Mechanics and Pathomechanics in the Overhead Athlete

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KEYWORDS

• Shoulder injury • Mechanics of throwing • Pathomechanics of throwing
• Kinetic chain

KEY POINTS

- Overhead throwing motions are accomplished through activation of the kinetic chain, which produces the normal mechanics.
- It is imperative to be able to identify normal mechanics in order to recognize abnormal mechanics which are known to contribute to injury.
- Since the body works and fails a unit, it should be comprehensively evaluated in order to detect deficits and/or impairments either proximally or distally to the site of symptoms, which then can be restored to allow normal kinetic chain function.

INTRODUCTION

The overhead throwing or serving motion is a complex dynamic activity involving the entire body. It results in the performance of a task that requires repetitive high velocity, high load, and a large range of motion activities with a high degree of precision. It is necessary to have knowledge about the normal mechanics of this motion to understand optimum function of this motion in creating performance, and it is necessary to have knowledge of the altered mechanics or pathomechanics, that exist and contribute to the dysfunction of this motion, creating poor performance and injury.

This article illustrates current knowledge regarding the mechanics of the overhead motion in normal function and discusses the known pathomechanics and how they seem to relate to altered performance, injury, and injury risk. This knowledge has implications for clinical evaluation, treatment guidelines, and rehabilitation protocols.

MECHANICS OF THE OVERHEAD MOTION: WHAT MAKES THE BALL GO

The overhead throwing motion is developed and regulated through a sequentially coordinated and task-specific kinetic chain of force development and a sequentially activated kinematic chain of body positions and motions.[1] The kinematics of both the

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baseball throw and tennis serve have been well described and may be broken down into phases.[2–4] These descriptions show how muscles can move the individual segments and show the temporal sequence of the motions. The kinetics are not as well described but are important due to the forces and motions that are developed. These forces and motions are applied to all the body segments to allow their summation, regulation, and transfer throughout the segments, resulting in performance of the task of throwing or hitting the ball. The term, *kinetic chain*, is used to collectively describe both of these mechanical linkages. Using these definitions and terminology allows a unifying concept to understand the overall mechanics.

An effective athletic kinetic chain is characterized by 3 components[4]: (1) optimized anatomy in all segments; (2) optimized physiology (muscle flexibility and strength and well-developed, efficient, task-specific motor patterns for muscle activation); and (3) optimized mechanics (sequential generation of forces appropriately distributed across motions that result in the desired athletic function).

The kinetic chain has several functions: (1) using integrated programs of muscle activation to temporarily link multiple body segments into one functional segment (eg, the back leg in cocking stance and push-off and the arm in long axis rotation prior to ball release or ball impact) to decrease the degrees of freedom (DOFs) in the entire motion[2,5,6]; (2) providing a stable proximal base for distal arm mobility; (3) maximizing force development in the large muscles of the core and transferring it to the hand[2,7,8]; (4) producing interactive moments at distal joints that develop more force and energy than the joint itself could develop and decrease the magnitude of the applied loads at the distal joint[9–14]; and (5) producing torques that decrease deceleration forces.[12–16]

Several studies have clearly established the basic roles of the kinetic chain, both in baseball and tennis.[7,9–11,14,17–21] Each body part has specific roles in the entire motion.[2] The feet are contact points with the ground and allow maximum ground reaction force for proximal stability and force generation. The legs and core are the mass for the stable base and the engine for the largest amount of force generation. The shoulder is the funnel for force regulation and transmission and the fulcrum for stability during the rapid motion of the arm. The arm and hand is the rapidly moving delivery mechanism of the force to the ball or racquet.

