Biomechanics of the Elbow during Baseball Pitching

Sherry L. Werner, MS[1]
Glenn S. Fleisig, MS[2]
Charles J. Dillman, PhD[3]
James R. Andrews, MD[4]

By understanding pitching biomechanics, therapists can develop better preventive and rehabilitative programs for pitchers. The purpose of this study was to quantify and explain the joint motions, loads, and muscle activity that occur at the elbow during baseball pitching. Seven healthy, adult pitchers were examined with synchronized high-speed video digitization and surface electromyography. Elbow extension before ball release corresponded with a decrease in biceps activity and an increase in triceps activity. A varus torque of 120 Nm, acting to resist valgus stress, occurred near the time of maximum shoulder external rotation. Previous cadaveric research showed that the ulnar collateral ligament by itself cannot withstand a valgus load of this magnitude. Triceps, wrist flexor-pronator, and anconeus activity during peak valgus stress suggests that these muscles may act as dynamic stabilizers to assist the ulnar collateral ligament in preventing valgus extension overload.

Key Words: *biomechanics, elbow, baseball pitchers*

Arm motion in throwing is extremely violent. Perhaps no throw is more dynamic than baseball pitching, and, as a result, there is a high incidence of elbow injuries in pitchers (3, 7, 10–12). If better preventive and rehabilitative programs are to be developed, it is important to understand the biomechanics of the pitching motion. The purpose of this study is to quantify the joint kinematics (ie., ranges of motion and joint velocities), joint kinetics (ie., joint forces and torques), and muscle activity about the elbow and explain the relevance of these results for injury prevention and rehabilitation. Previous studies have reported either joint kinetics (4, 6) or muscle activity (3, 8, 10), but this study represents the first effort to simultaneously quantify and correlate both.

METHODS

Testing Procedure

Seven healthy college and minor league pitchers were tested in an indoor biomechanics laboratory. The pitchers had an average height of 1.8 m and an average mass of 89.7 kg. Each athlete pitched from an indoor mound (Athletic Training Equipment Company, Santa Cruz, CA) to a strike zone ribbon suspended over a home plate located the proper regulation distance from the mound (18.44 m). After each athlete took as many warm-up throws as desired, he threw seven pitches for data collection. The mean ball velocity for the seven subjects was 36.4 m/sec.

Instrumentation

Two synchronized 500 frames/second cameras (Motion Analysis Systems Division, Eastman Kodak Company, San Diego, CA) captured video data for each pitch. Video data from the fastest pitch thrown by each pitcher into the strike zone were manually digitized to determine three-dimensional motion (Peak Performance Technologies, Inc., Englewood, CO).

Surface electromyographic (EMG) activity of the biceps, triceps, wrist flexor-pronator group, wrist extensor group, and anconeus were collected using a telemetry system (Transkinetics, Canton, MA). Initiation of EMG collection illuminated an LED in the view of the high-speed cameras in order to synchronize EMG and video data.

Kinematics

Kinematic parameters—position, velocity, and acceleration—were calculated for both the shoulder and elbow joints. Elbow flexion was meas-

---

[1] Graduate Assistant, Biomechanics Lab, Penn State University, University Park, PA. Ms. Werner was a biomechanist at the American Sports Medicine Institute when this study was conducted.
[2] Director of Research, American Sports Medicine Institute, 1313 Thirteenth Street South, Birmingham, AL 35205
[3] Executive Director, Steadman Sports Medicine Foundation, Vail, CO. Dr. Dillman was Director of Research at the American Sports Medicine Institute when this study was conducted
[4] Medical Director and Chairman of the Board, American Sports Medicine Institute, Birmingham, AL

ured as the angle formed between a vector from the shoulder to the elbow (ie., the upper arm) and a vector from the elbow to the wrist (ie., the forearm). If the arm was fully extended and the forearm was in line with the upper arm, for instance, elbow flexion would be 0°.

