoint centered between the radial and ulnar styloid processes; (e) on the head of the third metacarpal on the dorsal aspect of the throwing hand (Figure 1). The rigid stick was used to identify the radial and ulnar styloid processes, which was similar to a previous method (Sakurai et al., 1993) that used 30 cm sticks. Any potential problems due to inertial characteristics of the rigid stick were not addressed in the previous study. Different lengths were tested to optimize the separation of markers for digitizing and to minimize potential movement due to inertial characteristics. Based on our ability to digitize
pilot test data and the qualitative analysis of high-speed video data (1000 Hz) filmed with an Ektapro 1000 (Eastman Kodak Company, San Diego, CA), 24 cm was determined to be the optimal length. We determined that any potential effects would occur after ball release when the arm was decelerated. The stick was attached to the wrist with adhesive tape covering the width of the subject’s wrist to minimize potential movement. All testing was conducted in an indoor facility, with each subject throwing from an ATEC (Athletic Training Equipment Company, Sparks, NV) indoor pitching mound. The experimental setup is shown in Figure 2.

Five trials were collected for each of four pitch variations (fastball, curveball, change-up, slider) that the subject threw regularly in practice and competition. Additional trials were collected as needed until three strikes had been thrown. The order of pitch variation was randomized for each subject. Although data were collected on all four pitch variations, only three pitchers threw slider pitches, while all pitchers threw fastball, curveball, and change-up pitches. Therefore, only fastball, curveball, and change-up data were analyzed. All pitchers threw to a strike zone net located behind a home plate placed 18.44 m from the pitching rubber. There was a brief rest of approximately 60 s between pitches. A motion analysis three-dimensional (3-D) automatic digitizing system (Motion Analysis Corporation, Santa Rosa, CA) was used to digitize the location of the reflective markers. Four electronically synchronized 200 Hz CCD cameras transmitted pixel images of the reflective markers directly into a video processor without being recorded onto video. Three-dimensional marker locations were calculated with Motion Analysis Expertvision 3-D software utilizing direct linear transformation (DLT) (Abdel-Aziz & Karara, 1971).

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. The wires were positioned so that the markers made a matrix approximately 1.0 m × 0.9 m × 1.2 m in size suspended approximately 0.5 m above the ground, where the 1.0 m dimension was aligned with the direction of throwing. The matrix was designed to encompass the motion of the upper extremity of the throwing side. The root mean square error in calculation of three-dimensional marker location was found to be less than 1.0 cm (Fleisig et al., 1996). Ball velocity was recorded from a Jugs Tribar Sport radar gun (Jugs Pitching Machines Company, Tualatin, OR).

The positional 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 (Fleisig et al., 1996). 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).

Digitized locations for the throwing shoulder and elbow markers were translated to estimated joint center locations (Fleisig et al., 1996). Digitized locations of wrist and hand marker locations were mathematically translated to estimated centers for the wrist and head of the third metacarpal, utilizing the estimated elbow joint center location and anatomical measurements taken for each subject (see the appendix).

In each time frame, local reference frames were calculated at the shoulder, the elbow, the wrist, and the hand. The unit vectors in the elbow, wrist, and hand reference frames were calculated in the following sequence: $Z_S$ was a vector from the shoulder joint
center to the elbow joint center, \( Z_E \) was a vector from the throwing elbow joint center to the throwing wrist joint center, \( X_E \) was the cross-product of \( Z_E \) and \( Z_S \), \( Y_E \) was the cross-product of \( Z_E \) and \( X_E \), \( Z_W \) was a vector from the throwing elbow joint center to the throwing wrist joint center, \( Y_{\text{temp}} \) was a vector from the ulnar wrist marker to the radial wrist marker, \( X_W \) was the cross-product of \( Y_{\text{temp}} \) and \( Z_W \), \( Y_W \) was redetermined as the cross-product of \( Z_W \) and \( X_W \) and used for all remaining calculations, \( Z_H \) was a vector from the wrist joint center to the center of the third metacarpal head, \( X_H \) was the cross-product of \( Y_W \) and \( Z_H \), and \( Y_H \) was the cross-product of \( Z_H \) and \( X_H \). All reference frame vectors were normalized to unit length.

