BIOMECHANICS OF PITCHING

K. R. Campbell

The Bennett Institute for Sports Medicine
Of The Children's Hospital
Baltimore, Maryland, USA

INTRODUCTION

Baseball pitching is a complicated movement involving a series of body motions ultimately designed to propel the ball at a high velocity to a specified target. The demand for high velocity and the repetitive nature of pitching, pitchers often throw in excess of 100 pitches over the course of a game, imposes large loads on the musculoskeletal system and increases the likelihood of injury.

It has been suggested that proper pitching technique is of the utmost importance for avoiding injury (Middleton, 1990). Because of the relation between throwing mechanics and injury, there has been a strong medical interest in pitching and injury mechanisms. George Bennett, a professor of orthopedics and former semi-professional baseball player, was one of the first to academically investigate baseball injuries (Bennett, 1941). Several authors have subsequently described pathologies prevalent in pitchers. Andrews et al. (1985) discussed elbow injuries and glenoid labral tears in pitchers. Young pitchers, overly enthusiastic, increase the frequency of throwing and the forces involved, often without adequate supervision or instruction. Improper techniques may become patterns that predispose the individual to injury. Dotter (1953) first described "Little Leaguer's Shoulder" as a fracture of the humeral epiphyseal growth plate caused by baseball pitching. "Little Leaguer's Elbow" was described by Brogden and Chow (1960) to explain the association between pitching and epicondylar injuries.

To more fully understand pitching mechanics, researchers have studied the overhand throwing pattern. Atwater (1979) presented an overview of throwing movements. DiGiovine et al. (1992) described the muscle activation patterns in pitching. More recently the advent of high speed video and more automated reduction of data have made the analysis of pitching more practical. Fleisig et al. (1991) described the kinematics of pitching for a sample of collegiate and professional pitchers. Feltner and Dapena (1988) reported the forces and moments acting at the shoulder and elbow for eight collegiate pitchers.

Most of the previous studies that have analyzed pitching mechanics have examined collegiate, adult, or professional pitchers. Little data has been presented regarding the pitching mechanics of younger athletes. The previous studies also have generally presented data on a limited number of subjects. The purpose of this paper is to review our work on pitching and to provide an overview of the kinematics and kinetics of pitching from a large age-specific data base. In addition, the differences in pitching technique associated with age and level of experience will be discussed. The results will be presented for whole body kinematic studies of the pitching motion and for kinetic analyses of the upper extremity in pitching.

KINEMATICS

We have studied 149 male baseball pitchers ages 9 to 27 years at The Bennett

Institute Biomechanics Laboratory between 1990 and 1993. Subjects were grouped by age and level of competition. The subjects were assigned to one of three groups for the kinematic results that follow. Group I consisted of 55 boys aged 9 to 12 years. Group II consisted of 55 pitchers ranging in age from 13 to 16 years. Finally group III consisted of 39 collegiate and professional male pitchers.

Subjects were asked to throw overhand fastballs using their normal game condition pitching technique. Pitching was performed inside the laboratory over age appropriate distances from the pitcher's mound to home plate. Pitchers threw from a portable indoor pitching mound to a catcher using a standard baseball. They were given opportunity to warm up and become familiar with the test conditions. They were instructed to throw fastballs as hard as they would normally pitch during a game situation. Data were recorded for five pitches.

Reflective markers were attached to the subjects at standard anatomic locations that included: wrist, lateral elbow, acromium, greater trochanter, lateral knee joint line, lateral malleolus, and second metatarsal. A marker was also placed on the ball. The pitching motion was recorded with five high-speed (200 Hz) video cameras. Three dimensional coordinates were calculated utilizing the Direct Linear Transformation technique (Abel-Aziz and Karara, 1971). Ball release was determined by monitoring the wrist ball distance. An increase in this distance above a tolerance value determined the instant of ball release. Ball velocity was measured using a radar gun. The three dimensional trajectory data were smoothed using a Butterworth low pass digital filter with a cut-off frequency of 14 Hz.