To achieve its role in kinetic chain function, the shoulder must develop precise ball-and-socket kinematics to create maximum concavity-compression[22] that optimizes functional stability throughout the entire range of rapid motion. Requirements for functional stability include optimum alignment of the humerus and glenoid within $\pm 30^\circ$ angulation,[16] co-contraction and compression force couples of the rotator cuff and shoulder muscles,[23,24] a stable scapular base,[25] adequate balanced rotational range of motion,[26–28] and labral integrity to act as a washer, allowing best fit of the humerus into the glenoid.[29]

Tasks performed in baseball and tennis occur as a result of the summation of speed principle, which states that in order to maximize the speed at the distal end of a linked system, the movement should start with the proximal segments (the hips and core) and progress to the distal segments (shoulder, elbow, and wrist).[12] Each segment in this linked system can influence motions of its adjacent segments. For example, during a baseball pitch, stability of the back and stride legs allow rotation of the trunk, which, in turn, allows for maximal throwing arm external rotation. The stable lower extremity serves as a platform for trunk and upper extremity motion, where the amount of trunk rotation is proportionate to the amount of arm motion, which can occur. Variations in motor control and physical fitness components, such as strength, flexibility, and muscle endurance, can affect the efficiency and effectiveness of all segments of the linked system.[5,6,30]

Efficient mechanics can be improved by decreasing the possible DOFs throughout the entire motion.[5,6,31,32] There are 244 possible DOFs in the body from the foot to the hand.[5] Most models of maximum efficiency in body motions find that limiting DOFs to approximately 6 to 8 maximizes the total force output and minimizes effort and load.[32] DOFs can be limited by coordinated muscle activation coupling, called *integrative complexes*, that constrain and couple positions and motions so that several segments move as one.[31] Examples include the back leg stance position in baseball cocking, where the body is stabilized over the planted leg,[2] and the long axis rotation motion in baseball or tennis, where shoulder internal rotation, a minimally moving elbow, and forearm pronation allow the hand to rotate around the long axis from shoulder to wrist.[20]

The few independent DOFs are called nodes and represent key positions and motions in the overhead tasks.[2] These key positions are correlated with optimum force development and minimal applied loads and are considered the most efficient methods of coordinating kinetic chain activation. There may be multiple individual variations in other parts of the kinetic chain, but these are the most basic and the ones required to be present in all motions. The baseball pitching motion can be evaluated by analyzing a set of 8 progressive positions and motions (**Fig. 1**, **Table 1**).[18] These include trunk control over the back leg, hand in pronation "on top of the ball" in cocking, front leg directly toward home plate, control of lumbar lordosis in acceleration, hips facing home plate, arm cocking–scapular retraction/arm horizontal abduction/shoulder external rotation to maintain cocked arm in the scapular plane, "high" elbow above shoulder, and long axis rotation—coupled shoulder internal rotation/forearm pronation—at ball release.[2,9–11,14,17,33] The tennis serve motion can be evaluated by analyzing a set of 8 nodes or positions and motions that are correlated with optimum biomechanics (**Fig. 2**, **Table 2**).[2] These include optimum foot placement, adequate knee flexion in cocking progressing to knee extension at ball impact, hip/trunk counter-rotation away from the court in cocking, back hip tilt downwards in cocking, hip/trunk rotation with a separation at approximately 30°, coupled scapular retraction/arm rotation to achieve cocking in the scapular plane, back leg to front leg motion to create a shoulder-over-shoulder motion at ball impact, and long axis rotation into ball impact and follow-through.[2–4] These nodes can be evaluated by visual observation or by video recording and analysis. An example of tennis-specific pathomechanics is illustrated in **Fig. 3**, with detailed descriptions of the deleterious motions listed in **Table 2**.

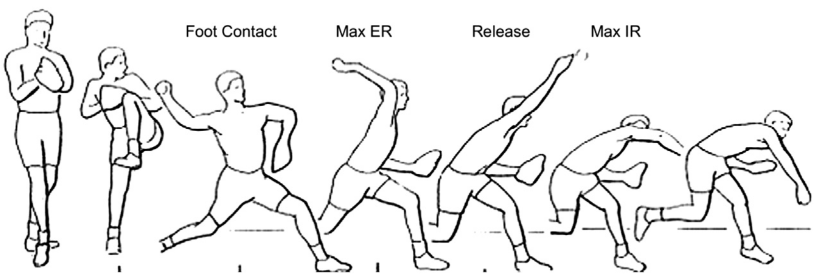

Fig. 1. The phases of throwing. The proper nodes are illustrated throughout the sequence. They include back hip and leg loading, hand on top of the ball, controlled lumbar lordosis, lead foot toward home plate, both hips facing home plate, and long axis rotation. *Abbrevations:* Max ER, maximal external rotation; Max IR, maximal internal rotation. (*From* Fleisig GS, Escamilla RF, Andrews JR, et al. Kinematic and kinetic comparison between pitching and football passing. Journal of Applied Biomechanics 1996;12:207–24; with permission.)