A computer program was written, using principles of vector algebra, to calculate kinematic parameters. Kinematic parameters included wrist flexion/extension, radial/ulnar deviation, and forearm pronation/supination (Figure 3). Flexion/extension was defined as the angle between wrist vector \( X_W \) and hand vector \( X_H \) in the plane defined by \( X_H \) and \( Z_H \). Radial/ulnar deviation was defined as the angle between \( Y_W \) and \( Y_H \) in the plane defined by \( Y_H \) and \( Z_H \). Forearm pronation/supination was defined as the angle between \( Y_W \) and \( Y_E \) in the plane defined by \( X_E \) and \( Y_E \). Linear and angular velocities and accelerations were determined with finite differences utilizing the five-point central difference method.

Data were analyzed relative to the arm-cocking, arm acceleration, and arm deceleration phases of the throwing motion as described in previous studies (Dillman et al., 1993; Fleisig et al., 1995, 1996). The definition of the arm-cocking phase was modified from previous descriptions. Previously, the arm-cocking phase was defined from the instant of foot contact until the time of maximum shoulder external rotation (MER). The instant of foot contact could not be determined with the current method, so an alternate event in the early cocking phase was identified. This event was determined from the calculation of shoulder external rotation and defined as the instant shoulder external rotation reached 90° (90ER). Dillman et al. (1993) showed that foot contact occurs just before the shoulder is externally rotated 90°. Qualitative assessment using additional high-speed videography confirmed this for the subjects in the present study.

The arm acceleration phase was defined from MER until the instant of ball release (REL). An automated method for determining REL for the fastball was demonstrated utilizing 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, REL for the fastball pitch was automatically determined to occur two video frames after the wrist passed the elbow in the global X direction (Wrist Pass). Since there was 0.005 s between consecutive video frames, REL during the fastball was therefore defined to have occurred between 0.01 and 0.015 s after Wrist Pass. Since this method has only been used previously for fastball pitches, we used qualitative video analyses to quantify the time from Wrist Pass to REL for each pitch variation.

For each subject, video data (1000 Hz) were collected with a Kodak Ektapro 1000 video camera (Eastman Kodak Company, San Diego, CA) from a position perpendicular to the sagittal plane of the pitcher’s motion. Using the high-speed video recording for each pitch variation thrown by each subject, we quantified the time from Wrist Pass to REL. Mean times from Wrist Pass to REL for the fastball, curveball, and change-up were 0.010 ± 0.001 s, 0.010 ± 0.001 s, and 0.012 ± 0.002 s, respectively. Since all these times were within the accuracy of the automated method used for the fastball, the automated method was used for all pitch types. Therefore, the REL for the fastball, curveball, and change-up was determined as the second frame after the wrist passed the elbow in the global X direction (i.e., between 0.010 s and 0.015 s after Wrist Pass). The arm deceleration phase was defined as the time from REL until the time of maximum shoulder internal rotation.
Figure 3 — Illustration of kinematic parameters and graphs of angular displacement data versus time during arm cocking from the instant of 90° shoulder external rotation (90ER) until maximum external rotation (MER), during arm acceleration from MER until ball release (REL), and during arm deceleration from REL until maximum internal rotation (MIR) for (a) wrist flexion/extension, (b) radial/ulnar deviation, and (c) pronation/supination. Data are time-matched at the time of 90ER and REL and averaged for fastball (●), curveball (○), and change-up (●) for all subjects.

(MIR). Kinematic and temporal parameters were analyzed relative to events that defined the beginning and end of these phases (Tables 1 and 2).