Continuous joint angles were calculated for the stride knee, throwing elbow, and shoulder (abduction, horizontal adduction, and internal/external rotation). Hip and upper torso/shoulder rotation were calculated about a vertical axis as were trunk forward and lateral flexion. Angular velocity was also continuously determined throughout the pitching motion. Stride characteristics with regard to length, direction, and foot angle were also determined.

For statistical analysis, group mean values were compared for each variable at three specific points in the pitching cycle: foot contact (FC), ball release (BR), and follow through (FT). FT was defined as a point 0.03 s after BR. These points in time represent specific events in the pitching cycle and are frequently presented in the literature. Additionally, the duration of the delivery phase, the time from FC to BR, was determined. Within the delivery phase the following maximum values for angular velocity and time of occurrence were examined: hip rotation, torso rotation, shoulder horizontal abduction, shoulder internal rotation, shoulder external rotation, and elbow extension. The maximum angles of shoulder abduction, shoulder external rotation and elbow flexion were identified. Analysis of variance was performed using SuperANOVA software (Abacus Concepts, Inc., Berkeley, CA) using Games-Howell post hoc tests.

Mean ball velocity increased significantly with age and experience of the groups (48.9, 63.9, and 77.6 mph for groups I, II, and III respectively). The duration of the delivery phase was not different across groups.

Stride length was defined as the ratio of the distance between the ankle markers at FC and the subject's leg length. The stride length measures were 2.5, 2.4, and 2.5 times leg length for groups I, II, and III respectively. Stride direction was defined as the perpendicular distance from the lead ankle to a line through the trailing ankle extending to the center of home plate and represents the intended direction of the pitch. Positive values indicate a more "open" position. Average stride direction was significantly more "open" in group I than in groups II and III (15.1, 7.3, and 8.3 cm respectively).

Table 1. Mean group angle data.

		Group I		Group II		Group III	
Knee flexion angle	FC	44.2	(12.6)	42.8	(11.1)	42.6	(10.3)
	BR	41.1	(13.4)	43.1	(13.4)	40.7	(13.1)
	FT	37.7	(14.1)	39.8	(15.9)	36.2	(14.3)
Hip rotation angle	FC	56.6	(16.1)	52.1	(12.8)	53.2	(9.7)
	BR	0.0	(10.8)	-1.7	(10.7)	2.1	(10.4)
	FT	-4.4	(10.8)	-5.1	(10.3)	-1.3	(10.2)
Trunk forward angle	FC	2.8	(7.4)	4.8	(6.8)	4.3	(6.8)
	BR	24.7	(9.2)	27.2	(10.5)	29.1	(10.0)
	FT	32.8	(10.2)	36.7	(11.3)	39.1	(11.2)
Trunk lateral angle	FC	6.2	(9.6)	9.8	(10.0)	10.9	(1.4)
	BR	25.1	(8.0)	27.5	(12.3)	27.8	(12.4)
	FT	30.2	(8.8)	32.5	(13.0)	33.3	(13.2)
Torso angle	[1]FC	85.9	(18.6)	93.6	(17.7)	98.6	(13.6)
	BR	-16.1	(8.0)	-15.1	(8.8)	-17.0	(8.9)
	FT	-30.3	(7.9)	-31.2	(10.4)	-33.4	(9.2)
Shoulder abduction angle	FC	78.8	(14.2)	83.5	(13.3)	82.6	(10.7)
	[1]BR	69.8	(8.0)	70.6	(9.0)	75.0	(9.8)
	FT	88.4	(7.1)	87.0	(8.2)	90.9	(9.2)
Shoulder horizontal adduction angle (abduction: -)	[1]FC	-6.3	(14.1)	-11.5	(15.3)	-17.6	(13.4)
	BR	15.8	(10.6)	14.8	(7.8)	14.1	(7.6)
	FT	11.5	(8.7)	9.4	(9.1)	11.1	(8.9)
Shoulder external rotation angle	[3]FC	91.2	(24.7)	81.7	(29.2)	72.8	(28.2)
	[2]BR	125.3	(15.1)	132.7	(13.1)	135.6	(12.5)
	FT	31.9	(18.7)	31.4	(13.6)	30.3	(11.3)
Elbow flexion angle	FC	105.4	(15.9)	99.7	(17.5)	100.9	(18.3)
	BR	50.3	(17.3)	49.3	(11.8)	50.0	(7.9)
	[1]FT	35.7	(10.6)	37.5	(7.5)	40.8	(7.4)

