BIOMECHANICS OF THE ELBOW IN THE THROWING ATHLETE

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The biomechanics of the elbow have been examined during the baseball pitch, the football pass, the tennis serve, the javelin throw, and the underhand softball pitch. Primary emphasis has been placed on the baseball pitch, because most throwing injuries occur during this motion. The baseball pitch is divided into six phases. They are wind-up, stride, arm cocking, arm acceleration, arm deceleration, and follow-through. Low muscle activity and low elbow joint forces and torques occur during the wind-up and stride phases. The wind-up and stride position the body in preparation for the highly dynamic movements that follow. High muscle activity and high elbow joint forces and torques are generated during the arm cocking, arm acceleration, and arm deceleration phases. Consequently, hard and soft tissue injuries about the elbow occur during these highly dynamic phases of the pitch. Overall, elbow joint forces and torques are greatest during the arm cocking and arm deceleration phases of the pitch. The follow-through phase consummates the pitching motion and positions the athlete in a good, balanced position ready to resume play. Similarly to the wind-up and stride, low muscle activity and low elbow joint forces and torques occur during the follow-through phase.
KEY WORDS: kinematics, kinetics, electromyography, throwing, throwing injuries

Before discussing injuries and treatment of the elbow in the throwing athlete, it is vital to understand the biomechanics of the elbow joint. Biomechanics is a function of kinematics, kinetics, and electromyography. Kinematics describes how something is moving without stating the causes behind the motion. Specifically, it quantifies linear and angular displacement, velocity, and acceleration–the effects of the motion. Elbow kinematics during throwing include elbow flexion angles, elbow angular velocities, and elbow angular accelerations. High speed videography or cinematography is often used to collect kinematic data.

Kinetics explains why an object moves the way it does; it quantifies both the forces and torques that cause the motion. Elbow kinetics includes the forces and torques about the elbow causing elbow motion to occur. Inverse dynamics equations are often used in conjunction with videographic or cinematographic data to estimate the net force or torque acting about the elbow.

Electromyography is used to quantify muscle activity. Surface electrodes are often used to detect muscle activity from larger surface muscles, whereas indwelling electrodes are often used to detect muscle activity from smaller deep muscles.

In this report, the biomechanics of the elbow in the throwing athlete are examined. Both the overhand and underhand throwing motion will be discussed, including the baseball pitch, the football pass, the tennis serve, the javelin throw, and the underhand softball pitch. Most of the emphasis will be given to the baseball pitch, because more injuries result from baseball pitching than from other throwing motions.

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BIOMECHANICS OF THE ELBOW DURING BASEBALL PITCHING

One of the most demanding activities on the elbow in sports is the baseball pitch. The prevalence of overuse injury to the elbow caused by pitching is well documented.[1-7] Most of these overuse throwing injuries occur because of repetitive trauma to the elbow. An understanding and application of proper pitching biomechanics not only helps maximize performance, but also helps minimize injuries that are often caused by faulty pitching biomechanics.

Although the baseball pitch is one continuous motion, it is helpful to divide the motion into phases. Werner et al[8] separated the pitch into six phases. They are: 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

The objective of the wind-up phase is to put the pitcher in a good starting position. The wind-up starts when the pitcher initiates the movement (Fig 1A) and is completed when the front knee has reached its maximum height (Fig 1B). The time from when the stance foot pivots to when the knee has achieved maximum height and the pitcher is in a balanced position is typically 0.5 to 1.0 second. Minimal elbow kinetics and muscle activity are present during this phase.[3,8-10] The elbow is flexed througout the phase, and elbow flexion is maintained by isometric contractions of the elbow flexors (Table 1).[10-12]

Stride

The stride phase begins at the end of the wind-up, when the lead leg begins to fall and move toward the target and the two arms separate from each other (Figs 1D and 1E).