Another kinematic parameter which is important for understanding elbow biomechanics is internal/external rotation of the shoulder. Shoulder rotation was measured as the rotation of the forearm in the sagittal plane. Internal and external rotation were defined consistent with medical standards. A pitcher standing upright with his arm abducted 90° and flexed 90° at the elbow would, therefore, have 0° of rotation when his forearm pointed anteriorly and 90° of external rotation when his forearm pointed superiorly.

Kinetics

Kinetic parameters—those that describe forces and torques—were estimated using methods described by Feltner and Dapena (4, 5). In this method, joint loads (ie., forces and torque) were calculated using accelerations from motion analysis data and estimated body segment masses and inertias from cadaveric literature (1, 2). Results were presented as loads applied by the proximal segment onto the distal segment.

For the elbow, loads were, therefore, presented as the forces and torques applied by the upper arm to the forearm. Compression force at the elbow represented the force needed to be applied to prevent the forearm from distracting out of the elbow joint. If the forearm tried to distract in the distal direction, the upper arm would need to apply a compression force to the forearm in the proximal direction.

Varus torque was measured as the torque needed to prevent the forearm from rotating in the valgus direction. If the forearm tried to rotate into valgus, the upper arm would need to apply a varus torque to the forearm to prevent valgus extension.

Flexion and extension torque were measured as the torque applied to the forearm by the upper arm in the flexion/extension plane of motion. If the torque was applied in the same direction that the arm was moving, then it was a concentric torque. If the torque was applied in the opposite direction of the arm's motion, then it was resisting the motion and was an eccentric torque.

Electromyography

A pair of surface electrodes were placed approximately 1.25 cm apart on each muscle tested. Skin preparation was monitored with a Checktrode electrode tester (UFI, Morro Bay, CA), and impedance values of 10,000 ohms or below were accepted. The EMG data were conditioned with a 60-Hz, high-pass digital filter and then rectified. For each subject, the EMG data for the three trials with the highest ball velocities were averaged.

There is a high incidence of elbow injuries in baseball pitchers.

RESULTS

Kinematics

Figure 1 shows a sequence of the motions during the pitch. Mean kinematic, kinetic, and EMG results from the time the front foot contacts the mound (Figure 1F) until after the ball is released are shown in Figure 2. The moments of maximum external rotation (Figure 1H) and ball release (Figure 1I) are indicated on Figure 2 as "MER" and "REL," respectively. Elbow flexion remained nearly constant until shortly before MER. The elbow then extended from 85 to 20° near the time of ball release. These results are almost identical to the results reported by Feltner and Dapena (89 to 20°) (4). The rapid downward slope of the elbow flexion curve shown in Figure 2A just prior to REL correlated to a maximum elbow extension velocity of approximately 2300°/sec. Similarly, Feltner and Dapena reported a maximum elbow extension velocity of 2200°/sec (4).

External rotation reached a maximum value of 185°. Feltner and Dapena reported a maximum external rotation of only 80° but used a different definition for external rotation (4). By the standard rotation definition as defined in this study, Feltner and Dapena's result correlated to 170°.

Kinetics

A compression force, acting to resist distraction at the elbow, gradually increased from the time of front foot contact until near the time of ball release (Figure 2B). The maximum compression force was 780 N. This graph is almost identical in magnitude and shape to results of previous studies (4).

Extension/flexion and varus/valgus torque are shown in Figure 2C. Extension torque increased until it reached a maximum value of 40 Nm near the time the elbow began to extend. After release, a maximum flexion torque of 55 Nm occurred. Feltner and Dapena reported similar torque patterns but of slightly lesser magnitude (4). Varus torque increased until a peak value of 120 Nm before MER was reached, which was similar to previously reported results of 100 Nm (4). A peak valgus torque of 40 Nm occurred shortly after REL.

