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Kinetics of Baseball Pitching with Implications About Injury Mechanisms

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ABSTRACT

Elbow and shoulder kinetics for 26 highly skilled, healthy adult pitchers were calculated using high-speed motion analysis. Two critical instants were 1) shortly before the arm reached maximum external rotation, when 67 N-m of shoulder internal rotation torque and 64 N-m of elbow varus torque were generated, and 2) shortly after ball release, when 1090 N of shoulder compressive force was produced. Inability to generate sufficient elbow varus torque may result in medial tension, lateral compression, or posteromedial impingement injury. At the glenohumeral joint, compressive force, joint laxity, and 380 N of anterior force during arm cocking can lead to anterior glenoid labral tear. Rapid internal rotation in combination with these forces can produce a grinding injury factor on the labrum. After ball release, 400 N of posterior force, 1090 N of compressive force, and 97 N-m of horizontal abduction torque are generated at the shoulder; contribution of rotator cuff muscles in generating these loads may result in cuff tensile failure. Horizontal adduction, internal rotation, and superior translation of the abducted humerus may cause subacromial impingement. Tension in the biceps tendon, due to muscle contraction for both elbow flexion torque and shoulder compressive force, may tear the anterosuperior labrum.

In 1979, Atwater[4] reviewed the biomechanics of overarm throwing movements and of throwing injuries. This comprehensive study described the kinematics (i.e., motions) of throwing, based on motion analysis studies, and presented commonly believed injury mechanisms. In the 16 years since that publication, advances in medicine have led to further insight. Recent publications showing kinetics[11,13,14,25] (i.e., forces and torques) and muscle activity[9,16,18,21,23,25] during throwing allow an updated analysis of the biomechanics of throwing and the mechanisms of injury.

In this study, shoulder and elbow joint kinetic data are presented for a large sample of healthy, highly skilled baseball pitchers. Using these results, critical instants during the pitching motion are identified, and joint kinetics at these times are shown. Mechanisms of overuse injuries are described based on current medical knowledge, and kinetic data are used to investigate these proposed mechanisms.

MATERIALS AND METHODS

Twenty-six healthy, highly skilled adult male pitchers, with a mean age of 22 ± 2.3 years, were used for this study. These elite pitchers were selected from 264 pitchers tested, ranging in age from 10 to 36 years, based on their medical and athletic history and their performance during testing. A pitcher was considered healthy if he was not then injured or recovering from an injury at the time of testing, and had not undergone any surgery for at least 12 months.[10] Pitchers who had ever undergone surgery were not considered healthy if they believed that they had not returned to "one hundred percent."[10] A pitcher was considered a highly skilled adult if at the time of the study he was competing at the college or professional level and his fastest three pitches thrown into the strike zone during testing averaged at least 84 mph (37.5 m/s). These criteria were set to include only the highest quality pitchers possible while still maintaining a large sample of subjects.

After completing informed consent and history forms, each subject changed into testing attire consisting of tight-fitting spandex shorts, socks, and athletic shoes. Anthropometric measurements—height, weight, lengths of radius and of humerus—were then obtained. The subject was then instructed to perform his normal warm-up routine, including all stretching and nonthrowing drills. Next, reflective markers were attached to the distal end of the midtoe, lateral malleolus, lateral femoral epicondyle, greater trochanter, tip of the acromion, lateral humeral epicondyle, and wrist on each side of the subject. Since markers were

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placed on upper and lower extremities, motion of the full body could be digitized. The subject then concluded his warmup by throwing as many pitches as desired in the indoor testing facility. Finally, 10 fastball pitches were thrown for data collection.

In the testing facility, pitches were thrown from a portable pitching mound (Athletic Training Equipment Company, Santa Cruz, CA) toward a strike zone ribbon located over a home plate 60.5 feet (18.44 meters) from the pitching rubber (Fig. 1). Ball speed as it left a pitcher's hand was recorded with a radar gun (Jugs Pitching Machine Company, Tualatin, OR). Four high-speed (200 Hz), charge-coupled device cameras recorded the locations of the reflective markers on the pitcher. The three-dimensional location of each marker, based on data from the cameras, was automatically digitized with Expertvision software (Motion Analysis Corporation, Santa Rosa, CA).

Kinematic variables (angular displacement and velocity) at the "shoulder" (i.e., glenohumeral) and elbow joints were calculated as previously described by Dillman et al.[10] Kinetic values (joint force and torque) were calculated at the shoulder and elbow joints using the kinematic data, documented cadaveric body segment parameters,[6–8] and inverse dynamics equations.

