Biomechanical Analysis of the Throwing Athlete and Its Impact on Return to Sport

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Abstract: Throwing sports remain a popular pastime and frequent source of musculoskeletal injuries, particularly those involving the shoulder and elbow. Biomechanical analyses of throwing athletes have identified pathomechanic factors that predispose throwers to injury or poor performance. These factors, or key performance indicators, are an ongoing topic of research, with the goals of improved injury prediction, prevention, and rehabilitation. Important key performance indicators in the literature to date include shoulder and elbow torque, shoulder rotation, kinetic chain function (as measured by trunk rotation timing and hip-shoulder separation), and lower-extremity mechanics (including stride characteristics). The current gold standard for biomechanical analysis of the throwing athlete involves marker-based 3-dimensional) video motion capture. Emerging technologies such as marker-less motion capture, wearable technology, and machine learning have the potential to further refine our understanding. This review will discuss the biomechanics of throwing, with particular attention to baseball pitching, while also delineating methods of modern throwing analysis, implications for clinical orthopaedic practice, and future areas of research interest. **Level of Evidence:** V, expert opinion.

Throwing sports remain a popular pastime and frequent source of musculoskeletal injuries, particularly those involving the shoulder and elbow.[1-3] The biomechanics of throwing and their impact on injury risk have been extensively studied dating back to the 1980s.[4-7] Early work in understanding the patho-mechanics of throwing injuries relied on detailed video analysis,[4] radar,[8] and electromyography.[5,6] Although increased sophistication of 3-dimensional (3D) motion capture and complex data analysis have engendered a more nuanced understanding of throwing mechanics, the fundamental principles have remained unchanged. These principles include the phases of throwing,[7] kinetic chain,[9] upper-extremity biomechanics,[5,6,10] and throwing pathomechanics.[8] Understanding these foundational concepts is a prerequisite for understanding modern throwing analysis. This review will discuss the biomechanics of throwing, with particular attention to baseball pitching, while also delineating methods of modern throwing analysis, implications for clinical orthopaedic practice, and future areas of research interest.

Biomechanics of Throwing

Phases of Throwing

Throwing a baseball is a complex movement that requires coordination of many steps in a specific sequence to maximize performance and reduce injury risk. The phases of throwing (Fig 1) include wind-up, stride, arm cocking, arm acceleration, arm deceleration, and follow through.[7,9,11] Each phase creates or transfers energy through the body to the arm and to the baseball. While originally described for baseball pitching, these phases are largely consistent for football throwing as well.[12]
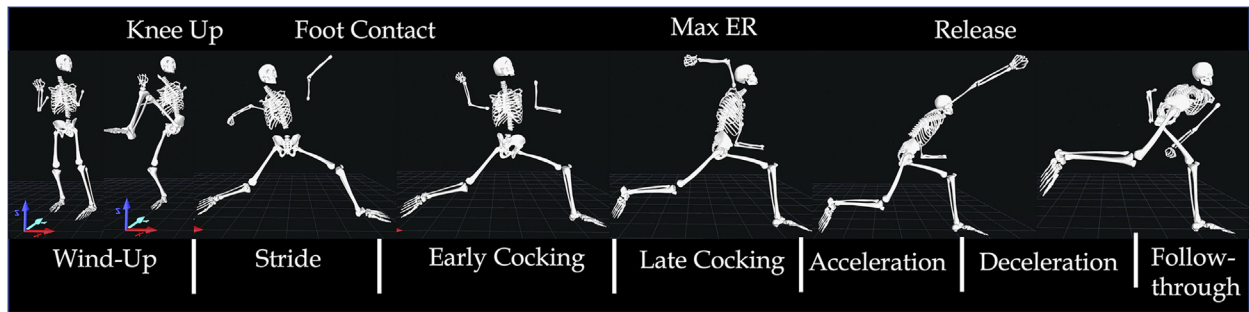
Fig 1. The phases of pitching (as described by Fleisig et al.[8]) demonstrated with skeletal diagrams created during video throwing analysis. (ER, external rotation.)

The throw begins with the wind-up phase, where weight is transferred to the drive leg and potential energy is stored in the form of drive knee bending and truncal rotation. The drive leg exhibits a hip hinging pattern to activate the posterior chain.[11] The stride leg (or lead leg) is lifted to shift the center of mass over the drive leg. This phase ends when the knee lift reaches its peak and center of mass begins to shift toward the stride leg.[11]