The three trials having the greatest pitch velocity and number of pitches thrown for strikes for each pitch variation were used for analysis. Differences among pitch types were analyzed with a repeated-measures analysis of variance method. To help control for Type I error resulting from multiple comparisons, only $p$ values <.01 were considered significant. Post hoc pairwise comparisons among pitch types were conducted using the Student–Newman–
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Keuls test with the \( p \) value <.05. Comparisons between types of pitches were (a) fastball (FA) versus curveball (CU), (b) FA versus change-up (CH), and (c) CU versus CH.

**Results**

**Arm-Cocking Phase**

Similar magnitudes and patterns were observed for the FA and CH throughout the arm-cocking phase, which is illustrated with the graph of average data for all subjects time-
Table 2  Differences (p < .01) Among Temporal Data (Seconds) for Kinematic Events Relative to Ball Release for Fastball (FA), Curveball (CU), and Change-Up (CH) Pitches

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FA</th>
<th></th>
<th>CU</th>
<th></th>
<th>CH</th>
<th></th>
<th>Sig. dif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90ER</td>
<td>-0.114</td>
<td>0.014</td>
<td>-0.124</td>
<td>0.017</td>
<td>-0.125</td>
<td>0.010</td>
<td>a,b</td>
</tr>
<tr>
<td>MER</td>
<td>-0.024</td>
<td>0.009</td>
<td>-0.028</td>
<td>0.009</td>
<td>-0.030</td>
<td>0.007</td>
<td>a,b</td>
</tr>
<tr>
<td>REL</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIR</td>
<td>0.055</td>
<td>0.022</td>
<td>0.056</td>
<td>0.028</td>
<td>0.058</td>
<td>0.007</td>
<td></td>
</tr>
<tr>
<td>Peak angles</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wrist extension</td>
<td>-0.038</td>
<td>0.031</td>
<td>-0.050</td>
<td>0.058</td>
<td>-0.059</td>
<td>0.046</td>
<td></td>
</tr>
<tr>
<td>Radial deviation</td>
<td>-0.058</td>
<td>0.040</td>
<td>-0.053</td>
<td>0.044</td>
<td>-0.060</td>
<td>0.051</td>
<td></td>
</tr>
<tr>
<td>Forearm supination</td>
<td>-0.041</td>
<td>0.047</td>
<td>-0.036</td>
<td>0.049</td>
<td>-0.045</td>
<td>0.043</td>
<td></td>
</tr>
<tr>
<td>Wrist flexion</td>
<td>0.022</td>
<td>0.017</td>
<td>0.023</td>
<td>0.039</td>
<td>0.021</td>
<td>0.016</td>
<td></td>
</tr>
<tr>
<td>Ulnar deviation</td>
<td>0.021</td>
<td>0.024</td>
<td>0.013</td>
<td>0.038</td>
<td>0.015</td>
<td>0.022</td>
<td></td>
</tr>
<tr>
<td>Forearm pronation</td>
<td>0.038</td>
<td>0.017</td>
<td>0.028</td>
<td>0.019</td>
<td>0.039</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>Peak angular velocity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wrist flexion</td>
<td>0.003</td>
<td>0.014</td>
<td>-0.006</td>
<td>0.005</td>
<td>-0.002</td>
<td>0.010</td>
<td></td>
</tr>
<tr>
<td>Ulnar deviation</td>
<td>0.005</td>
<td>0.021</td>
<td>0.001</td>
<td>0.040</td>
<td>0.000</td>
<td>0.028</td>
<td></td>
</tr>
<tr>
<td>Forearm pronation</td>
<td>0.017</td>
<td>0.011</td>
<td>0.021</td>
<td>0.004</td>
<td>0.022</td>
<td>0.007</td>
<td></td>
</tr>
</tbody>
</table>

Significant differences (p < .05) between (a) FA vs. CU, (b) FA vs. CH, (c) CU vs. CH.