Table 1
Baseball nodes and possible consequences

	Node	Normal Mechanics	Pathomechanics	Result	To be Evaluated
1	Foot position	Directly toward home plate	Open or closed	Increased load on trunk or shoulder	Hip and/or trunk flexibility and strength
2	Knee motion	Stand tall	Increased knee flexion	Decreased force to arm	Hip and knee strength
3	Hip motion	Facing home plate	Rotation away from home plate	Increased load on shoulder and elbow	Hip and trunk strength
4	Trunk motion	Controlled lordosis	Hyperlordosis and back extension	Increased load on abdominals and "slow arm"	Hip and trunk strength
5	Scapular position	Retraction	Scapular dyskinesis	Increased internal and external impingement with increased load on rotator cuff muscles	Scapular strength and mobility
6	Shoulder/scapular motion	Scapulohumeral rhythm with arm motion (scapular retraction/humeral horizontal abduction/ humeral external rotation)	Hyper angulation of humerus in relation to glenoid	Increase load on anterior shoulder with potential internal impingement	Scapular and shoulder flexibility and strength
7	Elbow position	High elbow (above 90° abduction)	Dropped elbow (below 90° abduction)	Increased valgus load on elbow	Scapular position and strength, trunk and hip flexibility and strength
8	Hand position	On top of ball	Under or on side of ball	Increased valgus load on elbow	Shoulder and elbow position

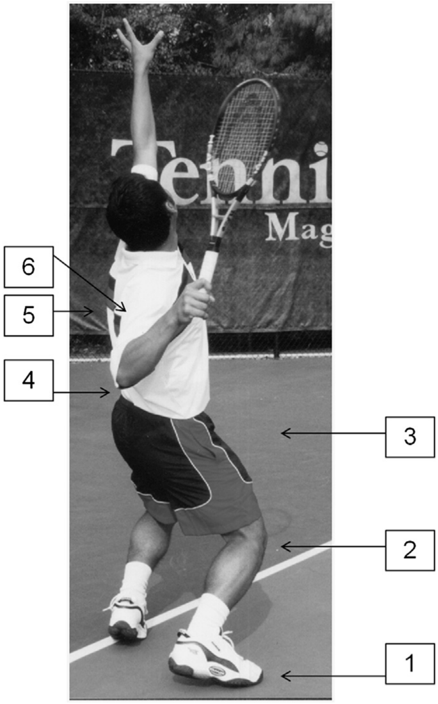

Fig. 2. Proper tennis serve nodes for optimal performance. The number sequence correlates with the normal description in **Table 2**. There is proper foot position and loading, adequate knee bend, back hip counter-rotation and tilt away from the court, X-angle of approximately 30°, trunk rotation, and arm cocking in line with the scapula. (*Adapted from* Lintner D, Noonan TJ, Kibler WB. Injury patterns and biomechanics of the athlete's shoulder. Clin Sports Med 2008;27(4):527–52.)

Adequate performance of the kinetic chain requires optimum anatomy and physiology. Optimum anatomy must be present in all of the joints in the kinetic chain. Joint injury (such as sprained ankles, unresolved knee injury or stiffness, hip tightness, and back injury) can have deleterious effects for core stability, force production, interactive moment production, and arm position.[4,30] Optimum physiology requires adequate muscle strength, flexibility, and endurance throughout the kinetic chain. It also requires proper muscle activation patterns for core stability, force development, integrative complexes, joint stabilization, and segment deceleration.[4] The optimized anatomy can then be acted on by the optimized physiology to create task-specific mechanics to achieve the kinematics and kinetics that produce the desired result of optimal performance in throwing or hitting the ball, creating the lowest possible risk of injury.