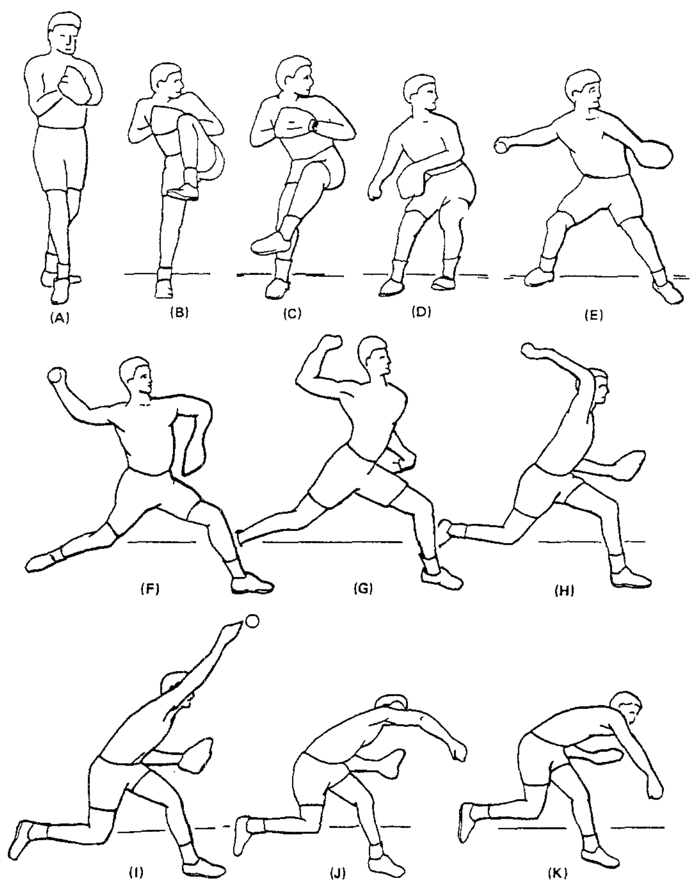

Fig 1. Sequence of positions during the baseball pitch. (Reprinted with permission.[8])

The stride phase ends when the lead foot contacts the mound (Fig 1F). A typical stride lasts 0.50 to 0.75 seconds. Moderate activity from the elbow flexors are needed to control elbow flexion and extension. As the hands separate the elbow flexors first contract eccentrically as the elbow extends, and then concentrically as the elbow flexes near the completion of the stride. The elbow is flexed 80° to 100° at lead foot contact.[8,9,13] Minimal elbow kinetics and muscle activity are present during the stride phase (Table 1).[4,8-10,12]

Arm Cocking

The arm cocking phase, which lasts 0.10 to 0.15 seconds, begins at lead foot contact and ends at maximum shoulder external rotation (MER) (Figs 1F through 1H). "Arm cocking" is a more accurate description of this phase than "cocking," because only the arm is cocked during this entire phase.[8] Some parts of the body, such as the pelvis and lower extremities, accelerate or decelerate during this phase. Shortly after the arm cocking phase begins, the pelvis and upper torso rotate to face the batter.

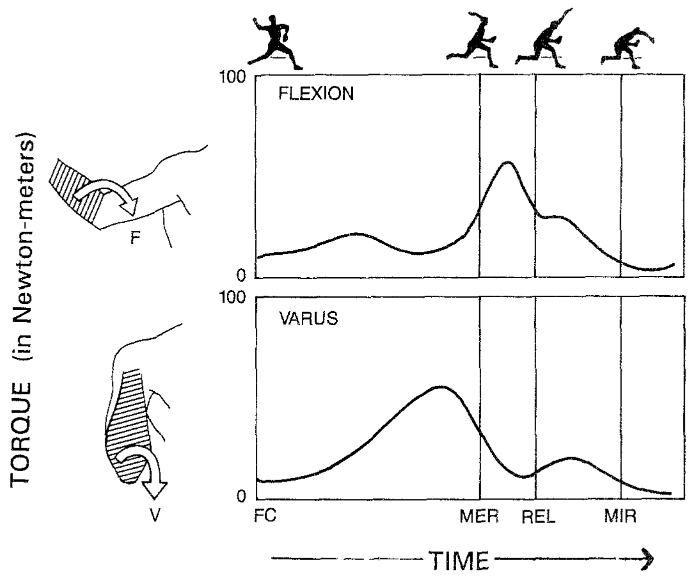

Fig 2. Torques applied onto the forearm at the elbow in the flexion and varus directions. The instants of foot contact (FC), maximum external rotation (MER), ball release (REL), and maximum internal rotation (MIR) are shown. (Reprinted with permission.[4])