matched at 90ER and REL (Figures 3 and 4). Although the wrist was extended and radially deviated for all pitch types from the instant of 90ER to MER (Table 1), at the instant of 90ER, the CH and FA pitches had significantly greater wrist extension compared to the CU. Peak wrist extension for the CU pitch was 33% less than during the CH and 24% less than during the FA. Throughout arm cocking, the forearm was supinated for the CU, while the forearm changed from pronation to supination during the last third of arm cocking for the FA and CH. Peak supination for the CU was 88% greater than for the FA and 78% greater than for the CH. Just before the end of arm cocking, supination was initiated for each pitch type (Figure 3). The timing of peak angle values was not significantly different during arm cocking (Table 2); however, the instant of 90ER occurred significantly later in the phase (closer to REL) during the FA compared to the CU and CH. Similarly, the instant of MER occurred significantly closer to REL for the FA compared to the CU and CH, although the duration of the arm-cocking phase was less for the FA group.

Arm Acceleration Phase

Consistent with the arm-cocking phase, similar magnitudes and patterns were observed for the FA and CH throughout the arm acceleration phase (Figures 2 and 3). The only parameter found to have a significant difference between the FA and CH was ball velocity. Although similar patterns were observed for the CU compared to the FA and CH, the
magnitudes for the CU were noticeably different, including the large amount of ulnar deviation that occurred during the acceleration phase (Figure 3b). During the CU pitch, rapid ulnar deviation occurred simultaneously with wrist flexion while the forearm was in a more supinated position.

Peak wrist flexion velocities reached 2,600 to 3,000°/s for all pitch variations, while peak ulnar deviation velocities ranged between 1,800 and 2,200°/s (Table 1). The average time of peak wrist flexion velocity during the FA pitch occurred just after (0.003 s) REL; this was later than for the CU pitch, which occurred just prior (–0.006 s) to REL (Table 2).

For all pitch types, the forearm pronated throughout the majority of the acceleration phase (Figure 3). During the FA and CH pitches, the forearm pronated from a neutral position until a peak occurred before REL. The forearm pronated from a supinated posi-
tion at MER to a pronated position at REL for the CU pitch. At REL, a significantly greater amount of forearm pronation occurred during the FA and CH compared to the CU.

During this phase, the wrist continuously flexed from an extended and radially deviated position to a neutral or slightly flexed and ulnar-deviated position (Figure 3). Wrist flexion at REL was greater for the CU compared to the FA and CH. The greatest ball velocity occurred for the FA, and the lowest velocity occurred during the CU (Table 1). Significant differences were found among all pitch comparisons.

**Arm Deceleration Phase**

During the deceleration phase, high radial deviation and forearm pronation velocities occurred (Table 1). A radial deviation velocity of 1,500 to 2,300°/s was reached for all pitch types. Peak radial deviation velocity during the CU was 29% greater than for the FA and 54% greater than for the CH. Rapid radial deviation occurred during the CU as the wrist returned to a radial/ulnar position similar to the FA and CH (Figure 3b). After REL, the forearm briefly supinated and then continued to pronate for all pitches (Figure 3c), reaching a maximum value approximately halfway through this phase. The pattern was similar for all pitches although the magnitudes were different. Peak pronation velocities reached over 4,000°/s for all pitch variations. The time of peak pronation velocity occurred significantly earlier in the deceleration phase for the FA compared to the CU and CH (Table 2).

**Discussion**

Significant differences were found for each pitch comparison, although the greatest number of differences occurred between the CU pitch and the FA and CH pitches, while comparisons between the FA and CH pitches produced the least number of differences. The differences between wrist flexion/extension and forearm pronation/supination for each pitch type were noted at the start of the arm-cocking phase (90ER) and continued throughout the motion. Sakurai et al. (1993) found similar differences between the FA and CU pitches for wrist extension (34%) and forearm supination (110%), which, along with ball velocity, were the only statistical differences found in that study (Table 3).

