Biomechanics and Pathology of the Overhead Throwing Motion: A Literature Review

Peter Huijbregts, PT, MSc, MHSc, MTC, CSCS

Abstract: This article describes the electromyographic, kinematic and kinetic analysis of the overhead throwing motion. Pathology associated with this motion is described, based on a literature review and inferred from data of said analysis. The goal of this article is to improve the therapist's understanding of the biomechanics of the overhead throwing motion to facilitate evaluation and treatment decisions.

Key Words: Throwing, Shoulder, Biomechanics, Pathology

Pain and decreased function of the shoulder are common complaints for which a patient may be referred to a physical therapist. Dealing with shoulder problems in the non-athletic population can be quite challenging, but any problem the therapist might have with managing of this population pales compared to the difficulties one may experience in trying to return the throwing athlete to a previous level of function. The purpose of this article is to increase the therapist's understanding of the pathology associated with the throwing motion in order to facilitate interpretation of evaluation findings and to help determine appropriate management strategies. I will describe the mechanics of the well-researched overhead throwing motion and discuss the pathology associated with this motion. Discussion of treatment strategies is outside of the scope of this article, but based on the information presented here, the therapist should be able to make an appropriate choice from the many conservative protocols available[1-3].

Address all correspondence and request for reprints to:
Peter Huijbregts, PT, MSc, MHSc, MTC, CSCS
South Haven Community Hospital
Rehab Department
955 South Bailey Avenue
South Haven, MI 49090
USA

Methods for motion analysis

Throwing is part of many athletic activities, but the throwing motion most extensively researched is without a doubt the overhead baseball pitching motion. When reviewing literature on the mechanics of the overhead throwing motion, one can distinguish three different approaches for describing the mechanics of this motion:

1. electromyographic data,
2. kinematic analysis,
3. kinetic analysis.

A vast body of research exists on the electromyographic activity of glenohumeral and scapulothoracic musculature during the overhead throwing motion. The electrical activity measured during the dynamic motion (usually) by way of intramuscularly placed electrodes is described as a percentage of the electrical activity measured during a maximal isometric contraction (MVC or maximal voluntary contraction) of the same muscle, prior to dynamic testing[4,5].

A second way of analyzing the throwing motion is kinematics, the branch of mechanics that deals with the motion of a body without reference to force or mass[6]. Researchers will use high-speed camera systems and markers on the athletes' bodies to get information regarding measures such as joint range of motion, angular velocity, and angular acceleration of the motion studied[7,8,9].

The kinematic data play an important role in calculating the kinetic data[9]. Kinetics is the branch of mechanics that deals with the motion of a body under the action of given forces and/or moments[6]. Simply put, kinematics supplies data in terms of joint angles, velocities and acceleration, whereas kinetics is expressed as forces and torques.

Total body kinematics of the overhead throw

All too often overlooked in rehabilitating the throwing athlete is the fact that the overhead-throwing motion is a total body motion with a possibility of causative factors for injury in any place throughout the kinematic chain. We will, therefore, start by reviewing the total body kinematics of the overhead throw of the baseball pitcher.

In general, literature distinguishes five distinct phases in the overhead throw: wind-up, early cocking, late cocking, acceleration and follow-through (see figure 1). Because of the differences found in muscular activity and magnitudes of deceleration, some authors[4,7,9] distinguish a deceleration phase as the first part of follow-through.

The wind-up phase in the overhead baseball pitch is a preparatory phase, centered around flexion. A right-handed thrower has a flexion pattern of the left lower extremity with considerable hip and knee flexion. There also will be a flexion movement of the spine. Both hands are in contact with the ball, and the shoulders are in an internal rotation-adduction position with bilateral elbow flexion. The pitcher is facing the batter with the left side of the body[7,10].

Early cocking starts when the left hand loses contact with the ball. The right shoulder moves from adduction and internal rotation to abduction and external rotation. The pitcher steps with the previously flexed left leg in the direction of the batter, and the trunk moves into extension, right rotation and left sidebending[10].