Elbow joint forces and torques are generated throughout the arm cocking phase. A low to moderate flexion torque of 0 to 32 nm is produced at the elbow throughout the arm cocking phase (Fig 2).[4] Consequently, the elbow flexors show low to moderate activity, but primarily during the middle third of the arm cocking phase.[8,10,12]

A large valgus torque is produced at the elbow, caused in part by pelvis and upper torso rotation and rapid shoulder external rotation. A maximum varus torque of 52 to 76 nm (mean of 64 nm) is generated shortly before MER to resist valgus torque at the elbow (Fig 3).[4] The flexor and pronator muscle mass of the forearm displays moderate to high activity, which helps contribute to varus torque (Table 1).[12]

TABLE 1. Muscle Activity During Pitching*

	N	Windup	Stride	Arm Cocking	Arm Acceleration	Arm Deceleration	Follow- through
Elbow and forearm muscles							
Triceps	13	4 ± 6	17 ± 17	37 ± 32	89 ± 40	54 ± 23	22 ± 18
Biceps	18	8 ± 9	22 ± 14	26 ± 20	20 ± 16	44 ± 32	16 ± 14
Brachialis	13	8 ± 5	17 ± 13	18 ± 26	20 ± 22	49 ± 29	13 ± 17
Brachioradialis	13	5 ± 5	35 ± 20	31 ± 24	16 ± 12	46 ± 24	22 ± 29
Pronator teres	14	14 ± 16	18 ± 15	39 ± 28	85 ± 39	51 ± 21	21 ± 21
Supinator	13	9 ± 7	38 ± 30	54 ± 38	55 ± 31	59 ± 31	22 ± 19
Wrist and finger muscles							
Extensor carpi radialis longus	13	11 ± 8	53 ± 24	72 ± 37	30 ± 20	43 ± 24	22 ± 14
Extensor carpi radalis brevis	15	17 ± 17	47 ± 26	75 ± 41	55 ± 35	43 ± 28	24 ± 19
Extensor digitorum communis	14	21 ± 17	37 ± 25	59 ± 27	35 ± 35	47 ± 25	24 ± 18
Flexor carpi radialis	12	13 ± 9	24 ± 35	47 ± 33	120 ± 66	79 ± 36	35 ± 16
Flexor digitorum superficialis	11	16 ± 6	20 ± 23	47 ± 52	80 ± 66	71 ± 32	21 ± 11
Flexor carpi ulnaris	10	8 ± 5	27 ± 18	41 ± 25	112 ± 60	77 ± 42	24 ± 18

*Means and standard deviation, expressed as a percentage of the maximal manual muscle test.
Adapted and reprinted with permission[12] from Mosby-Yearbook. 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.