PATHOMECHANICS IN THE OVERHEAD MOTION: WHAT HAPPENS WHEN THE BALL DOES NOT GO

Overhead athletes with a painful shoulder have been shown to have a multitude of possible causative factors contributing to the presenting complaints of pain and decreased function, either by causing the anatomic injury or increasing the dysfunction from the injury. They may be alterations in anatomy, physiology, and/or

Table 2
Tennis nodes and possible consequences

	Node	Normal Mechanics	Pathomechanics	Result	To be Evaluated
1	Foot position	In line, foot back	Foot forward	Increased load on trunk or shoulder	Hip and/or trunk flexibility and strength
2	Knee motion	Knee flexion greater than 15°	Decreased knee flexion less than 15°	Increased load on anterior shoulder and medial elbow	Hip and knee strength
3	Hip motion	Counter-rotation with posterior hip tilt	No hip rotation or tilt	Increased load on shoulder and trunk; inability to push through increasing load on abdominals	Hip and trunk flexion flexibility and strength
4	Trunk motion	Controlled lordosis; X-angle ∼30°	Hyperlordosis and back extension; X-angle <30° (hypo), X-angle >30° (hyper)	Increased load on abdominals and "slow arm"; Increase load on anterior shoulder	Hip, trunk, and shoulder flexibility
5	Scapular position	Retraction	Scapular dyskinesis	Increased internal and external impingement with increased load on rotator cuff muscles	Scapular strength and mobility
6	Shoulder/scapular motion	Scapulohumeral rhythm with arm motion (scapular retraction/ humeral horizontal abduction/ humeral external rotation)	Hyperangulation of humerus in relation to glenoid	Increase load on anterior shoulder with potential internal impingement	Scapular and shoulder strength and flexibility
7	Shoulder over shoulder	Back shoulder moving up and through the ball at impact, then down into follow-through	Back shoulder staying level	Increased load on abdominals	Front hip strength and flexibility, back hip weakness
8	Long axis rotation	Shoulder internal rotation/ forearm pronation	Decreased shoulder internal rotation	Increased load on medial elbow	Glenohumeral rotation

X-angle, measurement of hip/trunk separation angle, the angle between a horizontal line between anterior aspect of both acromions and horizontal line between both anterior superior iliac spines when viewed from above, first described by McLean and Andrisani.[62]

Note: Numbers 1–6 occur prior to the acceleration phase of the service motion whereas numbers 7 and 8 occur after ball impact.

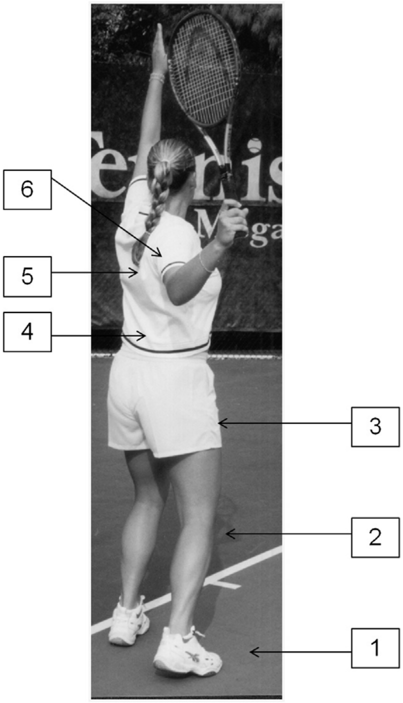

Fig. 3. Improper tennis serve nodes suggested to negatively affect function. The number sequence correlates with the pathomechanics description in **Table 2**. There is minimal foot loading, minimal knee flexion, ho hip rotation or tilting, no trunk rotation, and X-angle of 0°. (*Adapted from* Lintner D, Noonan TJ, Kibler WB. Injury patterns and biomechanics of the athlete's shoulder. Clin Sports Med 2008;27(4):527–52.)