The late-cocking phase starts when the left foot of the pitcher hits the ground[10,11]. This is the start of a derotation movement of trunk and legs that will contribute to accelerating the ball. The right arm and ball still move in the same direction of horizontal abduction and external rotation.

Acceleration starts with the switch-over from shoulder external to shoulder internal rotation. This rotation is the most important movement of the acceleration phase. In this phase, the shoulder also moves from horizontal abduction to horizontal adduction and back in the direction of horizontal abduction, just prior to ball release[7,8].

Ball release by the right hand marks the end of acceleration. The arm, which has been immensely accelerated for the throwing motion, now has to be decelerated. One sees a flexion of the left lower extremity and flexion with a left rotation of the trunk. The shoulder goes from a minimal abduction movement to adduction

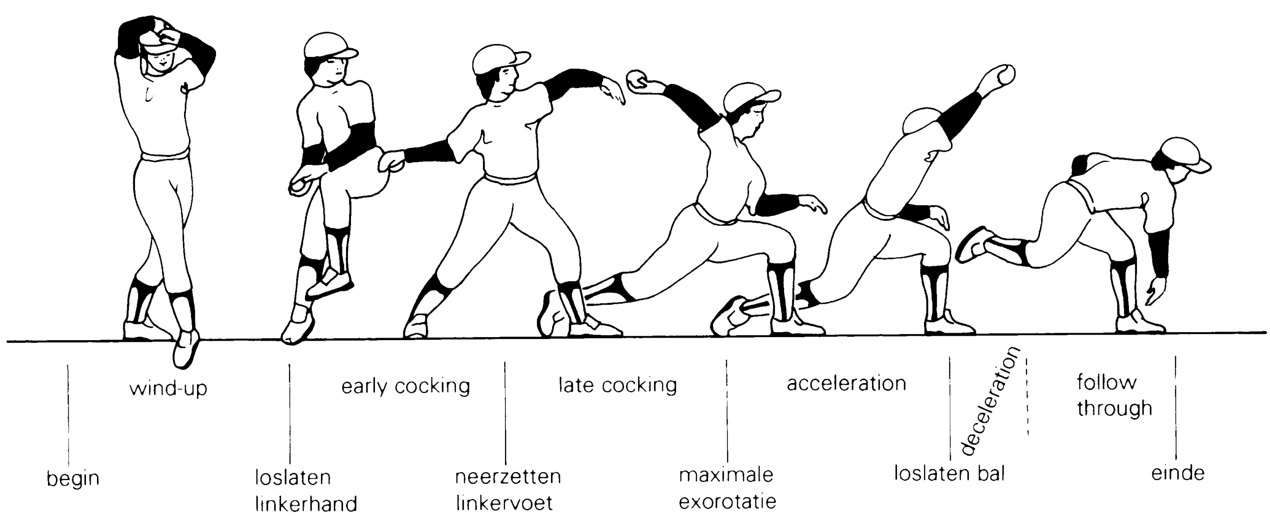

Fig.1: The overhead throwing motion (with permission from Huijbregts PA, Clarijs JP. Krachttraining in revalidatie en sport. Utrecht: De Tijdstroom BV, 1995)

with internal rotation. Especially in the first part of the follow-through (the deceleration phase) the shoulder complex muscles are very active in decelerating the throwing arm[7]. Fleisig et al[9] define the deceleration phase as the time between ball release and attaining maximal internal rotation. The second part of the follow-through is the body follow-through: the trunk and lower extremity motion already described decrease the force requirements about the shoulder and, thus, the potential for injury[12].

The overhead throw is a very fast activity. Braatz et al[10] mention a time frame of 110 to 280 (ms) for late cocking and acceleration. Fleisig et al[9] measured an average time of 0.139±0.017 (s) from foot contact to ball release, a period which, as we have seen, corresponds to the late cocking and acceleration phases combined.