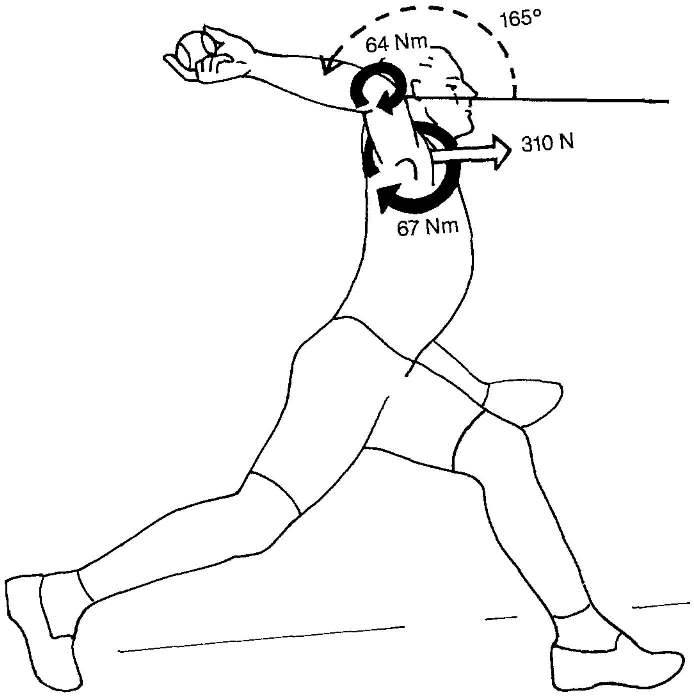

Fig 3. Shortly before maximum external rotation was achieved, the first critical instant occurred. At this instant the arm was externally rotated 165° and the elbow was flexed 95°. Among the loads generated at this time were 67 nm of internal rotation torque and 310 N of anterior force at the shoulder, and 64 nm of varus torque at the elbow. (Reprinted with permission.[4])

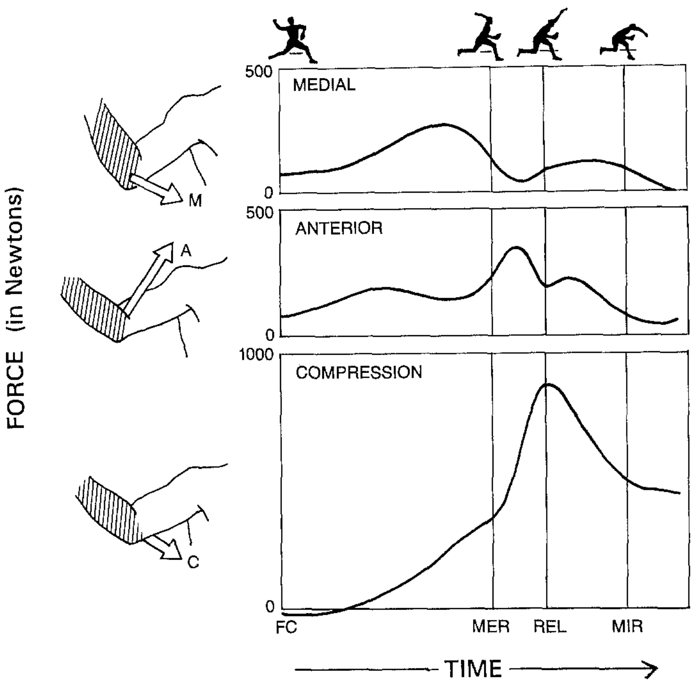

Fig 4. Forces applied onto the forearm at the elbow in the medial, anterior, and compressive directions. The instants of foot contact (FC), maximum external rotation (MER), ball release (REL), and maximum internal rotation (MIR) are shown. (Reprinted with permission.[4])

Because these muscles originate at the medial epicondyle, they contract to help stabilize the elbow. Large tensile forces on the medial aspect of the elbow result from the valgus torque placed on the arm. Repetitive valgus loading may eventually lead to injury to the ulnar collateral ligament (UCL). Furthermore, inflammation of the medial epicondyle (ie, medial epicondylitis) or adjacent tissues (ie, flexor/pronator tendinitis) may also occur, with the latter occurring more frequently in baseball pitchers.

An in vitro study by Morrey and An[14] showed that the UCL contributes approximately 54% of the resistance to valgus. Assuming that the UCL produces 54% of the 52 to 76 nm maximum varus torque generated by an elite pitcher, the UCL would then provide approximately 30 to 40 nm of varus torque. This is similar to the 32 nm failure load reported by Dillman et al.[3] Thus, during baseball pitching, the UCL appears to be loaded near its maximum capacity.[4] However, this result is only an approximation of the UCL's contribution in throwing because the cadaveric research does not account for muscle contributions. Muscle contraction during this phase may reduce the stress seen on the UCL by compressing the joint and adding stability.[8]

Valgus torque can also cause high compressive forces on the lateral elbow, that can lead to lateral elbow compression injury.[4] Specifically, valgus torque can cause compression between the radial head and humeral capitellum.[15] According to the in vitro study by Morrey and An,[14] 33% of the varus torque needed to resist valgus torque applied by the forearm is supplied by joint articulation. Thirty-three percent of the 52 to 76 nm maximum varus torque generated during pitching is 17 to 25 nm. Assuming that the distance from the axis of valgus rotation to the compression point between the radial head and the humeral capitellum is approximately 4 cm, then the compressive force generated between the radius and humerus to produce 17 to 25 nm of varus torque is approximately 425 to 625 N.[4] Muscle contraction about the elbow or loss of joint integrity on the medial side of the elbow can cause this compressive force to increase. Excessive or repetitive compressive force can result in avascular necrosis, osteochondritis dissecans, or osteochondral chip fractures.[15]