[1] Group I significantly less than Group III
[2] Group I significantly less than Group II and Group III
[3] Group I significantly greater than Group III

Table 1 presents the angular position data for the three groups at FC, BR, and FT. The lead leg angle was 43° at FC. The stride knee flexes at FC and then stabilizes remaining constant or, more typically, increases slightly through BR and FT. Hip angle data revealed that the hips are open approximately 54° at FC and closed to near 0° at BR. The torso is considerably more open at FC with values of 85.9, 93.6, and 98.6° for groups I, II, and III respectively. Trunk forward flexion was calculated as the angle between a line connecting the mid-point of the hip and shoulder markers and the vertical line in the frontal plane. Pitchers were nearly upright at FC and demonstrated increased flexion during acceleration to BR (26.7°) and the FT phases (35.9°). Trunk lateral flexion measures, calculated as the angle between the line from mid-hip to mid-shoulder and the vertical reference in the lateral plane, demonstrated a slight lean away from the throwing arm at FC increasing to 27° at BR.

Figure 1 presents typical angular position data for elbow flexion, shoulder abduction, shoulder horizontal adduction, and shoulder internal/external rotation. It can be seen that the elbow is flexed approximately 100° at FC. Maximum elbow flexion occurred between FC and BR and elbow extension actually began before maximum external rotation of the shoulder was achieved.

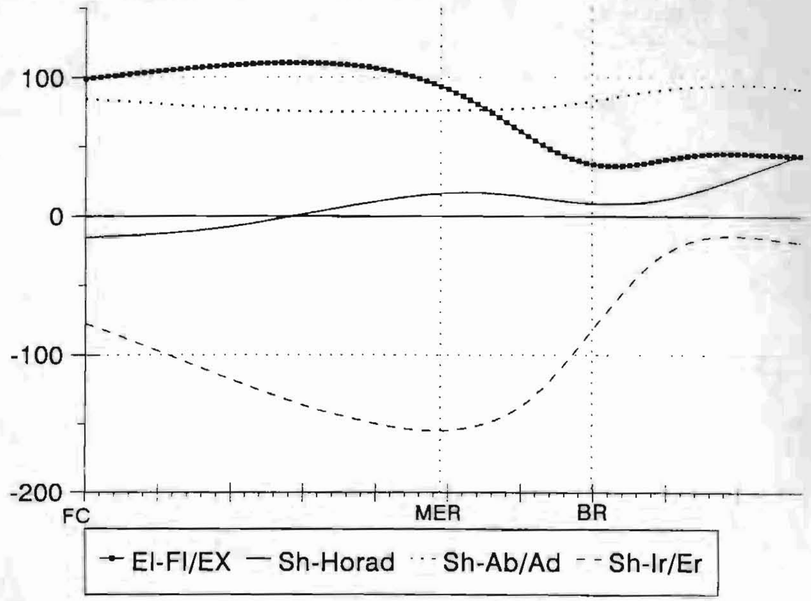

Figure 1. Shoulder and elbow angles.

Shoulder abduction was measured as the angle formed by the upper arm and a line connecting the mid-point of the hip and shoulder markers. Typically the arm is maintained between 70 and 90° of abduction. Shoulder horizontal adduction is defined as 0° when the upper arm is aligned with a line through the shoulder markers in the transverse plane (abduction -, adduction +). At FC, the arm is horizontally abducted between -6 and -18°. The arm is brought forward to 30° of adduction during acceleration. As rapid internal rotation begins, the arm horizontally abducts and BR is achieved with 10° of adduction. This angle continues to increase in FT.