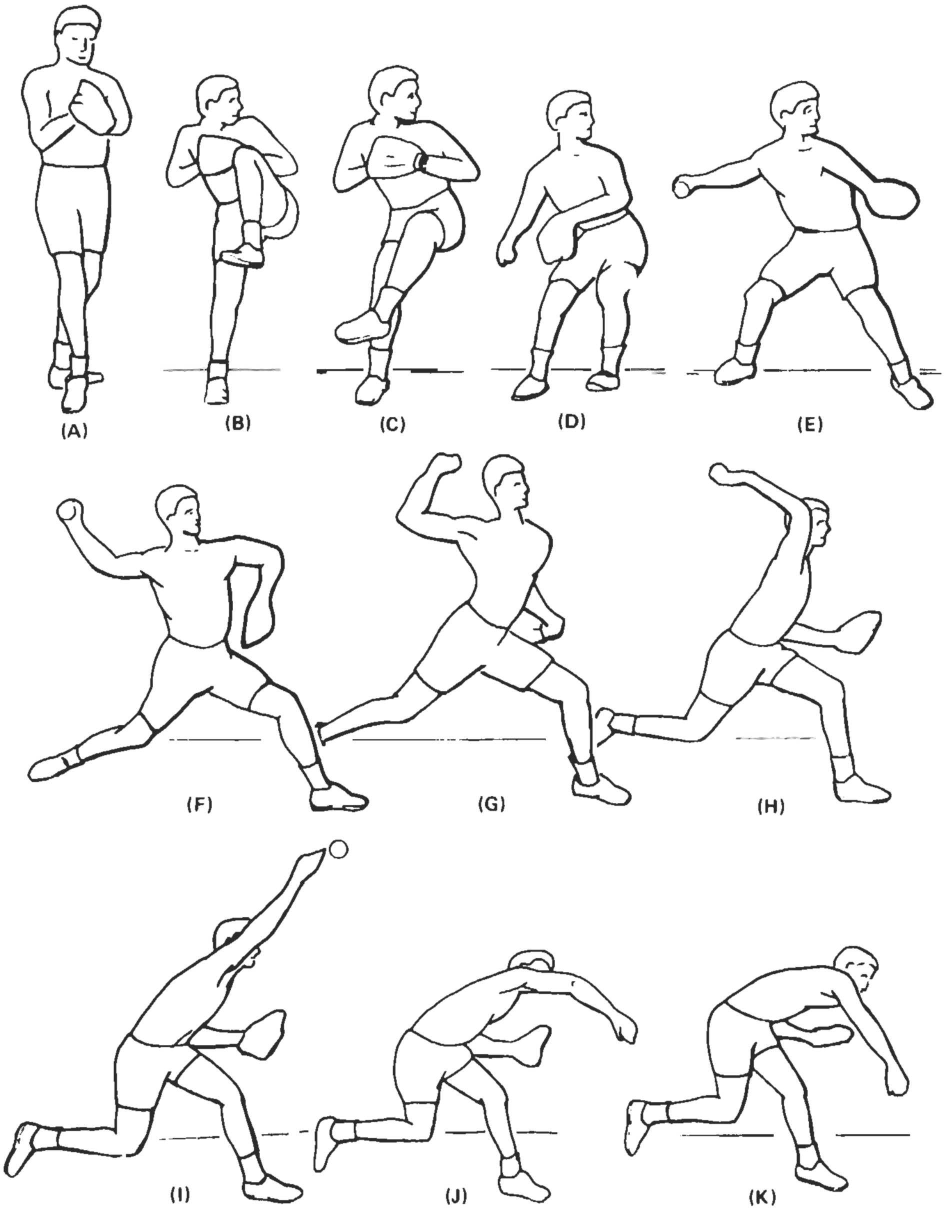

FIGURE 1. *Sequence of positions during the baseball pitch.*

Electromyography

The biceps muscle actively fired until the onset of elbow extension (Figures 2A and 2D). The biceps was also active after REL. The triceps muscle was active during elbow extension. Indwelling EMG research has shown similar activity and also showed the presence of minimal biceps activity during the time of elbow extension (3).

The wrist flexor-pronator group showed muscle activity throughout the pitch, with maximum activity before MER. This is consistent with results from one indwelling EMG study (10), while another study showed maximum activity between MER and REL (3). The wrist extensor group showed some activity before MER and maximum activity after REL. Previous studies found wrist extensor activity throughout the pitch (3, 10).