To interpret kinetic data, it is essential to understand in which direction the loads are applied. For example, if a person stands with an arm abducted, shoulder torque could be interpreted as either abduction or adduction torque: Because of the force of gravity, an *adduction* torque is applied by the arm to the trunk at the shoulder; to balance this and keep the arm abducted, the muscles about the shoulder apply an *abduction* torque to the arm. In this study, shoulder kinetics was reported as the summation of all internal force and torque applied to the arm by musculature, osseous, and other tissue to the arm (hence, in the example provided, shoulder torque would be reported as an abduction torque). Elbow kinetics was reported as the summation of all internal force and torque applied to the forearm by musculature, osseous, and other tissue. This convention was consistent with previous reports.[11,13,14,25]

Force applied to the arm at the shoulder was separated into three components: anterior-posterior, superior-inferior, and compressive forces. Shoulder torque was separated into adduction-abduction, horizontal adduction-abduction, and internal-external rotation. Force applied to the forearm at the elbow was divided into three components: medial-lateral, anterior-posterior, and compressive forces. Elbow torque was separated into only two components: flexion-extension and varus-valgus. Supination-pronation torque at the elbow could not be calculated with the model used; however, Feltner and Dapena[13] showed that these torques were fairly minimal. Joint kinetics for each pitcher was normalized by his height and weight.

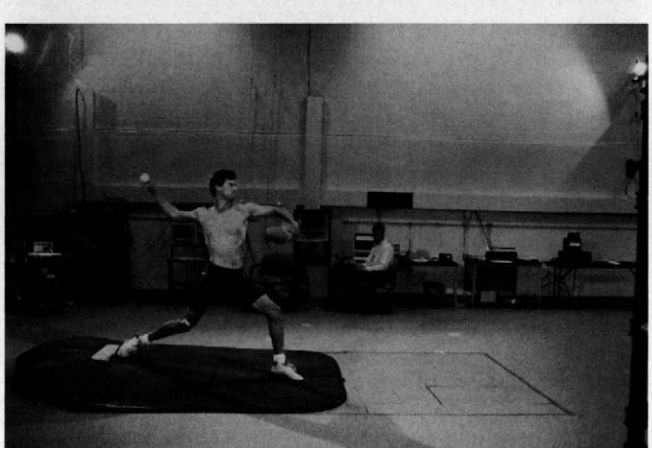

Figure 1. Testing setup.

The three fastest pitches thrown by each elite pitcher into the strike zone were analyzed. Data for each subject's three pitches were synchronized, by matching both the time of front foot contact and the time of ball release, and then averaged. Data were then averaged for the entire group of elite pitchers, to determine mean values and standard deviations. The interval from foot contact to release for the group averaged 0.139 ± 0.017 seconds.

To simplify interpretation of kinetic data, the pitching motion was divided into six phases as previously defined by Dillman et al.,[10] Fleisig et al.,[14] and Werner et al.[25] The windup phase began when the pitcher initiated his first movement; it ended when the lead leg was lifted and the throwing hand was removed out of the glove. Next was the stride phase; it ended when the front foot contacted the mound. The arm cocking phase followed, ending when the throwing arm reached maximum external rotation. Subsequently, the arm acceleration phase occurred, ending with ball release. The time from ball release until the arm reached maximum internal rotation was defined as the arm deceleration phase. The final phase was follow-through; it started at the time of maximum internal rotation and ended when the pitcher had reached his balanced fielding position. Kinetics during arm cocking, arm acceleration, and arm deceleration were reported in this study because the highest levels of kinetics occur during these phases.[10,11,13–15,25]

RESULTS

Forces applied to the upper arm at the shoulder are presented in Figure 2, and torques applied to the upper arm at the shoulder are presented in Figure 3. Forces and torques applied to the forearm at the elbow are shown in Figures 4 and 5, respectively.

The patterns and magnitudes of joint kinetics in this study were similar to those reported by Feltner and Dapena,[13] who studied eight collegiate pitchers, and by Werner et al.,[25] who studied seven collegiate and minor league pitchers. Table 1 is a summary of maximum kinematic and kinetic values at the shoulder from the current study and previous studies. Maximum elbow kinematics and kinetics are summarized in Table 2. In each of these tables, results from this study are shown in the first data column.

Based on the data from the current study, two critical instants were identified. The first occurred near the end of the arm cocking phase, when 64% of the time from foot contact until ball release had been completed (Fig. 6). At this instant the elbow was flexed 95° ± 10°, and the arm