biomechanics. They can combine to produce an alteration in the normal mechanics, resulting in pathomechanics that may create decreased efficiency in the kinetic chains, impaired performance, increased injury risk, or actual injury.[12,21,34] These pathomechanics contribute to the disabled throwing shoulder (DTS),[35] a general term that describes the limitations of function that exist in symptomatic overhead athletes—from baseball players to tennis players—in that they cannot optimally perform the task of throwing or hitting the ball. In a large percentage of cases, DTS is the result of a cascade to injury,[35] a process in which the body's response to the inherent demands of throwing or hitting results in a series of alterations throughout the kinetic chain that can affect the optimal function of all segments in the chain. The most common sites of pathomechanics include the legs and core, scapula, and shoulder. In a closed system, such as the kinetic chain, alteration in one area creates changes throughout the entire system.[29] This is known as the catch-up phenomenon, where the changes in the interactive moments alter the forces in the distal segments.[12,36] The increased forces place extra stress on the distal segments, which often result in the sensation of pain or actual anatomic injury.

Legs/Core

The legs and core connect the body to the ground, producing the ground reaction force that is important for force development, create the proximal base of stability required for distal mobility, and generate more than 50% of the kinetic energy and force delivered to the hand.[7,36] Alterations creating pathomechanics in this area are seen in up to 50% of DTS patients.[1] Alterations can be seen in foot position, knee motion, hip motion/strength, and core stability.

Altered foot position can be a factor in both baseball and tennis. Lead foot placement in baseball should be directed straight toward home plate.[18] Deviations that close the body (stride toward third base for a right-handed pitcher) cause a pitcher to throw across the body, affecting performance (ball/strike ratio) and increasing loads on the hip and oblique muscles. Deviations that open up the body (stride toward first base for a right-handed pitcher) cause a pitcher to throw outside the target area and place increased load on the abdominal muscles, anterior shoulder, and medial elbow. In tennis, positioning of the back foot in a foot forward position alters the ability of the body to rotate into cocking, placing increased stress on the trunk and shoulder (**Fig. 4**). A commonly altered foot position is a compensation for weakness in hip and in trunk flexibility and strength (see **Table 2**).

Alteration of knee flexion has also been associated with increased stresses in the arm. Tennis players who did not have adequate bend in the knees, breaking the kinetic chain and decreasing the contribution by the hip and trunk, had 23% to 27% increased loads in horizontal adduction and rotation at the shoulder and valgus load at the elbow.[21] Quadriceps inflexibility and decreased eccentric strength may alter knee motion.

Weakness or tightness at the hip can also affect other segments. Decreased hip flexibility in rotation or strength in abduction (positive Trendelenburg) was seen in 49% of athletes with arthroscopically proved posterior superior–labral tears.[37] Vad and colleagues[38] reported a 33% increase of low back pain in professional golfers with tight hip muscles. Altered hip and trunk motion was found to increase shoulder loads.[39] The musculoskeletal alterations could potentially be due to tissue maladaptations from repetitively imposed loads.[40] Strength imbalances around the hip and lumbar spine have been demonstrated by many studies, suggesting that these deficits may play a role in the dysfunction of the kinetic chain.[41,42]

Fig. 4. Example of the foot forward position.

Scapula

Scapular dyskinesis is also seen in virtually every athlete with DTS. Dyskinesis represents an alteration of static scapular position or dynamic scapular motion in coordination with arm motion. The altered position and motions create a loss of control of retraction and posterior tilt, resulting in protraction, anterior tilt, and excessive internal rotation. Functional problems include external impingement due to anterior tilt,[43–45] internal impingement due to internal rotation and glenoid antetilting,[46] decreased rotator cuff strength,[47,48] and increased anterior capsular strain.[49] Dyskinesis is associated with 67% to 100% of shoulder injuries.[50]

Shoulder

Alterations in glenohumeral rotation are consistently found in overhead athletes with DTS and are the factors most highly associated with shoulder pain and injury.[1,34,51] They create multiple problems in and around the throwing shoulder, including scapular dyskinesis due to a wind-up of the tight posterior structures,[25] external impingement due to anterior superior humeral head translation in follow-through,[26,52] and posterior superior humeral head translation in cocking and anterior superior translation in flexion, which increase labral shear.[27,35] Increased evidence suggests that both glenohumeral internal rotation deficit (GIRD) and total range-of-motion deficit (TROMD) create the pathomechanics.[34,51]