In addition to a varus torque, a maximum 240 to 360 N medial force is applied by the upper arm onto the forearm to resist lateral translation of the forearm at the elbow (Fig 4). This force is significantly greater when throwing a fastball or curveball than during a slider or changeup (Table 2). The greater medial force during arm cocking in the curveball compared with other off-speed pitches (eg, changeup and slider) may be related to medial elbow injuries. Further research is needed to address this issue. The forearm is supinated more during the arm cocking phase for a curveball than for a fastball, which may also be related to elbow injuries.[16]

Other forces are also produced at the elbow during arm

TABLE 2. Elbow Biomechanics Compared Between Different Pitches

	Fastball	Curveball	Changeup	Slider
Arm cocking				
Elbow medial force (N)	290	270	240	240
Arm acceleration				
Elbow extension velocity (°/s)	2,400	2,400	2,100	2,400
Arm deceleration				
Elbow compressive force (N)	790	730	620	780

Adapted and reprinted with permission[35] from Williams & Wilkins. Escamilla RF, Fleisig GS, Alexander E, et al: A kinematic and kinetic comparison while throwing different types of baseball pitches. Med Sci Sports Exerc 26:S175, 1994 (abstr).

cocking. A maximum anterior force of 80 to 240 N is applied by the upper arm onto the forearm to resist posterior translation of the forearm at the elbow.[4] Similarly, a maximum compressive force of 150 to 390 N is applied by the upper arm to the forearm to resist elbow distraction.[4]

The elbow achieves a maximum flexion of 85° to 105° approximately 30 milliseconds before MER (Fig 5).[4,8] Maximum elbow flexion appears to be controlled by the triceps muscle, which shows moderate activity during the last third of the arm cocking phase.[8,12] This hypothesis is supported by data from Roberts[17] that show that, if the triceps muscle is paralyzed by a radial nerve block, the elbow "collapses" and continues flexing near its limit (approximately 145° elbow flexion). This collapse is caused by a centripetal flexion torque at the elbow that is created by the rapidly rotating upper torso and arm. The triceps muscle apparently contracts eccentrically and then isometrically in resisting the centripetal elbow flexion torque that occurs during late arm cocking. At approximately the time that the elbow reaches maximum elbow flexion (ie, approximately 30 milliseconds before MER), the elbow flexors become inactive and the triceps contract concentrically to aid in elbow extension.[4,8] The interactions between muscle activity, elbow joint torque, and elbow extension are shown in Fig 5.