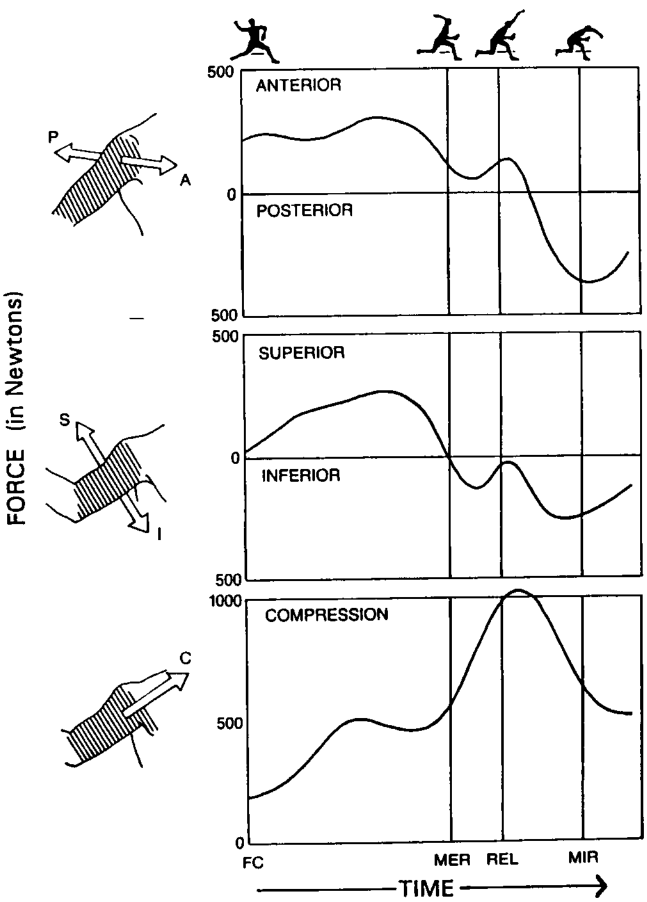

Figure 2. Forces applied to the arm at the shoulder in anterior-posterior (AP), superior-inferior (SI), and compression (C) directions. The instants of foot contact (FC), maximum external rotation (MER), ball release (REL), and maximum internal rotation (MIR) torque are shown.

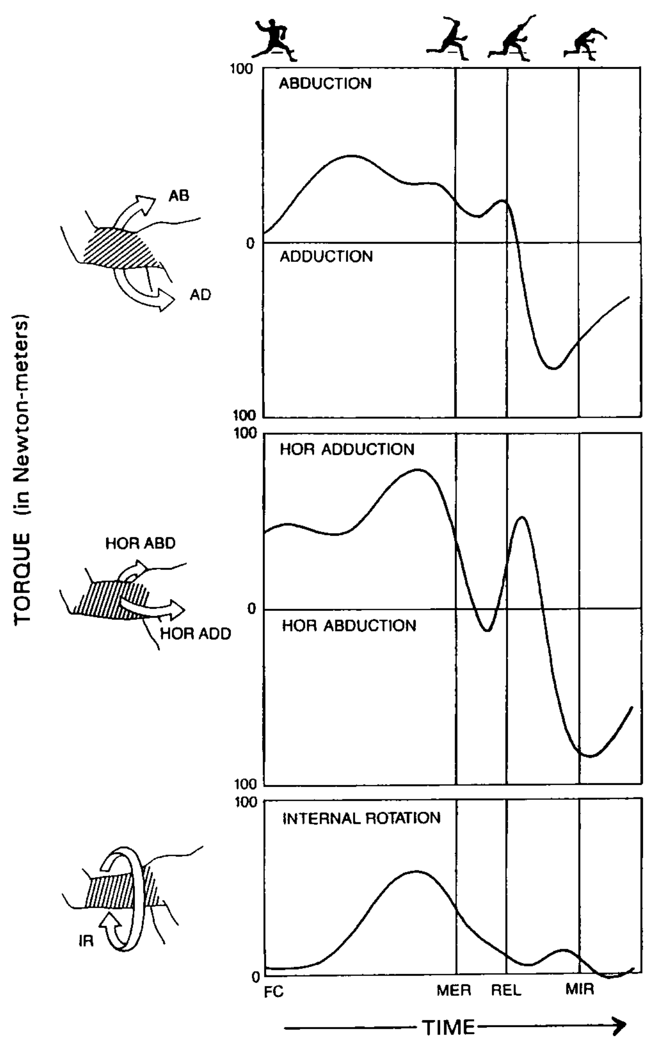

Figure 3. Torques applied to the arm at the shoulder in the abduction-adduction (AB-AD), horizontal adduction-abduction (HOR ABD, HOR ADD), and internal rotation (IR) directions. The instants of FC, MER, REL, and MIR torque are shown.

was externally rotated 165° ± 11°, abducted 94° ± 21°, and horizontally adducted 11° ± 11°. A maximum varus torque of 64 ± 12 N-m was generated at the elbow at this time. In addition, 16 ± 16 N-m of flexion torque, 300 ± 60 N of medial force, 160 ± 80 N of anterior force, and 270 ± 120 N of compressive force were produced. Large loads were also produced at the shoulder at this time, including 67 ± 11 N-m of internal rotation torque and 310 ± 100 N of anterior force. A 250 ± 80-N superior shear force, 480 ± 130-N compressive force, 87 ± 23 N-m horizontal adduction torque, and 44 ± 17 N-m abduction torque were also generated at the shoulder.