Shoulder internal/external rotation is defined such that when the arm is held parallel to the trunk with the wrist above the elbow, the angle is 90° of external rotation. Group I demonstrated a significantly greater external rotation angle at FC than groups II or III (91.2, 81.7, 72.8° respectively) and was less externally rotated at BR. This BR position was probably related to a decreased trunk forward flexion posture in the younger group. Maximum external rotation angles were 164.6, 166.7, and 168.5° for groups I, II, and III respectively.

Tables 2 and 3 present maximum rotational velocity values obtained during the delivery phase (Table 2) and the time of occurrence as a percent of the delivery phase duration (Table 3). Maximum hip rotation velocity ranged from 570 to 608 °/s. Torso rotation velocity maxima were significantly lower for group I than for groups II and III (994, 1167, and 1183 °/s). Similarly the younger group also demonstrated a decreased internal rotation velcoity maximum. Elbow extension velocity was also found to be significantly lower in group I than groups II or III.

Table 2. Mean group maximum angular velocities (°/s).

	Group I		Group II		Group III	
Hip rotational velocity	608.0	(121.3)	570.1	(123.6)	570.2	(117.4)
Torso rotational velocity	[2]993.6	(124.3)	1068.5	(185.9)	1182.5	(216.6)
Shoulder hor. add. velocity	587.8	(170.1)	703.3	(774.1)	625.6	(160.2)
Shoulder internal rotational velocity	[1]4160.1	(678.2)	4445.2	(805.4)	4765.7	(771.9)
Shoulder external rotational velocity	[1]1215.8	(476.4)	1327.7	(690.7)	1408.9	(265.0)
Elbow external velocity	[1]1823.4	(289.5)	1948.5	(377.0)	2079.2	(272.4)

[1] Group I significantly less than Group III
[2] Group I significantly less than Group II and Group III

Table 3. Percent of phase of the occurrence of maximum angular velocity.

	Group I		Group II		Group III	
Hip rotational velocity	[1]38.0	(14.7)	33.8	(15.6)	28.4	(17.0)
Torso rotational velocity	52.5	(15.4)	58.3	(19.8)	59.0	(14.3)
Shoulder hor. add. velocity	42.8	(14.3)	48.6	(15.1)	48.3	(14.2)
Shoulder internal rotational velocity	108.5	(5.0)	109.1	(4.0)	108.6	(4.5)
Shoulder external rotational velocity	34.5	(13.1)	39.9	(12.6)	37.3	(13.5)
Elbow extension velocity	93.0	(4.5)	93.0	(4.1)	93.3	(3.3)

[1] Group I significantly greater than Group III

The percent of the phase data for the occurrence of the maxima was used to identify the sequencing of the motions in the delivery phase. Generally it can bee seen that the sequencing of the maximum velocities suggests the role of the trunk and lower extremities early in the delivery with the upper extremity maxima being achieved later in the pitching motion.

In summary, the kinematic analysis of pitching has provided a description of pitching mechanics. These studies have revealed a surprising similarity between the different age groups. This was particularly true in the lower extremity and trunk kinematic parameters. The most consistent differences seemed to involve the shoulder and elbow kinematics. The younger pitchers had less shoulder abduction and internal rotation at BR than the older pitchers. Shoulder horizontal abduction velocities were significantly greater and shoulder external/internal rotation as well as elbow extension velocities were lower for the younger pitchers. These differences may be related to the decreased torso rotation and trunk forward flexion velocities found for the younger group. During cocking, as the trunk is driven forward and the torso begins to rotate forward, the abducted and externallt rotated arm lags behind. This "inertial lag" forces the arm into maximum external rotation. By decreasing the forward drive, the younger pitchers may be decreasing the lag effect and thus not obtaining as great a maximum rotation and likely decreasing the ability to obtain as large an internal rotation velocity as the other groups.