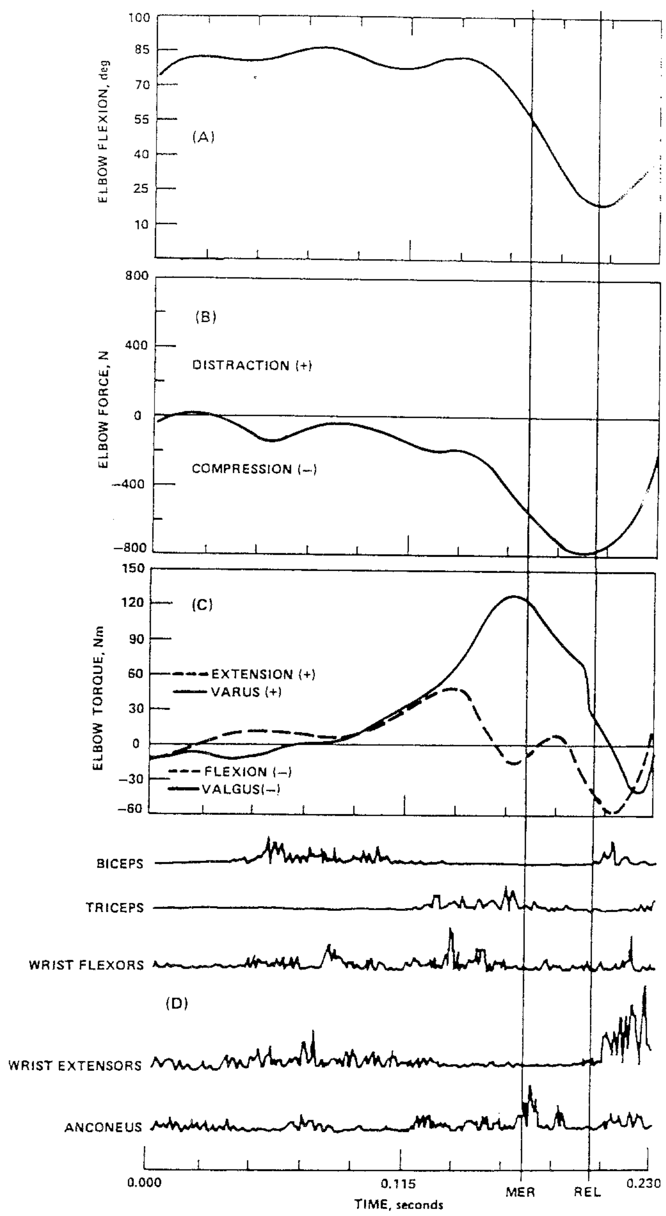

Fig 5. Time-matched measurements during the baseball pitch: (A) elbow flexion, (B) force applied at the elbow, (C) torque applied at the elbow, and (D) EMG muscle activity. (Reprinted with permission.[8])

Arm Acceleration

The arm acceleration phase is the short time from MER to ball release (Fig 1H and 1I). The entire phase lasts only a few hundredths of a second. Maximum elbow flexor torque of 40 to 60 nm is generated by low to moderate activity from the elbow flexors (Fig 2).[4,10,12] Contraction of the elbow flexors in this phase adds compressive force for joint stability and also controls the rate of elbow extension.

A maximum elbow angular velocity of 2,100° per second to 2,700° per second occurs at approximately halfway through the acceleration phase.[8] Maximum elbow angular velocity is similar among the fastball, curveball, and slider, but is significantly less during the changeup (Table 2). This rapid elbow extension may be primarily caused by centrifugal force acting on the forearm because of the rotating trunk and arm, because it is unlikely that the elbow extensors can shorten fast enough to generate the high angular velocity measured at the elbow.

Several studies have examined the role of the triceps in extending the elbow during the acceleration phase of throwing. Roberts[17] reported that a pitcher with a paralyzed triceps because of a differential nerve block was able to throw a ball over 80% of the speed attained before paralyzation. This seems to support the concept that the triceps contraction does not generate all of the elbow extension velocity and that centrifugal force is a major factor. Electromyography has shown high triceps and anconeus activity during the arm acceleration phase, suggesting that the triceps probably initiate or contribute to some of the angular velocity generated during this phase.[8,10,12,18] However, these muscles may function more as elbow stabilizers than as accelerators.[9]

Toyoshima et al[19] compared "normal throwing" (throwing using the entire body) with throwing using only the forearm to extend the elbow. The latter "forearm throw" involved a maximum voluntary effort to extend the elbow with the upper arm immobilized. If it is assumed that the triceps muscle shortened as fast as voluntarily possible during the "forearm throw," then the resulting elbow angular velocity would be the maximum that could be generated with maximum triceps contraction alone. The results from this study showed that "normal throwing" generated approximately twice the elbow angular velocity that could be achieved during the forearm throw. It was concluded that the elbow was swung open like a whip, and that the elbow angular velocity that occurs during throwing is because of the rotary actions of other parts of the body; such as the hips, trunk, and shoulder; rather than by the elbow extending capabilities of the triceps. It was further stated that in "normal throwing" the elbow contributed less than 43% to ball velocity, and that a larger contribution percentage to ball velocity resulted from body rotation.