A second critical instant for the shoulder occurred during the arm deceleration phase, when 108% of the foot contact to ball release time interval had been completed (Fig. 7). At this time the upper extremity was outstretched toward home plate: the elbow was flexed only 25° ± 10° while the arm was externally rotated 64° ± 35°, abducted 93° ± 10°, and horizontally adducted 6° ± 8°. At this critical instant a maximum compressive force of 1090 ± 110 N was generated at the shoulder. When this maximum compressive force was produced, minimal shear force in the anterior direction (80 ± 180 N) and inferior direction (100 ± 130 N) were present. A 26 ± 44 N-m adduction torque, 44 ± 51 N-m horizontal abduction torque, and negligible (7 ± 5 N-m) external rotation torque were produced at the shoulder at this time.

DISCUSSION

In her review of the biomechanics of overhand throwing, Atwater[4] found "more than half of the authors who reported medical findings or cases pertaining to throwing injuries also attempted to draw some relationships between the injuries they had documented and the overarm throwing motion." Such explanations were usually based on medical knowledge and principles of biomechanics. In the following discussion, kinetic results from the current study are evaluated relative to commonly described mechanisms of

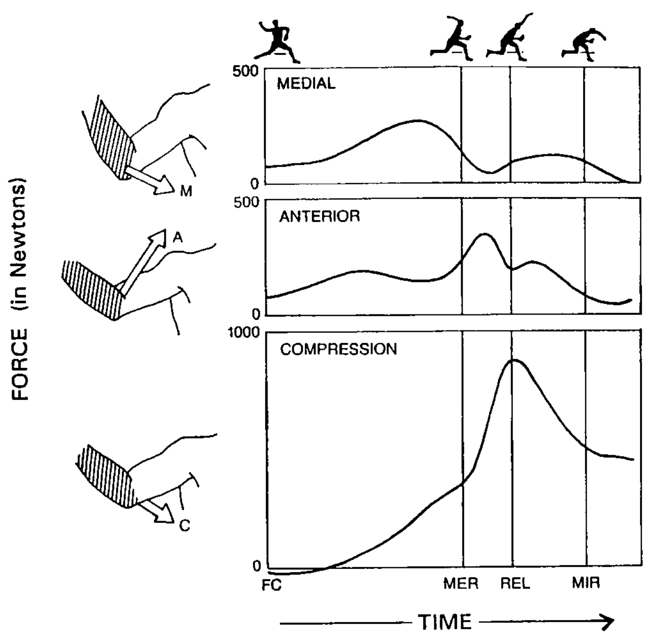

Figure 4. Forces applied to the forearm at the elbow in the medial (M), anterior (A), and compression (C) directions. The instants of FC, MER, REL, and MIR torque are shown.

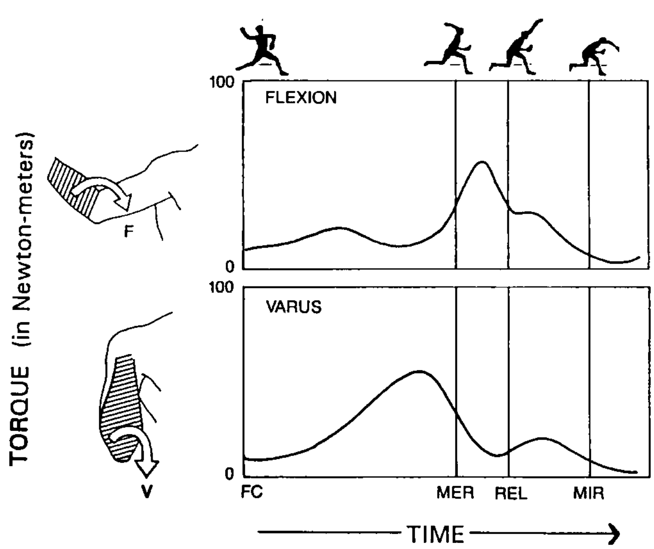

Figure 5. Torques applied to the forearm at the elbow in the flexion and varus directions. The instants of FC, MER, REL, and MIR torque are shown.

overuse throwing injury. Overuse injuries—that is, injuries resulting from accumulated microtrauma developed during repetitive use—are believed to be caused by the large forces and torques exerted at the shoulder and elbow joint during pitching.