KINETICS

Kinetic analysis has been previously performed for the upper extremity in pitching (Feltner and Dapena, 1988; Fleisig et al., 1991). In our analysis, the three dimensional coordinate systems are constructed in a slightly different manner than in previous studies. We also derive the moments and forces from a different formulation of the equations of motion. Our model of the throwing arm lumps the mass of the ball and hand into a single segment located distal to the forearm segment from FC to BR. This segment is defined by the line drawn from the wrist to the ball. When the ball is not identifiable as a separate marker, the hand and the ball masses are lumped at the wrist marker. The wrist is allowed only flexion and extension. During the FT, the hand is treated as a point mass at the wrist. Three dimensional segment based coordinate systems are determined for the forearm and upper arm. The cross product of the wrist to elbow and the elbow to shoulder vectors is used to define an elbow flexion/extension axis. This axis is defined as the forearm medial-lateral or X-axis. The vector from the wrist to the elbow defines the forearm longitudinal or Z-axis and the antero-posterior or Y-axis is defined as the cross product of the Z and X axes. The upper arm segmental coordinate system is similarly defined.

Segmental mass and inertial characteristics were determined from body mass and height measures. Standard Newtonian mechanics are employed to determine the joint reactive forces acting on the proximal and distal aspects of each rigid body. The three dimensional segmental coordinate systems were used to calculate Euler parameters that subsequently allow the computation of the local angular velocity and angular acceleration values for input to Euler's equations of motion. This allows the determination of the moments acting on each segment.

The forces and moments derived in this analysis are determined as acting in the segmental based coordinate systems. At the elbow, the values are presented as acting in the forearm coordinate system. Data for the upper arm are rotated into a "trunk based" shoulder coordinate system. This coordinate system is aligned such that the anterior-superior (Z) axis is parallel to the midline of the trunk, the medial-lateral (Y) axis runs from the throwing shoulder to the lead shoulder, and finally the anterior-posterior (X) axis is the cross product of the Z and Y axes. This coordinate system was chosen as it is desirable to examine the shoulder forces and moments in a system that more closely represents the position of the glenoid that an arm based system. It is recognized that this trunk based system does not contain sufficient specificity about the location of the scapula to actually know the orientation of the glenoid but the results seem to be more clinically relevant than the arm based system.

Figures 2 and 3 present the elbow forces and moments for a professional pitcher. The force data have been normalized by dividing by body weight (N) and the moment values have been normalized by dividing by the product of height and body weight (Nm). FC indicates foot contact, MER indicates maximum external shoulder rotation, and BR represents ball release. The compression distraction force at the elbow indicates that there is a proximal force on the forearm in excess of 90% body weight pulling the forearm toward the arm. The medial-lateral forces are primarily oriented in the medial direction (max = 20% BW) except for a brief low level lateral force in between MER and BR.

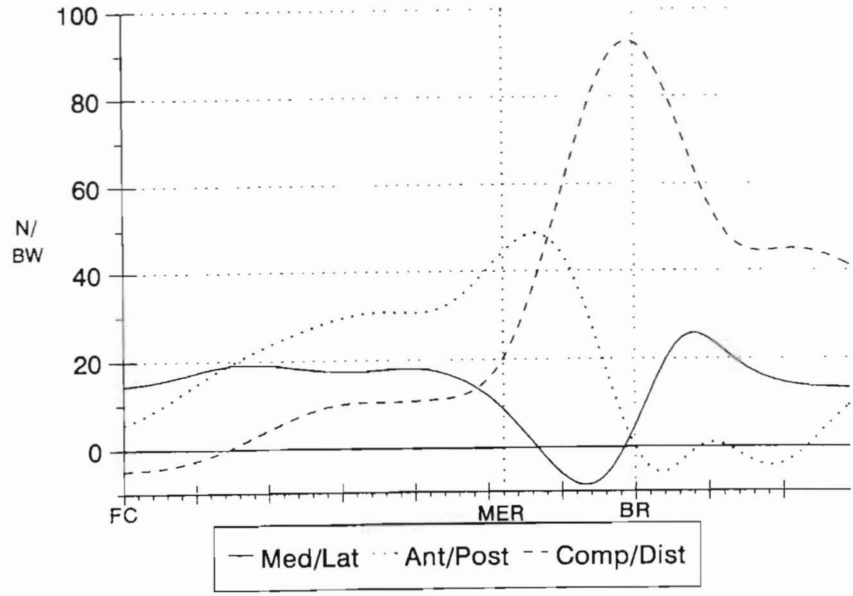

Figure 2. Elbow forces.