Anconeus activity was found throughout the pitch. The highest level of activity occurred immediately after MER.

DISCUSSION

The Six Phases of Pitching

In order to better understand the biomechanics of the elbow during pitching, it is helpful to divide the pitch into phases (3, 6–8, 10). The pitch can be broken down into six phases: wind-up, stride, arm cocking, arm acceleration, arm deceleration, and follow-through. A description of the biomechanics of the elbow during each phase is provided below.

Wind-up

In the wind-up phase, the pitcher put himself in a good starting position (Figures 1A–1C). Wind-up ended as the throwing hand left the glove and the front leg strided towards home plate. Minimal elbow kinematics and kinetics were present during this phase (4).

Stride

The stride phase began as the hands separated and ended when the front foot contacted the mound (Figures 1C–1F). The elbow reached 85° of flexion near the time of foot contact.

Arm Cocking

The arm cocking phase began when the front foot contacted the mound and ended when the arm was in maximum external rotation (Figures 1F–1H). "Arm" cocking was an accurate term, because only the arm was cocked during this entire phase. Some parts of the body, such as the hips and legs, actually accelerated or decelerated during this phase.

To stop the arm from externally rotating too far, an eccentric internal rotation torque was needed (7). As the arm rotated back, a varus torque (Figure 2C) to prevent valgus extension was needed. The ulnar collateral ligament (UCL) is believed to contribute to this varus torque, but