Elbow injuries

Valgus torque applied by the forearm to the elbow can lead to medial elbow injury, including muscle tears, avulsion fractures, medial collateral ligament spurs or ruptures, and ulnar nerve damage.[4] To prevent such injuries and maintain stability, a varus torque must be applied to the forearm at the elbow. Previous studies have reported a maximum varus torque between 100 and 120 N-m; in this study a maximum varus torque of 64 ± 12 N-m was generated (Table 2). When maximum varus torque was produced, the elbow was flexed 95° ± 14°. Morrey and An[20] showed in vitro that when the elbow was flexed 90° and a valgus load was applied to the elbow by the forearm, the ulnar collateral ligament (UCL) generated 54% of the varus torque needed to resist valgus motion. Although tension in the UCL may be different during pitching, because of muscle contraction, the UCL's contribution to varus torque is probably close to 54%. Assuming that the UCL produced 54% of the 64 N-m varus torque generated during pitching, the UCL provided 34.6 N-m. Preliminary cadaveric testing indicated that the UCL can produce a maximum varus torque of 32.1 ± 9.6 N-m before failing[12]; thus, the load on the UCL during pitching appears to be near its maximum capacity.

Valgus torque can also lead to lateral elbow compressive injury. Specifically, when there is a loss of joint integrity on the medial side of the elbow, valgus torque can cause compression between the radial head and humeral capitellum.[4] This compression can result in avascular necrosis, osteochondritis dissecans, or osteochondral chip fractures.[4] Morrey and An[20] reported that in vitro when the elbow was flexed 90°, 33% of the varus torque needed to resist valgus torque applied by the forearm was supplied by joint articulation. Thirty-three percent of the 64 N-m maximum varus torque generated during pitching was 21 N-m. Assuming that the distance from the axis of valgus rotation to the compressive point between the radial head and the humeral capitellum was approximately 4 cm, then the compressive force generated between the radius and humerus to produce 21 N-m of varus torque was approximately 500 N.

Elbow injuries have also been identified in the posteromedial region by Wilson et al.,[26] who explained that during arm acceleration "excessive valgus stress is applied to the elbow, causing a wedging effect of the olecranon into the olecranon fossa. This impingement leads to osteophyte production at the posterior and posteromedial aspect of the olecranon tip and can cause chondromalacia and loose body formation." Figure 5 shows that substantial varus torque was generated throughout the arm cocking and arm acceleration phases to resist valgus torque. During these phases, the elbow extended from approximately 85° to 20° (Table 2). This combination of varus torque and elbow extension supports the "valgus extension overload" mechanism described by Wilson et al.

Shoulder injuries

McLeod and Andrews[19] stated that any force that shifts the humeral head to the rim of the glenoid fossa during distraction will cause the humeral head to be reseated off-center, placing the labrum in jeopardy for injury. Specifically, translation and subluxation of the humeral head in the anterior or posterior direction can cause forceful en-

TABLE 1
Summary of shoulder data (Mean ± SD)

Parameter	This study	Dillman et al.[10]	Werner et al.[25]	Feltner and Dapena[13]	Pappas et al.[22]
Subjects					
Sample size	**26**	29	**7**	**8**	15
Trials analyzed per subject	3	3	1	1	10
Pitch speed (m/s)	38.3 ± 0.7	38 ± 1	36.4	**33.5**	
Arm cocking					
Maximum anterior shear force (N)	380 ± 90				
Maximum compressive force (N)	660 ± 110				
Maximum horizontal adduction torque (N-m)	100 ± 20			110 ± 20	
Maximum internal rotation torque (N-m)	67 ± 11			90 ± 20	
Maximum external rotation		**178°**	185°	170°[a]	160°
Maximum horizontal adduction		**14°**			
Arm acceleration					
Abduction at release		**95°**			90° ± 10°
Maximum internal rotation velocity (deg/sec)		6940		6100 ± 1700	6180
Arm deceleration					
Maximum posterior shear force (N)	400 ± 90				
Maximum inferior shear force (N)	310 ± 80				
Maximum compressive force (N)	1090 ± 110			860 ± 120	
Maximum adduction torque (N-m)	83 ± 26				
Maximum horizontal abduction torque (N-m)	97 ± 25				

[a] Angle measurements were converted from published values into values consistent with standard anatomic definitions.

TABLE 2
Summary of elbow data (Mean ± SD)

Parameter	This study	Werner et al.[25]	Feltner and Dapena[13]	Pappas et al.[22]
Subjects				
Sample size	**26**	**7**	8	15
Trials analyzed per subject	3	**1**	1	10
Pitch speed (m/s)	38.3 ± 0.7	**36.4**	33.5	
Arm cocking				
Maximum medial shear force (N)	300 ± 60			
Maximum varus torque (N-m)	64 ± 12	**120**	100 ± 20	
Maximum elbow extension torque (N-m)		**40**	20 ± 10	
Maximum elbow flexion		**85°**	81° ± 8°[a]	120°
Arm acceleration				
Maximum anterior shear force (N)	360 ± 60		320 ± 60	
Maximum flexion torque (N-m)	61 ± 11	**55**		
Maximum elbow extension velocity (deg/sec)		2300	2200 ± 400	4595
Arm deceleration				
Maximum anterior shear force (N)	260 ± 70			
Maximum compressive force (N)	900 ± 100	**780**	830 ± 80	
Minimum elbow flexion		20°	20°	24°

[a] See Table 1 footnote.

trapment of the labrum between the humeral head and the glenoid rim, resulting in labral tearing.[3] When the exact magnitudes of anterior-posterior and superior-inferior forces shown in Figure 2 are not produced, translation of the humerus will occur. Maintaining a stable joint may be difficult because of the large magnitudes and rapid changes that occur. Capsular laxity, as well as muscle weakness or fatigue, makes maintaining joint stability even more difficult, further increasing the chance of injury.