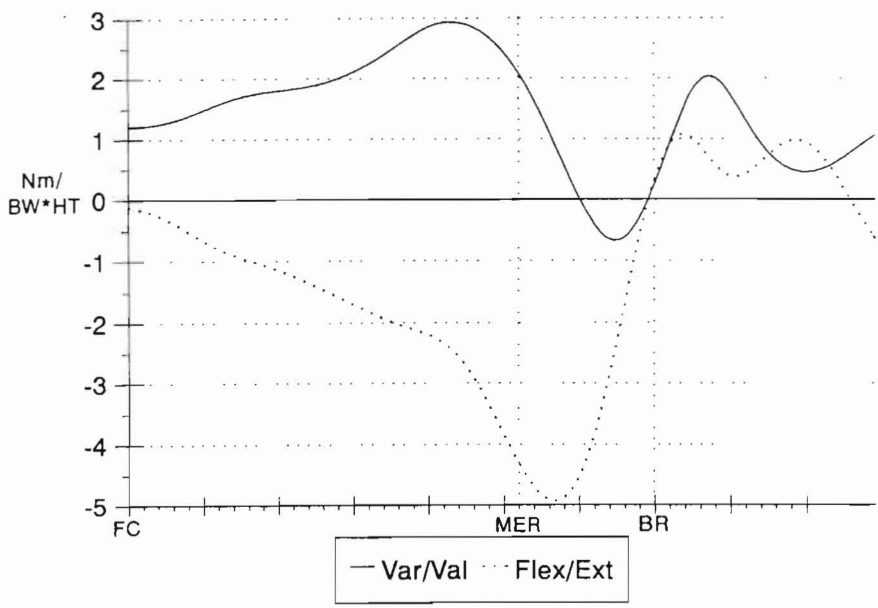

Figure 3. Elbow moments.

In Figure 3 it can be seen that the flexion/extension moment is positive through BR indicating an extension torque. This torque reached a maximum value of corresponding to approximately 80 Nm. This moment becomes a flexion moment at BR and remains in flexion through FT. The varus-valgus elbow moment is primarily valgus through the pitching motion. The data for this pitcher demonstrates a brief low level valgus moment just before BR. This valgus moment is often mentioned in terms of a valgus overload and represents a moment that must be exerted by the medial structures of the elbow or through compression of the lateral bony aspect to resist the movement into a varus alignment. Recent results from our lab have shown that a sample of ten 10-year old pitchers demonstrated a significantly greater valgus moment during acceleration, from FC to BR, than a sample of professional pitchers.

Figures 4 and 5 present shoulder kinetics. These are forces and moments that act on the upper arm that has been rotated in a trunk based shoulder coordinate system. The shoulder compression/distraction force is similar in form to the elbow force obtaining a maximum value of 800 N, greater than one body weight. This represents a force that the soft structures of the shoulder had to exert on the arm pulling it towards the shoulder to keep the upper arm from distracting. The superior/inferior force is oriented in a superior direction until midway between MER and BR and then this force becomes an inferior force. This anterior-posterior force is directed in an anteior orientation early in the cocking phase and becomes a low posterior force from MER to BR and subsequently becomes a larger posterior force in FT. This is consistent with the idea that this force serves to accelerate the arm forward early in the pitch and is an important decelerating force in FT.