Electromyographic analysis

Both in the wind-up, and in the (body) follow-through, the demands on the musculoskeletal system are relatively minor. This becomes evident when considering the maximal muscular activity measured about the shouldergirdle during both phases[4]: in the wind-up phase, no muscle exceeds 21% of the electrical activity of the maximum voluntary contraction (MVC), and in the follow-through phase, none of the muscles exceeds 42% MVC.

During early cocking, mainly the serratus anterior and the upper trapezius are active in their role as lateral rotators of the scapula[4]. In doing so, they support the very active deltoid and supraspinatus (which provide glenohumeral abduction) in abducting and elevating the shoulder complex[4].

During late-cocking, the abduction elevation remains relatively constant, possibly explaining the observed decreased activity of the deltoid and supraspinatus[4]. The posterior rotator cuff muscles, the infraspinatus and the teres minor, are very active in producing external rotation of the humerus; and they contribute significantly to anterior glenohumeral stability by controlling anterior translation of the humeral head[11,13]. The scapulothoracic muscles, especially the trapezius, the levator scapulae and the serratus anterior are very active in stabilizing the scapula. They produce a slight protraction-lateral rotation movement, which, by increasing the subacromial space with the relatively constant angle of abduction elevation decreases the chance of impingement in this phase[14]. The greatest amount of activity during this phase is found in the internal rotators of the shoulder. The pectoralis major, the latissimus dorsi, and especially the subscapularis are all highly active[4]. These muscles constitute the main ventral stabilizing factor in this phase of the movement, and their eccentric action during the extreme external rotation is the eccentric phase of the pliometric contraction or short stretch-shortening-cycle (SSC)[15] that will accelerate the ball in the upcoming acceleration phase.

Internal rotation is the main movement during acceleration, as witnessed by the high activity in all internal rotators, and especially the subscapularis. Scapular muscles are highly active in order to provide a stable base for this high-speed internal rotation[4]. The teres minor and the posterior deltoid are two other important muscles with high electromyographic activity. The triceps brachii contracts very strongly in this phase, but appears mainly to have a function in the elbow joint[4].

In the deceleration phase, the scapular muscles are again all very active in eccentrically slowing down the arm[14]. The total deltoid, teres minor, subscapularis and latissimus dorsi are also very active. The biceps brachii shows strong activity in eccentrically decelerating elbow extension[4].

Kinematic analysis

As discussed earlier, the overhead throwing motion is truly a total body movement. We will however, limit ourselves now to discussing the kinematics of the shoulder complex. During the cocking phases of the overhead throw the frontal plane movement of abduction-elevation increases to a range of motion in the order of 90 to 110 degrees, then stays constant until the beginning of follow-through, where for a very short period it slightly increases and promptly decreases again[7,8]. The greater amount of abduction one would expect in this throw is the result of the trunk movements described earlier.

In the transverse plane during early cocking horizontal abduction increases to between 30 and 50 degrees. This is followed by 14 to 20 degrees of horizontal adduction during late cocking. Horizontal adduction decreases again to approximately zero degrees with the upper arm in the frontal plane at the beginning of follow-through[7,8].

The rotational movement is the main movement of the acceleration phase[7,16]. There is a maximal excursion into external rotation of up to 175 degrees[7,16]. However, this is measured in relation to the ground; and excluding the contribution of the trunk, only 140 degrees was found to truly originate in the shoulder[8]. Ball release occurs in a position in which the forearm is almost vertical in relation to the ground but in which the shoulder is still 100 to 110 degrees externally rotated[7]. Angular speeds during acceleration of up to 7,000 degrees per second occur during the internal rotation movement, whereas angular decelerations of up to 500,000 degrees per second-squared clearly illustrate the demands placed upon active and passive structures of the shoulder in having to decelerate this internal rotation[4,7,17].