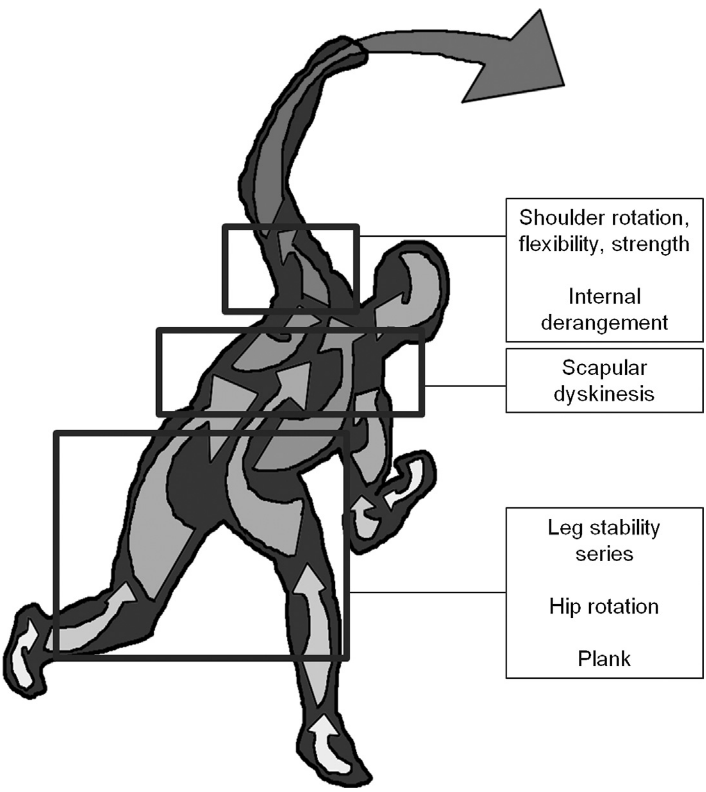

Fig. 5. Illustration of the kinetic chain and the areas of clinical evaluation, as described in **Table 3**.

Table 3
Proximal to distal kinetic chain evaluation

Examination Emphasis	Normal	Abnormal	Result	Evaluation
One leg stability: stance	Negative Trendelenburg	Positive Trendelenburg	Decrease force to shoulder	Gluteus medius strength
One leg stability: squat	Control of knee varus/valgus during decent	Knee valgus or corkscrewing during decent	Alters arm position during task	Dynamic postural control
Hip rotation	Bilateral symmetry within known normal limits	Side-to-side asymmetry and/or not within normal limits	Decrease trunk flexibility and rotation	Internal and external rotation of hip
Plank	Ability to maintain body position for at least 30 s	Inability to maintain body position	Decreased core stability and strength	Dynamic postural control in suspended horizontal position
Scapular dyskinesis	Bilateral symmetry with no inferior angle or medial border prominence	Side-to-side asymmetry or bilateral prominence of inferior angle and/or medial border	Decreased rotator cuff function and increased risk of internal and/or external impingement	Scapular muscle control of scapular position ("yes/no" clinical evaluation,[63,64] manual corrective maneuvers[25,47])
Shoulder rotation	Side-to-side symmetry or internal and external rotation values less than 15° or less than 5°	Side-to-side asymmetry of 15° or more in internal and/or external rotation or 5° or more of total range of motion	Altered kinematics and increased load on the glenoid labrum	Internal and external rotation of glenohumeral joint
Shoulder muscle flexibility	Normal mobility of pectoralis minor and latissimus dorsi	Tight pectoralis minor and/or latissimus dorsi	Scapular protraction	Palpation of pectoralis minor and latissimus dorsi
Shoulder strength	Normal resistance to testing in anterior and posterior muscles	Weakness and/or imbalance of anterior and posterior muscles	Scapular protraction, decreased arm elevation, strength, and concavity-compression	Muscle strength from a stabilized scapula
Joint internal derangement	All provocative and stress testing negative	Pop, click, slide, pain, stiffness, possible "dead arm"	Loss of concavity-compression and functional stability	Labral injury, rotator cuff injury or weakness, glenohumeral instability, biceps tendinopathy