The similarities between the FA and CH pitches are consistent with instructional techniques that emphasize throwing the CH in the same manner as the FA with a modified grip (McFarland, 1990). Previous kinematic comparisons of different pitches found similarities between the FA and CU pitches (Escamilla et al., 1998; Sakurai et al., 1993) and differences between the FA and CH pitches (Escamilla et al., 1998). However, the comparison by Escamilla et al. presented kinematics of the legs, trunk, shoulder, and elbow, and wrist and forearm data were not included. Differences between pitches appear to depend on the segment of the body studied. The CH and FA pitches appear to have kinematic differences at the shoulder and elbow but similarities at the wrist and forearm. The CU and FA pitches appear to have kinematic similarities at the shoulder and elbow but differences at the wrist and forearm. Instructional methods also emphasize throwing the CU with FA mechanics while altering forearm and wrist position (House, 1994; McFarland, 1990). McFarland emphasized maintaining consistent mechanics until the release point, where different mechanics are employed. House emphasized using fastball mechanics after establishing wrist and forearm position before the instant of foot contact. The current data appear to agree with the latter report, as kinematic differences between pitches were established by the instant of 90ER and remained consistent throughout the phase.

At the end of the arm-cocking phase, pronation was initiated for each pitch type (Figure 3). At this point in the phase, medial force and varus torque about the elbow reach
Table 3  Comparisons Among Mean (SD) Kinematic Data for Fastball and Curveball Pitches

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fastball</th>
<th>Curveball</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current</td>
<td>Elliott&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Arm cocking phase</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak angles (°)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wrist extension</td>
<td>41 (8)</td>
<td>42 (7)</td>
</tr>
<tr>
<td>timing&lt;sup&gt;e&lt;/sup&gt;</td>
<td>−0.038 (0.031)</td>
<td>−0.039 (0.011)</td>
</tr>
<tr>
<td>Radial deviation</td>
<td>15 (9)</td>
<td>19(9)</td>
</tr>
<tr>
<td>Forearm supination</td>
<td>17 (13)</td>
<td>19(9)</td>
</tr>
<tr>
<td>timing&lt;sup&gt;e&lt;/sup&gt;</td>
<td>−0.041 (0.047)</td>
<td>−0.076 (0.046)</td>
</tr>
<tr>
<td>Arm acceleration phase</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak angular velocity (°/s)</td>
<td>2,954 (789)</td>
<td>225</td>
</tr>
<tr>
<td>Wrist flexion</td>
<td>3 (11)</td>
<td>−2</td>
</tr>
<tr>
<td>Ulnar deviation</td>
<td>19 (15)</td>
<td>19 (9)</td>
</tr>
<tr>
<td>Forearm pronation</td>
<td>24 (17)</td>
<td>14 (14)</td>
</tr>
<tr>
<td>Ball velocity (m/s)</td>
<td>34 (2)</td>
<td>35 (2)</td>
</tr>
</tbody>
</table>

<sup>a</sup>Data from Elliott et al. (1986); <sup>b</sup>data from Sakurai et al. (1993); <sup>c</sup>data from Vaughan (1985); <sup>d</sup>data from Pappas et al. (1995).
<sup>e</sup>Timing relative to REL = 0.00.
a peak magnitude (Fleisig et al., 1995). Large elbow medial forces and varus torques are needed to resist valgus stress at the elbow as the radial head and capitellum compress laterally, tension occurs medially in the ulnar collateral ligament (UCL) and the flexor–pronator muscle mass of the forearm, and the olecranon wedges up against the medial wall of the olecranon fossa (Andrews, 1993; Fleisig et al., 1995; Werner et al., 1993; Wilson, 1983). These forces and torques are believed to contribute to various elbow injuries (Fleisig et al., 1995; Wilson, 1983). Fleisig et al. (1998) compared the kinetics of throwing different pitches and determined that peak elbow medial forces and varus torques were 15–20% greater in the FA and CU compared to the CH. The loads created by the CU were not statistically different than those created by the FA pitch. Based on the results from this study, any increased potential for elbow problems with the CU pitch may be related to the position of the forearm at the time of the peak loads. The greater amount of supination during the CU pitch may influence the ability of the elbow to accommodate the repetitive load; however, the different forearm positions do not appear to alter the electromyographic activity of muscles about the elbow. Sisto, Jobe, and Moynes et al. (1987) analyzed the dynamic electromyography of muscles about the elbow while subjects threw the FA and CU and found no significant difference throughout the motion.