Ahn[20] used computer simulations and optimization techniques in comparing theoretical data with experimental data. His data showed that hand velocity at ball release was approximately 80% of the experimental result when the resultant elbow joint torque was set to zero, approximately 95% of the experimental value when resultant wrist joint torque was set to zero, and approximately 75% of the experimental value when both the resultant elbow and wrist joint torques were set to zero. Consequently, he concluded that ball velocity at release was generated primarily by body segments other than the upper extremity (ie, lower extremities, hips, and trunk).

During arm acceleration, the need to resist valgus stress at the elbow can result in a wedging of the olecranon against the medial aspect of the trochlear groove and 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.[7] Figure 2 shows that substantial varus torque is generated throughout the arm cocking and arm acceleration phases to resist valgus torque. During these phases, the elbow extends through a range of approximately 65° (approximately 85° to approximately 20°).[4] This combination of elbow extension and resistance to valgus torque supports the "valgus extension overload" mechanism described by Wilson.[7] Campbell et al[21] found greater valgus torque (normalized by bodyweight × height) in 10-year-old pitchers than in professional pitchers at the instant of ball release, which they felt may be related to "Little League" elbow syndrome in young pitchers.

Arm Deceleration

The arm deceleration phase, which only lasts a few hundredths of a second, begins at ball release and ends when the shoulder has reached its maximum internal rotation (Figs 1I and 1J). An eccentric elbow flexion torque of approximately 10 to 35 nm is produced throughout the arm deceleration phase to decelerate elbow extension (Fig 2).[4,8] Moderate to high eccentric contractions of the elbow flexors have been reported during arm deceleration.[8,10,12] The pronator teres has also been shown to be quite active to decelerate elbow extension and pronate the forearm.[12,22] The biceps brachii and supinator muscles are responsible for controlling forearm pronation.

A maximum elbow compressive force of 800 to 1,000 N occurs just after ball release to prevent elbow distraction (Fig 4).[4] This compressive force is greatest when throwing fastball or slider pitches (Table 2). Elbow flexors are active to produce a compressive force as well as to terminate elbow extension before the olecranon impinges in the olecranon fossa.[8] Elbow extension terminates when the elbow is flexed approximately 20°.[8,9]

Follow-Through

The follow-through phase begins at maximum shoulder internal rotation and ends when the pitcher attains a balanced fielding position (Fig 1J and 1K). Motion of the larger body parts, such as the trunk and lower extremities, help dissipate energy in the throwing arm during this phase.[23] Forces and torques at the elbow during the follow-through are significantly less than the high levels attained during arm deceleration (Figs 2 and 4). During follow-through, the elbow flexes into a comfortable position as the trunk rotates forward and the arm moves across the body.[9]

BIOMECHANICS OF THE ELBOW DURING OTHER THROWING MOTIONS

Football Passing

The motion in throwing a football is qualitatively similar to throwing a baseball. This is the basis for the theory that a football can be used as an overload weighted implement for strengthening the arm of a baseball pitcher because it has been documented that overload training can increase ball velocity once pitching with regulation weight baseballs is resumed.[24-26] To compare and contrast baseball pitching and football passing, Fleisig et al[27] (in press) studied 26 baseball pitchers and 26 football quarterbacks using motion analysis. The 26 high school and college pitchers threw from a mound to a strike zone ribbon located 18.4 m away (ie, regulation distance). The 26 high school and college quarterbacks threw drop-back passes to a net located approximately the same distance that the pitchers threw from.

During arm cocking, a quarterback showed greater elbow flexion than pitchers, with an average of 113°. Also during arm cocking, a maximum medial force of 280 N and a maximum varus torque of 54 nm are produced at the elbow. During arm acceleration, the elbow reaches a maximum extension velocity of 1,760° per second. To decelerate the elbow, a quarterback generates a flexion torque of 41 nm and a compressive force of 620 N.

Although football passing is qualitatively similar to baseball pitching, significantly less force and torque are produced to decelerate elbow extension. These lower forces and torques may be related to the lower incidence of injury from the repetitive throwing that occurs in football. From these results, it is recommended that baseball pitchers do not throw footballs during the baseball season. However, throwing footballs and baseballs in the off-season may have some positive training benefits. This could be true especially for the adolescent or prepubescent athlete, whose objective should be to develop general fitness and athletic skills without committing to the specialization of one sport.