Also, multiple muscles around the shoulder have been found to develop tightness as a result of throwing. The most commonly affected muscles are the pectoralis minor, subscapularis, and latissimus dorsi. The pathophysiology is believed to result from chronic tensile overload and resulting scar or from a muscle adaptive response.[53] The tight pectoralis minor creates a tendency for scapular anterior tilt and acromial downward tilt, decreasing the arm's ability to cock or reach maximal abduction.[43,54,55] The tight subscapularis decreases arm external rotation, limiting arm cocking. The tight latissimus dorsi limits overhead positioning and cocking.

The ultimate pathomechanical factor in the DTS is loss of optimal concavity-compression and functional glenohumeral stability. This can result from a combination of malalignment of the humerus on the glenoid,[56] alteration of muscle force couples, scapular dyskinesis,[49,57] GIRD/TROMD,[26,27] rotator cuff disease,[1] and/or labral injury.[1,58] This results in the performance symptoms of loss of velocity and accuracy and the "dead arm"[37] and in the clinical symptoms of pain, clicking, sliding, weakness, and injury.

CLINICAL IMPLICATIONS

The body works as a unit to achieve optimum overhead throwing function and can fail as a unit in altered performance or the DTS. Therefore, the evaluation of overhead athletes with DTS needs to be comprehensive and can involve evaluation of the pertinent normal mechanics, evaluation of possible pathomechanics, identification of physiologic and biomechanical factors contributing to the pathomechanics, and the kinetic chain examination as well as identification of all pathoanatomic factors that may exist in the shoulder. Similarly, treatment should include optimization of the pathoanatomy as well as restoration of the pathophysiology and pathomechanics.[1]

Evaluation of mechanics and pathomechanics can be clinically accomplished by direct observation and/or video analysis of the motion. Specific methods for evaluation and criteria for determining presence (yes) or absence (no) of the nodes have been developed for baseball[18] and tennis[2,3] and are summarized in **Tables 1** and **2**. This examination can identify anatomic areas and mechanical motions that may be contributing to the symptoms and suggest areas for more detailed evaluation.

The kinetic chain examination should include a screening evaluation of leg and core stability, observational evaluation for scapular dyskinesis, and evaluation of various elements in the shoulder. It should be supplemented by a detailed examination of the areas highlighted by the symptoms or evaluation[30] (**Fig. 5**, **Table 3**).

The shoulder examination should be comprehensive, emphasizing evaluation of the anatomy (labrum, biceps, and/or rotator cuff internal derangement), physiology (muscle weakness/imbalance and flexibility), and mechanics (scapular dyskinesis, GIRD, and TROMD).

Treatment should also involve a comprehensive approach, including restoration of all kinetic chain deficits, altered mechanics, and functional joint stability. Rehabilitation should address all the physiologic and mechanical factors.[1,59–61] These include restoration of hip range of motion and leg strength, core stability and strength, scapular control, shoulder muscle flexibility and strength, and glenohumeral rotation. Surgery should address repairing joint structures to optimize the capability for functional stability.[1]

SUMMARY

Optimal performance of the overhead throwing task requires precise mechanics that involve coordinated kinetic and kinematic chains to develop, transfer, and regulate the forces the body needs to withstand the inherent demands of the task and to allow optimal performance. These chains have been evaluated and the basic components, called nodes, have been identified.

Impaired performance and/or injury, the DTS, is associated with alterations in the mechanics that are called pathomechanics. They can occur at multiple locations throughout the kinetic chain. They must be evaluated and treated as part of the overall problem.

Observational analysis of the mechanics and pathomechanics using the node analysis method can be useful in highlighting areas of alteration that can be evaluated for anatomic injury or altered physiology. The comprehensive kinetic chain examination can evaluate sites of kinetic chain breakage, and a detailed shoulder examination can assess joint internal derangement of altered physiology that may contribute to the pathomechanics.

Treatment of the DTS should be comprehensive, directed toward restoring physiology and mechanics and optimizing anatomy. This maximizes the body's ability to develop normal mechanics to accomplish the overhead throwing task.

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