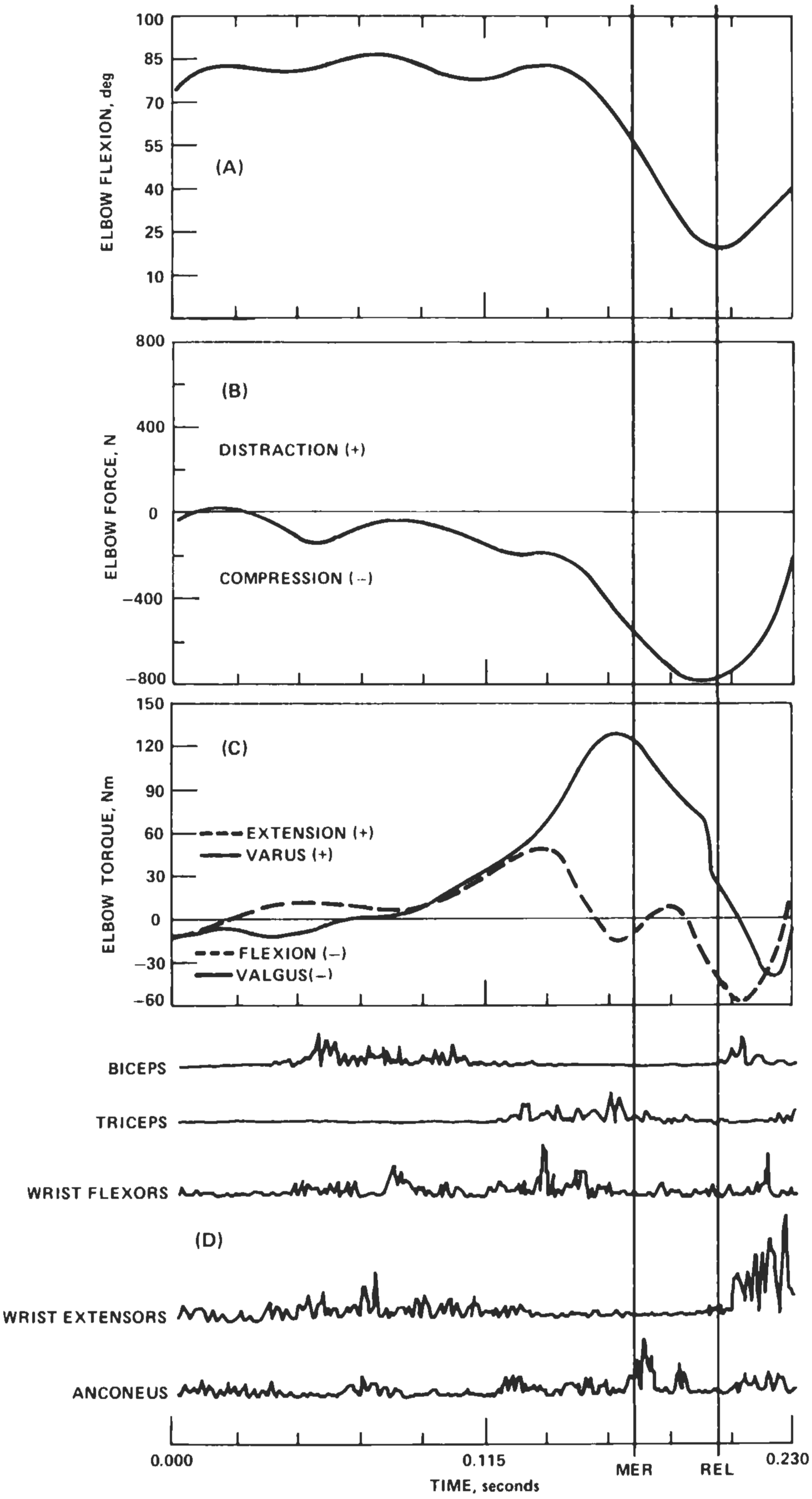

FIGURE 2. *Time-matched measurements during the baseball pitch: (a) elbow flexion, (b) force applied at the elbow, (c) torque applied at the elbow, and (d) EMG muscle activity.*

preliminary cadaver work indicated that the UCL is not strong enough to withstand this torque by itself (11). Contraction of the wrist flexor-pronator group (Figure 2D), which originates on the medial epicondyle, also provided varus torque. The anconeus and triceps were active during this phase as well (Figure 2D) and may have helped in minimizing the stress seen on the UCL by compressing the joint and adding stability.

Shortly before the arm reached MER, the arm began to extend at the elbow (Figure 2A) (4, 7). To extend the elbow, the triceps muscle applied some extension torque to the forearm (Figures 2C and 2D). This muscle activity and resulting extension torque, however, were not large enough to produce the high elbow angular velocity seen. Perhaps more important than the increase in triceps activity for generation of elbow extension velocity was the decrease in biceps activity (Figure 2D). After front foot contact, the shoulders rotated to face the batter (Figures 1F–1H). Centrifugal force generated by this shoulder rotation tried to swing the forearm's mass away from the body by extending the elbow. Contraction of the biceps during initial shoulder rotation prevented elbow extension. Decrease of biceps activity shortly before MER allowed centrifugal force to contribute to rapid elbow extension.

A study by Dobbins (reported by Roberts) showed that a pitcher with a paralyzed triceps due to a differential nerve block was able to throw a ball over 80% of the speed attained prior to paralyzation (9). This seems to support the concept that triceps contraction does not generate all of the elbow extension velocity seen in pitching.

Arm Acceleration

The arm acceleration phase was the short, dynamic time from MER to REL (Figures 1H–1I). As the elbow continued to extend, the forearm swung out to the side of the pitcher. Centrifugal force tried to distract the forearm out of the elbow joint, but a compression force was applied to maintain elbow integrity (Figure 2B). Triceps, wrist flexor-pronator, and anconeus activity during this phase, seen in Figure 2D, may have applied some of the compression force.

Arm Deceleration

The arm deceleration phase began with ball release and ended when the arm reached its maximum internal rotation (Figures 1I–1J). In this phase, the rapidly moving arm was decelerated. In particular, the elbow was decelerated with a flexion torque before full extension was reached (Figures 2A and 2C). Eccentric contraction of the biceps, a primary elbow flexor, was seen at this time (Figure 2D).