In addition to the overhead throw, the literature also mentions the three-quarter-throw, the side-arm throw and the underhand throw. The name of the specific throw originates in the position of the upper arm relative to the ground[10]. Dillman et al[7] state there is no difference in the amount of abduction with most throwing or racket sports. Braatz et al[10] mention that shoulder movements with most throwing techniques are virtually identical. Yoshikawa[8] confirms in his three-dimensional analysis of the throwing movement that there is no significant difference between a side-arm throw and an overhead throw when it comes to shoulder motion. The consequences for rehabilitation, specifically regarding the concept of using less stressful and, therefore, less traumatizing throwing techniques during rehab, are obvious. It may be appealing to the clinician to use the information available on kinematics of the overhead throw to make assumptions about the kinematics of other throwing techniques or possibly even about the kinematics of seemingly similar activities in racket sports. This, however, is as of yet not justified by research.

Kinetic analysis

Kinematic data, together with body segment measurements, are used to calculate the kinetic data, or forces and torques, during a movement, such as the overhead throw[9]. Fleisig et al[9] in their kinetic analysis identified two critical instants. The first occurred near the end of the late cocking phase when 64% of the time from foot contact to ball release had been completed. At this point the shoulder was abducted to 94±21 degrees, externally rotated to 165±11 degrees and horizontally adducted to 11±11 degrees. Fleisig et al[9] named this a critical instant mainly because of the maximum varus torque in the elbow generated at this point, with the high possibility of injury to the ulnar collateral ligament, the ulnar nerve, or the lateral compartment of the elbow joint. They also noted, however, the high loads at the shoulder at this point in the throwing motion : 67±11 (Nm) of internal rotation torque, 87±23 (Nm) horizontal adduction torque, 44±17 (Nm) abduction torque, 310±100 (N) anterior force, 250±80 (N) superior shear force and 480±130 (N) compressive force.

The second critical instant was found to occur during the deceleration, or when 108% of the foot contact to ball release time had been completed with 100% being the moment of ball release. The arm was externally rotated to 64±35 degrees, abducted 93±10 degrees and horizontally adducted 6±8 degrees. At this point, a maximum compression force of 1090±110 (N) was found in the shoulder with minimal anterior and inferior shear forces. Adduction torque was 26±44 (Nm), horizontal abduction torque was 44±51 (Nm) and external rotation torque was negligible.

Kinetic analysis shows that high forces and torques are generated in both shoulder and elbow during the overhead throwing motion. These high loads probably play an important role in the etiology of shoulder injuries in throwing sports. The pathology associated with throwing is discussed in the remainder of this article.

Pathology

Obviously enormous demands are placed on the musculature of the shoulder complex with regards to movement and stabilization of the joints involved because of an external rotation range of motion of 140 degrees at the end of late cocking[8], an internal rotation angular velocity of 7,000 degrees per second during acceleration and an angular deceleration of 500,000 degrees per second-squared during deceleration[4,7], not to mention the considerable magnitude of the forces and torques during the overhead throw, as discussed in the section on kinetics. So what happens in the event of muscular weakness or muscular fatigue, for instance after multiple throws, when these muscles are no longer able to supply the required amount of force, speed, and acceleration for the appropriate duration at the right point in time?

Muscular fatigue will decrease the contribution of the active structures and, if a similar power output is to be maintained, it will necessarily increase the contribution of the passive structures. The anterior band of the inferior glenohumeral ligament complex has a major role in limiting the abduction-external rotation movement of the overhead throw[13,18]. Increased length of this and other involved structures is responsible for the often observed hypermobility in external rotation[19,20]. Disruption of the anterior band is the most common lesion responsible for anterior glenohumeral laxity[21]. Hypermobility and laxity, however, do not equal instability. In fact, some authors[10,17] state that this hypermobility allows the pitcher to accelerate the ball through a larger range of motion, thus increasing pitching performance. Hypermobility does, however, increase the demand on the stabilizing muscles. The inherently high muscular demands of the overhead throw, combined with this acquired hypermobility, might lead to tensile failure in the connective tissue structures of the muscles involved. We have seen how both the infraspinatus, and especially the teres minor are highly active from late cocking into deceleration[4]. Ventral capsuloligamentous laxity increases their role as ventral stabilizers and is perhaps responsible for the clinically observed palpatory tenderness of them[4,16]. Overuse injuries to the posterior structures might result in the again frequently observed posterior capsular tightness, causing restrictions in internal rotation and horizontal adduction[19,20].