The wrist flexion velocities calculated in the current study were high, although Vaughn (1985) found slightly greater wrist flexion velocities at 3,300°/s. The ball velocities for the FA and CU pitches were similar to velocities determined by Sakurai et al. (1993), although the duration of the acceleration phases determined by Sakurai et al. (1993) was longer than the current study. Sakurai et al. determined that MER occurred 0.035 s before REL for the FA and CU pitches, while in the current study MER occurred closer to REL for both the FA (0.024 s) and CU (0.028 s) pitches (Table 2). These discrepancies may be due to the methods of determining REL, although Sakurai et al. did not report their specific method of determining REL. These discrepancies may also be attributed to varying pitching techniques for the study populations.

During the CU pitch, rapid ulnar deviation occurred simultaneously with wrist flexion while the forearm was in a more supinated position. This movement may illustrate the objective of teaching methods for the CU that describe the motion as snapping the wrist or twisting the hand with the fingers pulling downward over the top of the ball to impart an eccentric force and create forward spin of the ball (Kindall, 1993; McFarland, 1990). Stevenson (1985) showed that subjects used a thumb–middle-finger–index-finger or a middle-finger–thumb–index-finger release sequence when throwing the CU. As described by House (1994), the supinated position of the forearm would enable the pitcher to impart an eccentric force on the ball to create the forward rotation. Greater ulnar deviation velocity for the CU pitch was evident from graphical data (Figure 4b), although a significant difference was not found. Wrist position at REL reported in this study differed from the values reported by Sakurai et al. (1993) and Pappas et al. (1995) (Table 3). Sakurai et al. determined that the wrist was in an extended position for the FA (−19°) and CU (−18°) pitches at REL, and Pappas et al. determined that the wrist was in a flexed position for FA (27°). Vaughn (1985) and Elliott et al. (1986) concluded, as was concluded in the current study, that the wrist was in a neutral or slightly flexed position. These discrepancies may be attributed to filming methods used in various studies. Sakurai et al. used a two-camera system, whereas Vaughn and Elliott used a three-camera system, and a four-camera system was used in the current study. A two-camera system limits the ability to view the entire motion; therefore, the location of the cameras may have influenced Sakurai et al.’s ability to analyze wrist kinematics at release. Sakurai et al. indicated that camera positions were selected to view upper limb movement before ball release and they located two
cameras behind the pitcher. Camera locations for the studies by Elliott et al. and Vaughan and for this study included a sagittal view that would improve the ability to analyze wrist kinematics at ball release. The previous studies included analyses of the upper extremity or entire body, while in the current study we focused on the forearm and wrist. The small size of the wrist joint and the large path traveled by the wrist during the throwing motion cause difficulties when the objective is to analyze the entire body as well. Discrepancies may also be attributed to variations in angular calculation methods. Sakurai used calculations based on vectors determined from marker locations, while in this study we used calculations based on vectors determined from joint center locations estimated from marker locations. Elliott and Vaughan utilized calculations determined from digitized joint locations.

As discussed by Atwater (1979), forearm pronation after ball release appears to be a natural method of decelerating the arm; however, a brief forearm supination occurred just after release, which could not be explained. Based on qualitative analysis of high-speed video data (1000 Hz), the calculated forearm motion did not appear to be caused by the independent movement of the rigid stick. However, the influence of the rigid implement on the calculated forearm movement appeared to affect the time of MIR at the end of the deceleration phase. The greatest variability in pronation data occurred during the deceleration phase. The previous authors who used a similar method (Sakurai et al., 1993) did not publish velocity data or any displacement data after REL, which therefore does not allow for comparison. Based on the variability of pronation/supination data during the deceleration phase and the lack of comparative data, the results for forearm pronation/supination from this phase should be interpreted with caution.