Andrews and Angelo[1] found that most rotator cuff tears in throwers were located from the midsupraspinatus posterior to the midinfraspinatus area. They believed that these tears were a consequence of tensile failure, as the rotator cuff muscles tried to resist distraction, horizontal adduction, and internal rotation at the shoulder during arm deceleration. Compression force (Fig. 2) and horizontal adduction torque (Fig. 3) were seen during arm deceleration in this study. Furthermore, DiGiovine et al.[9] showed that the posterior shoulder muscles (i.e., teres minor, infraspinatus, and posterior deltoid) were very active during this phase. The belief that the posterior shoulder muscles are susceptible to injury during arm deceleration, as they resist glenohumeral distraction and horizontal adduction, thus is consistent with available biomechanical data.

McLeod and Andrews[19] reported that degeneration of the labrum resulting from humeral translation may be increased because of the "shoulder grinding factor." They proposed that if the humeral head translates anteriorly or posteriorly then internal rotation and compressive force acting on the humerus will cause it to grind on the labrum. Maximum internal rotation velocity has been shown to reach 6100 to 7510 deg/sec, making it one of the fastest known

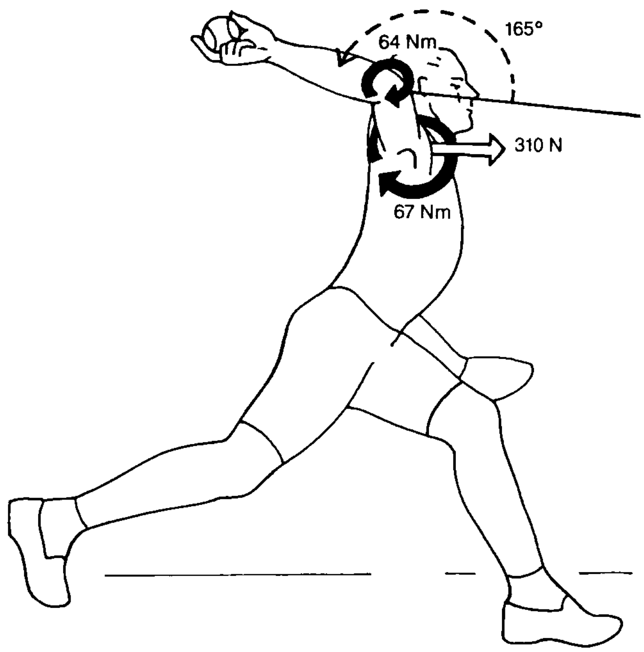

Figure 6. Shortly before maximum external rotation was achieved, the first critical instant occurred; at this instant, the arm was externally rotated 165°, and the elbow was flexed 95°. Among the loads generated at this time were 67 N-m of internal rotation torque and 310 N of anterior force at the shoulder, and 64 N-m of varus torque at the elbow.

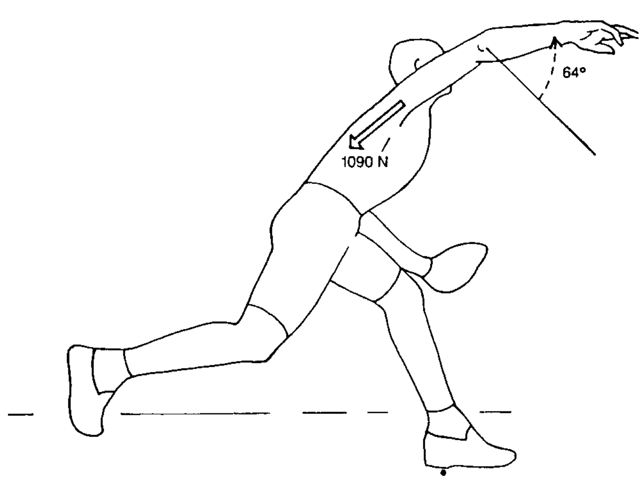

Figure 7. Shortly after ball release, the second critical instant occurred; at this instant, the arm was externally rotated 64°, and the elbow was flexed 25°. Among the loads generated at this time was 1090 N of compressive force at the shoulder.

human motions (Table 1). Figure 2 shows that during arm internal rotation (the entire interval from maximum external to maximum internal rotation), between 600 and 1100 N of compressive force was applied.