Of course, the glenohumeral muscles are not the only ones affected by fatigue. Scapulothoracic muscular fatigue can result in insufficient lateral rotation-protraction of the scapula, leading to an increased tensile demand on ventral glenohumeral structures during late cocking, and a decrease of the subacromial space[4,5,11,14,22,23].

One of the major pathologies in throwing athletes is the subacromial impingement syndrome, a collective term[24] for conditions such as rotator cuff tendonitis, rotator cuff tears, subacromial bursitis, and bicipital tendonitis. Classically, it was believed that subacromial impingement occurred against the anterior one-third of the acromion, the coracoacromial ligament, and the AC-joint[24]. Some explanations for this type of impingement include:

1. A relative decrease in the force-producing capacity of the external rotators, as compared to the internal rotators, causing impingement of the major tubercle against the acromion, because the infraspinatus and teres major, the main humeral head depressors during abduction, are unable to supply sufficient external rotation and depression[19]. The inability to generate 310±80 (N) of inferiorly directed force during deceleration, for instance, by these humeral head depressors would cause superior translation of the humeral head, decreasing the subacromial space[9].
2. Increased ventrocranial translation of the humeral head as a result of either posterior capsular tightness[17,19,20,22,23,25], or due to ventral muscle guarding[21].
3. Inadequate positioning of the scapula in lateral rotation and protraction during late cocking as a result of scapulothoracic muscle fatigue, muscle tightness, and/or changes in the available scapulothoracic range of motion as a result of adhesions between scapula and thorax, an increased thoracic kyphosis, or hypomobility of costovertebral joints with a fixation of ribs in an expiratory position[13,26].
4. Glenohumeral hypermobility, leading to instability because the force-producing capabilities of the active stabilizers are exceeded, with unwanted humeral head translation. Impingement is very common in patients with instability. Warner et al[19] found that 68% of the 28 patients with instability in their study also presented with subacromial impingement.
5. Physiological decrease in the dimensions of the subacromial space as a result of the combination of flexion, horizontal adduction, and internal rotation in the follow-through phase of throwing[9], superimposed on other pathology.

Another possible area where subacromial impingement might occur is against the postero-superior edge of the labrum[17,24,25]. For this, the term "inside impingement" is suggested to distinguish it from the "outside impingement" described above. Jobe et al[24] state that during surgery of the shoulder in throwing athletes tears are normally found not on the outside of the tendon but on its undersurface. They also mention that there are commonly no signs of subacromial space inflammation, fibrosis, and adhesions in the throwing athlete's shoulder. This is inconsistent with the hypothesis of mechanical subacromial impingement of the outside of the rotator cuff tendons against the undersurface of acromion, coracoacromial ligament, and AC-joint. Jobe et al[24] also found evidence of postero-superior labrum deformation by the major tubercle in cadavers. The deformation impinged the infraspinatus, supraspinatus, and teres minor undersurface at a position of 90 degrees abduction with 90 degrees of external rotation. They confirmed this finding both in in vivo motion studies with volunteers who had Steinmann pins inserted in their shoulders, and during arthroscopic shoulder surgeries. Jobe et al[24] state that this impingement is increased by anterior translation of the humeral head in unstable shoulders and that increased activity of the posterior deltoid in an effort to compensate for an insufficiently active rotator cuff will add to this compression of the humeral head against the glenoid. Glousman et al[5], in their study of electromyographic activity of selected muscles in throwers with and without unstable shoulders, find a significant decrease in subscapularis activity but no significant increase in deltoid activity in the unstable shoulders at the late-cocking position. The activity of the posterior deltoid was not specifically researched, however, so the role of the posterior deltoid remains hypothetical. Jobe et al[24] note that it is this "inside impingement" that causes the often observed posterior shoulder tenderness rather than the tensile overload to the posterior rotator cuff mentioned earlier.