Tennis

The motion involved in serving is similar to overhand throwing. During the serving motion, the elbow moves through a flexion range of approximately 100° (116° to 20°).[28] During ground strokes the elbow range of motion is significantly smaller (with 11° for the forehand and 18° for the backhand).[28] Therefore, the muscles of the elbow appear to function as elbow stabilizers for the ground stroke motions.[29] During the serve there is high triceps activity (greater than 60% of a manual muscle test) during the acceleration phase as the elbow extends. Morris et al[29] concluded that both the pronator teres and triceps play a significant role in power production for the serve. Cohen et al[30] showed that the extension torque strength at the elbow was highly related to serving velocity. In their study, extension torque was analyzed as muscular strength measured with an isokinetic dynamometer. Kibler[28] indicated that the elbow joint contributes 15% of the force produced during the tennis serve.

As with the overhand throw, the tennis serve generates considerable angular velocity at the elbow. Kibler[28] indicated that the angular velocity for elbow extension reaches 982° per second and pronation reaches 347° per second. Conflicting with these conclusions was a study by Springings et al[31] investigating the effectiveness of arm segment rotations in producing racquet-head speed. Forearm pronation had the fastest rotation of 1,375° per second; however, it ranked fourth in terms of contribution. It was concluded that elbow extension did not contribute significantly to the forward speed of the racquet-head. It should be noted that this study analyzed only one player and the authors indicated that the lack of contribution of elbow extension may be because of technical flaws with this player's particular technique.

Javelin

There have been a number of biomechanical analyses of javelin throwing. Most of these studies concentrated on the kinematic analysis of various factors related to performance. Consequently, the stress or load experienced at the elbow has not been quantified extensively. Mero et al[32] investigated the contribution of body segments to the javelin throw during Olympic competition. During the thrust phase (the time from final foot contact until javelin release), the elbow extends through a flexion range of approximately 40° (100° to 57°). Top throwers (ie, Olympic medal winners) have a 60° range of motion at the elbow (96° to 40°), which is more comparable with the flexion range for baseball pitchers. The maximum angular velocity for elbow extension during the thrust phase is 1,900° per second.

BIOMECHANICS OF THE ELBOW DURING UNDERHAND THROWING

Although the traditional view is that underhand pitchers have minimal risk for sustaining pitching related injuries, a survey by Loosli et al[33] found a high incidence of injuries to underhand pitchers. Thirty-one percent of these injuries were at or distal to the elbow. Unfortunately, there has been a limited amount of research investigating the motion involved in underhand throwing.

Barrentine[34] estimated the amount of force experienced at the elbow during underhand softball pitching. During the acceleration phase, a compressive force equivalent to 438 N is exerted to resist elbow distraction. Elbow distraction is caused by the centrifugal force on the forearm resulting from the upper arm rotating about the shoulder at 650° per second and the elbow flexing at 870° per second. A valgus torque of 45 nm is generated at the elbow to resist varus stress caused by the combination of elbow flexion and shoulder internal rotation. After ball release, a compressive force of up to 338 N is exerted to resist distraction at the elbow during follow-through. The magnitude of force exerted on the elbow is smaller in underhand softball pitching than in overhand baseball pitching. Based on the number of pitches thrown, frequency of pitching at full capacity, and anatomical differences between female underhand pitchers and male overhand pitchers (eg, carry angle), the underhand motion may not be as safe from overuse injuries as previously thought.

CONCLUSIONS

During the throwing motion, the elbow is stressed to its biomechanical limits. Through proper coordination with the rest of the body, the muscles around the joint generate rapid extension, flexion, pronation, and supination needed for sports performance. Hard and soft joint tissue are loaded to capacity to generate and control these rapid motions. These loads may include large tensile forces on medial soft tissue (eg, UCL), large compressive forces on lateral hard tissue (eg, radiocapitellar articulation), soft tissue tensile loads to prevent joint distraction, and hard tissue loads to withstand compression. In the next article, the clinical anatomy and pathomechanics of the elbow are discussed in more detail. Current concepts in the treatment of these injuries are examined in subsequent articles.

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