Andrews and Angelo[1] stated that throwing motions are particularly likely to produce subacromial impingement due to the flexed, horizontally adducted and internally rotated position of the arm. Supraspinatus, infraspinatus, and bicipital tendinitis, or even abrasion wear may occur.[1] During the arm deceleration phase, the arm horizontally adducted, internally rotated, and remained abducted. The inability to generate the 310 ± 80 N of maximum inferior force shown in Table 1 during this phase would cause superior translation of the humerus. Because the arm was abducted, horizontally adducted, and internally rotated, superior translation of the humerus could have caused impingement of the greater tuberosity, rotator cuff muscles, or biceps against the inferior surface of the acromion or coracoacromial ligament.

Shoulder laxity must not be minimized, however, as a throwing athlete should have sufficient flexibility to achieve extreme external rotation. In a study of professional baseball players tested with their arms abducted, position players averaged 132° of external rotation on their dominant sides and only 124° on their nondominant sides.[5] Pitchers had 141° on their dominant sides and 132° on their nondominant sides.[5] Maximum external rotation during pitching has been reported to be between 160° and 185° (Table 1). Although part of the measured rotation may be scapulothoracic motion, sternoclavicular rotation, and hyperextension of the spine,[10,11,14,15,22] a flexible joint is clearly needed. Thus, a balance between flexibility and stability is needed at the shoulder joint for proper pitching.

Another type of shoulder injury is what Snyder et al.[24] defined as a SLAP lesion: a tear to the superior labrum anterior and posterior. Although the common mechanism Snyder et al. found for a SLAP lesion was a fall on an abducted and flexed arm, they did observe incidents of SLAP lesions from throwing. Andrews et al.[2] observed a similar injury, a tear to the anterosuperior labrum, in a series of 73 baseball pitchers and other throwing athletes. A traumatic episode was not present for most of these patients, and injury was believed to result from repetitive overuse throwing. A specific injury mechanism was proposed in which forces imparted by the long head of the biceps brachii, particularly during arm deceleration, tear the labrum away from the glenoid.

The primary function of the biceps brachii is to supply elbow flexion torque. In this study a large eccentric flexion torque was found during both the arm acceleration and deceleration phases, reaching a maximum value of 61 ± 11 N-m shortly before ball release (Table 2). All three principal elbow flexors—the biceps brachii, brachialis, and brachioradialis—have been shown by EMG studies to be active during the arm acceleration phase.[9,23] Because the long head of the biceps brachii originates on the anterosuperior aspect of the glenoid labrum, contraction of the muscle needed for elbow flexion torque produced tension on the biceps tendon labrum complex.[3]

A secondary function of the biceps brachii is to resist humeral distraction. Contraction of the biceps was particularly efficient in applying a compressive force to the arm at the instant of maximum compressive force (Fig. 7), as reduced external rotation at this time allowed the long head of the biceps to be closely aligned with the compressive direction. This is consistent with EMG findings that the biceps brachii was active not only in the arm acceleration phase but also in the arm deceleration phase.[9,18,21,23,25] Laxity in the shoulder joint may result in increased shoulder compressive force needed, further increasing the demand on the biceps tendon labrum complex. This is supported by the findings of Glousman et al.,[16] who showed that the EMG activity level in the biceps was larger in shoulders with chronic anterior instability.

With improper mechanics, force in the biceps tendon may be unusually large. In an EMG comparison between professional and amateur pitchers, biceps activity was greater for the amateurs.[17] Because total force generated by the biceps is a combination of its contribution to elbow flexion torque and shoulder compressive force, evaluation of both these loads may help explain the relevance of the EMG findings. Figures 2 and 5 show that with proper pitching mechanics maximum elbow flexion torque occurred before maximum shoulder compressive force. With improper mechanics these two loads may occur closer together in time, requiring a greater total force by the biceps.

CONCLUSION

A quantitative description of shoulder and elbow biomechanics during pitching is presented in this study, based on the kinetics of a large sample of elite pitchers and on previously published data. The instant of maximum internal rotation torque during arm cocking and the instant of maximum compressive force during arm deceleration were identified as two critical points for the shoulder; the kinetic data supported the belief that most overuse injuries to the shoulder occur at these two instants or during the short time between them. Maximum elbow varus torque, produced at the time of maximum shoulder internal rotation torque, was identified as a critical load related to elbow injuries.

A need for balance between joint flexibility and joint laxity was seen. Insufficient flexibility may inhibit proper throwing mechanics; conversely, excessive laxity may increase injury probability due to improper motion within a joint and increased forces within certain tissues.

This study may help orthopaedic surgeons and other medical professionals better understand the biomechanics of proper pitching and mechanisms of overuse injury. An understanding of pitching biomechanics is valuable in the prevention, treatment, and rehabilitation of injuries. Future research may investigate the biomechanics of different throwing groups in baseball, such as youth pitchers or elite nonpitchers. The study of pitchers with inefficient mechanics may further improve the understanding of injury causes.