> ***Joint loads (ie., forces and torque) were calculated using accelerations from motion analysis data and estimated body segment masses and inertias from cadaveric literature.***

Activity of the triceps muscles, as well as activity of the anconeus and wrist flexor muscles, helped the joint's ligaments apply a compression force during this phase in order to stabilize the elbow and prevent elbow distraction (Figures 2B and 2D). Compression force needed was quite large, reaching a peak of 90% of body-weight. The wrist extensor group was also quite active during this phase, primarily to eccentrically decelerate wrist flexion (Figure 2D).

Follow-Through

The follow-through phase began when the arm reached maximum internal rotation and ended when the pitcher attained a balanced fielding position (Figures 1J–1K). Motion of the larger body parts, such as the trunk and legs, helped dissipate energy in the throwing arm during this phase (7).

CONCLUSIONS

In this study, the biomechanics of the elbow during pitching were presented and explained. The four primary functions of the elbow during pitching were as follows:

1) The wrist flexor-pronator group and other muscles helped the UCL generate a varus torque on the medial side of the elbow during arm cocking.
2) Increase in triceps activity, decrease in biceps activity, and centrifugal force due to rotation of the shoulders generated a large elbow extension angular velocity needed to help accelerate the ball.
3) A large eccentric elbow flexion torque was needed to decelerate the elbow before full extension could be reached.
4) Contraction of all muscles tested after ball release helped the elbow ligaments apply a large compression force to prevent distraction.

The ability to pitch effectively requires proper mechanics. Improper mechanics may lead to a decrease in performance or an increase in the risk of injury. Sufficient muscle strength and stamina are also critical in reducing the chance of injury. An understanding of the speeds and ranges of motion that are present in the pitching motion is necessary in the design and evaluation of optimal training and rehabilitation exercises. JOSPT

REFERENCES

1. Clauser CE, McConville JT, Young JW: Weight, volume, and center of mass of segments of the human body. AMRL-TR-69-70, Wright-Patterson Air Force Base, 1969
2. Dempster WT: Space requirements of the seated operator. WADC-TR-55-159, Wright Patterson Air Force Base, 1955
3. DiGiovine NM, Jobe FW, Pink M, Perry J: An electromyographic analysis of the upper extremity in pitching. J Shoulder Elbow Surg 1:15–25, 1992
4. Feltner M, Dapena J: Dynamics of the shoulder and elbow joints of the throwing arm during a baseball pitch. Int J Sport Biomechan 2:235–259, 1986
5. Feltner ME, Dapena J: Three-dimensional interactions in a two-segment kinetic chain. Part I: General model. Int J Sport Biomechan 5:403–419, 1989
6. Feltner ME: Three-dimensional interactions in a two-segment kinetic chain. Part II: Application to the throwing arm in baseball pitching. Int J Sport Biomechan 5:420–450, 1989
7. Fleisig GS, Dillman CJ, Andrews JR: Proper mechanics for baseball pitching. Clin Sports Med 1:151–170, 1989
8. Moynes DR, Perry J, Antonelli DJ, Jobe FW: Electromyography and motion analysis of the upper extremity in sports. Phys Ther 66:1905–1911, 1986
9. Roberts EM: Cinematography in biomechanical investigation. In: Cooper JM (ed), Selected Topics in Biomechanical Investigation. Proceedings of the C.I.C. Symposium on Biomechanics, pp 71–81. Chicago: The Athletic Institute, 1971
10. Sisto DJ, Jobe FW, Moynes DR, Antonelli DJ: An electromyographic analysis of the elbow in pitching. Am J Sports Med 15(3):260–263, 1987
11. Smutz WP, Dillman CJ, France EP, Werner SL, Andrews JR, Kupferman SP, Pavlatos CJ: Valgus extension overload injuries in pitching. Unpublished report. Orthopaedic Biomechanics Institute, Salt Lake City, UT, and American Sports Medicine Institute, Birmingham, AL, 1990
12. Wilson FD, Andrews JR, Blackburn TA, McCluskey G: Valgus extension overload in the pitching elbow. Am J Sports Med 11(2):83–88, 1983