Effective pitching mechanics are often based on minimizing visible distinguishing characteristics among pitches. It is difficult to determine whether the kinematic differences observed in this study can be identified by the hitter or other positional players during the pitching motion. Therefore, this information may be more beneficial to clinicians, coaches, and researchers in understanding the mechanics of the wrist and forearm and the differences created by different types of pitches. However, caution should be used in interpreting this data relative to the cause and prevention of injuries associated with throwing different types of pitches. Additional studies are needed to quantify kinetic parameters for the forearm and wrist and to analyze pitchers at different skill levels (e.g., high school and professional).

References


Appendix: Calculation of Wrist and Hand (Metacarpal) Joint Centers

A method was developed for determining the wrist and hand (third metacarpal) joint centers based upon the location of surface markers. This method was based on a procedure previously used to calculate shoulder and elbow joint center locations (Fleisig et al., 1996). Using joint centers determined with the previous method, we determined wrist and metacarpal joint centers with vector algebra and took anatomical measurements from each subject prior to the test. Measurements were wrist height at the distal end of the forearm at the styloid processes where the rigid stick was placed, and hand height at the head of the third metacarpal where the hand marker was placed.

The wrist joint center ($C_w$) was determined from the known center of the rigid stick markers ($C_s$), the elbow joint center ($C_e$), and the anatomical and rigid stick measurements ($A$) (Figure 5). The stick markers were used to determine the orientation of $Y_w$ of a local reference frame established at the wrist. The locations of $C_e$ and $C_s$ in the global reference frame were used to determine vector $P_w$ (Equation 1). The orientation of $Z_w$ was
determined by rotating the vector $P_w$ about the $Y_w$ axis a calculated angle of rotation ($Q_w$) (Equations 2 and 3).

\[ P_w = \dot{O}C_s - \dot{O}C_E \]  
\[ Q_w = \arcsin \left( \frac{A}{|P_w|} \right) \]  
\[ Z_w = R(Q_w)_y \left( \frac{\dot{V}_w}{|\dot{V}_w|} \right) \]

where

\[
R(Q_w)_y = \begin{bmatrix}
\cos Q_w & 0 & -\sin Q_w \\
0 & 1 & 0 \\
\sin Q_w & 0 & \cos Q_w
\end{bmatrix}
\]

The location of $C_w$ could be determined from the location of $C_E$ and a calculated distance on the $Z_w$ axis (Equation 4). Substituting Equation 3 into Equation 4, the location of $C_w$ could be determined with the location of $C_E$ and vector $P_w$ (Equation 5).

\[ \dot{O}C_w = \dot{O}C_E + |\dot{P}_w| \cos Q_w \left( \frac{\dot{V}_w}{|\dot{V}_w|} \right) \]  
\[ \ddot{O}C_w = \ddot{O}C_E + \cos Q_w \left( R(Q_w)_y \right) \ddot{P}_w \]
Similarly, the center of the head of the third metacarpal (C_H) was determined from known locations of the hand marker (C_B), C_W, and anatomical and marker measurements (B) (Figure 6). The axis of rotation (Y_H) of the local reference frame at the hand was determined with Y_W and P_H (Equations 6 and 7).

\[
\mathbf{X_H} = \hat{\mathbf{Y_W}} \times \mathbf{P_H} \quad (6)
\]

\[
\mathbf{Y_H} = \hat{\mathbf{P_H}} \times \mathbf{X_H} \quad (7)
\]

The orientation of Z_H was determined by rotating the vector P_H about the Y_H axis a calculated angle of rotation (\(\Theta_H\)). Similar to the method used to determine C_W (Equation 5), the location of C_H was determined with C_W and vector P_H (Equation 8).

\[
\mathbf{OC_H} = \mathbf{OC_W} + \cos \Theta_H \left[ \mathbf{R}(\Theta_H) \right] \mathbf{P_H} \quad (8)
\]

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