Another structure at risk for injury in the throwing athlete is the labrum[9]. Forces during any movement, including the overhead throw, are produced by both capsuloligamentous structures and by muscles. These internal forces must balance external forces to keep the humeral head in its physiological position. Muscular weakness, muscle fatigue and capsular laxity[9] might result in force requirements not being met. Translation and subluxation of the humeral head in an anterior or posterior direction might also result; this can cause a forceful entrapment of the labrum between the humeral head and the glenoid rim, resulting in labral tearing. This labral entrapment is intensified by internal rotation and compressive forces, referred to by Fleisig et al[9] as the "grinding factor." A faulty throwing technique may add to compressive forces on the labrum; e.g., insufficient body follow-through can lead to an increased compression of the anterior labrum[12].

Another type of labral injury is the SLAP-lesion, indicating the presence of a tear in the superior labrum, extending in both anterior and posterior directions[9]. The tendon of the long head of the biceps attaches to the supraglenoid tubercle, to the anterosuperior and postero-superior labrum, and to the lateral edge of the base of the coracoid[21]. With the arm in internal rotation, as during follow-through, the biceps tendon imparts forces to the posterior labrum; in external rotation, such as in late cocking, stress is transmitted to the anterior labrum. The amount of glenohumeral translation is reduced in all positions by contraction of the long head of the biceps, but mainly at 90 degrees of abduction[21]. Cadaver studies show an increase in torsional rigidity of 32% with a simulated long-head contraction[21]. The long head of the biceps brachii plays a main role in decelerating elbow extension: an eccentric elbow flexion torque of 61±11 (Nm) has been calculated to occur shortly before ball release[9]. The important role of the long head of the biceps in shoulder function is evident. Forces imparted to the labrum by the tendon of the long head of the biceps could however conceivably tear the labrum away from the glenoid rim[9]. Glousman et al[5] found a significant increase in the electromyographic activity of the biceps during the acceleration phase in throwers with glenohumeral instability. Fleisig et al[9] hypothesize that the increased biceps activity is intended to counteract the distracting forces in a lax glenohumeral joint, while at the same time increasing the demond on the biceps—labrum complex with the possibility of a SLAP-lesion. In cadaver studies, this superior labral lesion involving the long head of the biceps has been shown to increase stress on the inferior glenohumeral ligament complex during the late-cocking position[21], in this way contributing to glenohumeral joint laxity, predisposing the athlete's shoulder to further instability.

Conclusion

The overhead throwing motion requires precise coordination between the active and passive structures involved. Muscular fatigue, muscular weakness, muscular tightness, restrictions in joint range of motion, capsuloligamentous laxity, and faulty throwing techniques may lead to a cascade of trauma involving joint surfaces, labrum, bursae, tendons, capsule, ligaments, and muscles. Jobe et al[24] propose an instability continuum that very adequately describes the pathology of the athlete's shoulder:

1. instability, resulting in
2. subluxation, leading to
3. impingement, eventually causing
4. a rotator cuff tear.

Clearly a precise knowledge of the biomechanics of the shoulder and more specifically of the throwing motion is essential in order to successfully rehabilitate the throwing athlete. Throwing has been discussed here not only as a movement in the shoulder complex but also as a total body movement. Physical therapists should be cautious not to concentrate solely on the shoulder for causative factors. For example, changes in the thoracic surface of the scapulothoracic junction need to be considered. Nor should the therapist limit the evaluation to the upper quadrant: Braatz et al[10] mention limited rotation of the left hip or limited great toe extension as causative factors for shoulder complaints in right-handed throwing athletes. Successful rehabilitation of the throwing athlete requires the biomechanical knowledge discussed in this article in order to perform a thorough evaluation to identify the causative factors for the individual patient, as well as to guide the intervention of specific manual mobilization, exercise, modalities, and patient education. ■

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