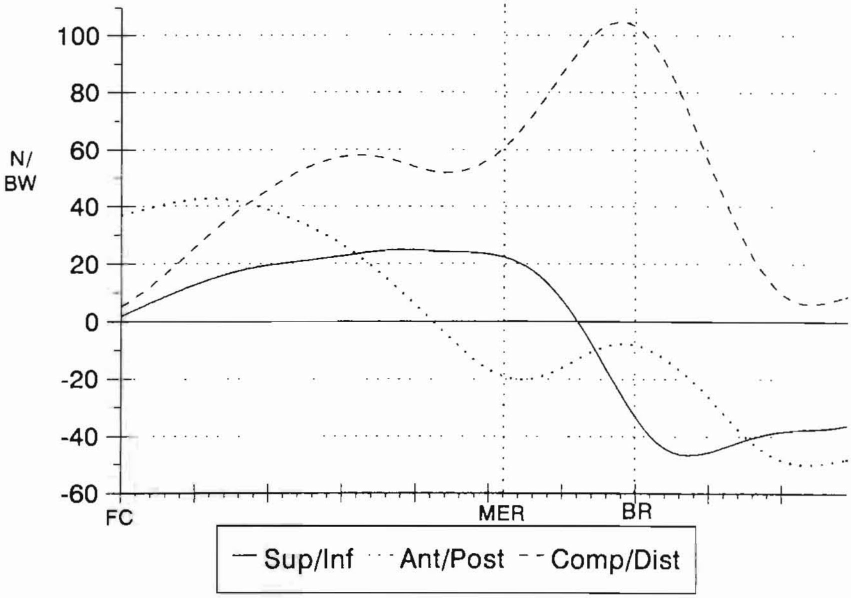

Figure 4. Trunk forces.

In Figure 5 it can be seen that the shoulder internal/external rotation is positive or in internal rotation throughout the pitching motion. The maximum value of this moment is approximately 50 Nm. It is interesting to note that this is an internal rotation moment as the arm is externally rotating. This supports the notion that the arm is externally rotated through an inertial lag and that the net internal shoulder rotation moment is serving to control this external rotation eccentrically. The shoulder horizontal abduction/adduction moment was in horizontal abduction briefly before MER. At this point there was a brief horizontal abduction moment present. This brief horizontal abduction moment corresponds to the time when the arm horizontally abducts from 30° to near 10° during the rapid internal rotation. In FT, the horizontal adduction moment becomes a horizontal abduction moment to decelerate the arm. The abduction/adduction moment indicates a negative or low abduction moment until mid MER-BR at which time the moment becomes an adduction moment.

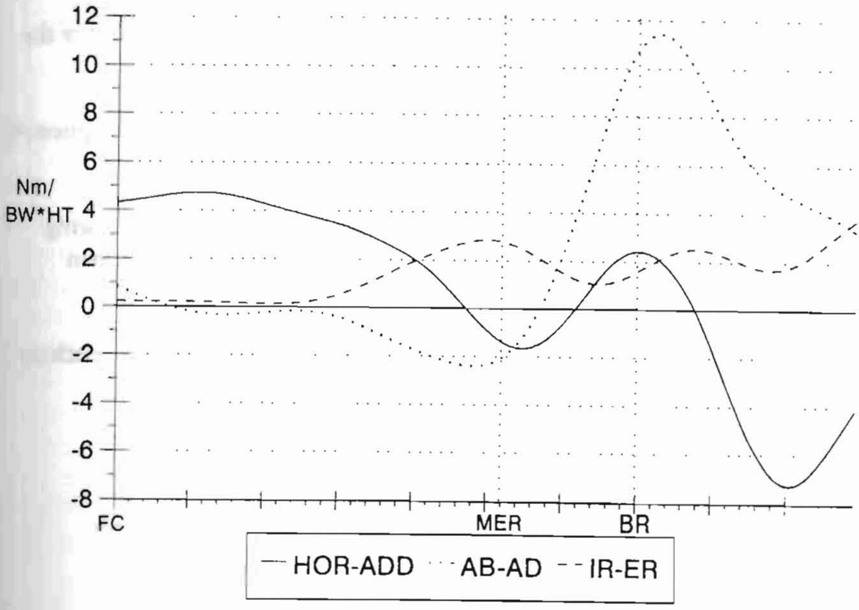

Figure 5. Trunk moments.

CONCLUSIONS

These analyses have given us a better understanding of the demands of the pitching motion. This information has been useful in determining appropriate training and rehabilitation programs for pitchers. In the future, the relationship among the kinematics and kinetics, injury, and successful pitching will be investigated.

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