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REFERENCES

1. Andrews JR, Angelo RL: Shoulder arthroscopy for the throwing athlete. *Tech Orthop 3:* 75–81, 1988
2. Andrews JR, Carson WG, McLeod WD: Glenoid labrum tears related to the long head of the biceps. *Am J Sports Med 13:* 337–341, 1985
3. Andrews JR, Kupferman SP, Dillman CJ: Labral tears in throwing and racquet sports. *Clin Sports Med 10:* 901–911, 1991
4. Atwater AE: Biomechanics of overarm throwing movements and of throwing injuries. *Exerc Sport Sci Rev 7:* 43–85, 1979
5. Brown LP, Niehues SL, Harrah A, et al: Upper extremity range of motion and isokinetic strength of internal and external shoulder rotators in major league baseball players. *Am J Sports Med 16:* 577–585, 1988
6. Clauser CE, McConville JT, Young JW: *Weight, Volume, and Center of Mass of Segments of the Human Body.* Wright-Patterson Air Force Base, OH, Aerospace Medical Research Laboratory, AMRL-TR-69–70, 1969
7. Dapena J: A method to determine the angular momentum of a human body about three orthogonal axes passing through its center of gravity. *J Biomech 11:* 251–256, 1978
8. Dempster WT: *Space Requirements of the Seated Operator.* Wright-Patterson Air Force Base, OH, Wright Air Development Center, WADC-TR-55–159, 1955
9. DiGiovine NM, Jobe FW, Pink M, et al: An electromyographic analysis of the upper extremity in pitching. *J Shoulder Elbow Surg 1:* 15–25, 1992
10. Dillman CJ, Fleisig GS, Andrews JR: Biomechanics of pitching with emphasis upon shoulder kinematics. *J Orthop Sports Phys Ther 18:* 402–408, 1993
11. Dillman CJ, Fleisig GS, Werner SL, et al: Biomechanics of the shoulder in sports: Throwing activities, in Matsen FA, Fu FH, Hawkins RJ (eds): *The Shoulder: A Balance of Mobility and Stability.* Rosemont, IL, AAOS, 1993, pp 621–633
12. Dillman CJ, Smutz P, Werner S, et al: Valgus extension overload in baseball pitching (abstract). *Med Sci Sports Exerc 23 (Suppl 4):* S135, 1991
13. Feltner M, Dapena J: Dynamics of the shoulder and elbow joints of the throwing arm during a baseball pitch. *Int J Sport Biomech 2:* 235–259, 1986
14. Fleisig GS, Dillman CJ, Andrews JR: Biomechanics of the shoulder during throwing, in Andrews JR, Wilk KE (eds): *The Athlete's Shoulder.* New York, Churchill Livingstone, 1994, pp 355–368
15. Fleisig GS, Dillman CJ, Andrews JR: Proper mechanics for baseball pitching. *Clinical Sports Med 1:* 151–170, 1989
16. Glousman R, Jobe F, Tibone J, et al: Dynamic electromyographic analysis of the throwing shoulder with glenohumeral instability. *J Bone Joint Surg 70A:* 220–226, 1988
17. Gowan ID, Jobe FW, Tibone JE, et al: A comparative electromyographic analysis of the shoulder during pitching. *Am J Sports Med 15:* 586–590, 1987
18. Jobe FW, Moynes DR, Tibone JE, et al: An EMG analysis of the shoulder in pitching. *Am J Sports Med 12:* 218–220, 1984
19. McLeod WD, Andrews JR: Mechanisms of shoulder injuries. *Phys Ther 66:* 1901–1904, 1986
20. Morrey BF, An K-N: Articular and ligamentous contributions to the stability of the elbow joint. *Am J Sports Med 11:* 315–319, 1983
21. Moynes DR, Perry J, Antonelli DJ, et al: Electromyography and motion analysis of the upper extremity in sports. *Phys Ther 66:* 1905–1911, 1986
22. Pappas AM, Zawacki RM, Sullivan TM: Biomechanics of baseball pitching: A preliminary report. *Am J Sports Med 13:* 216–222, 1985
23. Sisto DJ, Jobe FW, Moynes DR, et al: An electromyographic analysis of the elbow in pitching. *Am J Sports Med 15:* 260–263, 1987
24. Snyder SJ, Karzel RP, Del Pizzo W, et al: SLAP lesions of the shoulder. *Arthroscopy 6:* 274–279, 1990
25. Werner SL, Fleisig GS, Dillman CJ, et al: Biomechanics of the elbow during baseball pitching. *J Orthop Sports Phys Ther 17:* 274–278, 1993
26. Wilson FD, Andrews JR, Blackburn TA, et al: Valgus extension overload in the pitching elbow. *Am J Sports Med 11:* 83–88, 1983