The stride phase includes all motion from the maximum lead knee lift until foot strike. Early in this phase, the athlete maintains their hip hinge with the drive leg but pushes into the ground generate a ground reaction force that will allow them to move linearly toward their target (Fig 2). The length of the stride has been shown to correlate with both velocity[13] and elbow varus torque,[14] but a stride length of greater than 80% body height may protect against those elbow torque increases.[15] Stride location is also important; the foot should land in line with the drive leg with the foot pointed slightly internal.[16] As the lead leg gets closer to the ground, the pelvis begins to rotate independently of the torso, creating what is commonly known as hip–shoulder separation. By the completion of the stride phase, the throwing arm should have around 90° shoulder abduction, >35° shoulder external rotation, and >90° elbow flexion to minimize risk of injury.[17,18]

The arm cocking phase begins at foot strike and ends at maximum shoulder external rotation (MER). The lead leg serves as a stable base for rotation for the remainder of the throw, so lead knee flexion should be at its greatest at foot strike and decrease before ball release. Soon after foot strike the pelvis should stop rotating, allowing for energy transfer up to the torso. Rotation of the upper half will close the hip–shoulder separation previously created and allow for the throwing arm to externally rotate even more. Ideally, the shoulder will reach 170° to 180° of MER while maintaining 90° shoulder abduction and >90° elbow flexion.[9] Limitations of external rotation can reduce ball velocity[19] and increase shoulder joint loading.[20]

Once MER has been achieved, the arm begins to accelerate toward the throwing target. This phase, appropriately named the arm-acceleration phase, consists of the time between MER and ball release. While the arm moves towards the target, the torso continues to rotate and tilt forward until stopping rotation just before ball release, generating and transferring as much energy as possible to the arm. During this time, the lead knee is extending to better stop the pelvis and transfer energy from the lower extremities to the torso to the arm. The shoulder switches from externally rotating to internally rotating and the elbow extends to transfer energy to the hand and baseball at ball release. This phase creates the highest demands of force and torque on the shoulder and elbow with peak angular velocities for professional pitchers of ~6,200 deg/s and ~4,600 deg/s for shoulder internal rotation and elbow extension, respectively.[21]

Following ball release, the arm deceleration phase continues until maximum shoulder internal rotation. Now that the athlete's arm has reached this extremely high angular velocity and released the ball, the arm must decelerate in a safe, controlled manner. After ball release, the torso rotates and tilts forward again to clear space for the arm as the forearm continues to pronate as well. The muscles of the shoulder, arm, upper back, and chest work under high stress to slow down the arm and decrease joint loading.

The follow-through phase consists of any movement after the shoulder reaches maximum shoulder internal rotation until the arm is no longer in motion. This phase can look very different for each athlete depending on their arm slot, lower half mechanics, and other factors.

Kinetic Chain

Throwing athletes generate velocity through a synchronized transfer of core and lower-extremity energy to upper-extremity torque, rotation, and angular velocity. Potential energy stored during the wind-up through weight transfer and truncal rotation loads the body like a torsion spring. This energy is then
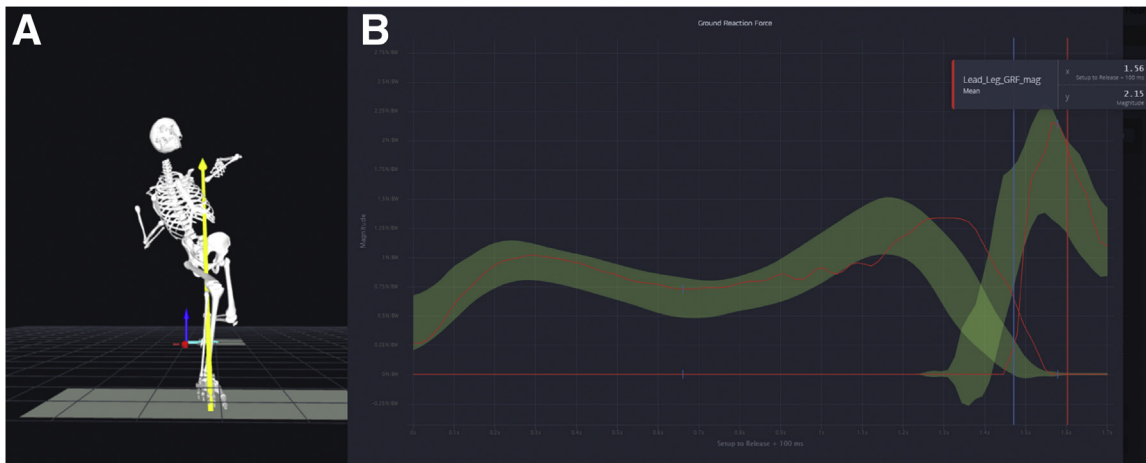
Fig 2. Example of ground reaction force measurement during throwing analysis. (A) Skeletal model based on 3-dimensional marker data. The yellow vector represents the resultant ground reaction force measured with force plates embedded in the pitching mound. (B) Representative graph of the plant leg and lead leg ground reaction force. The green area represents the mean for college pitchers.

transferred to the shoulder and elbow and converted to kinetic energy and centripetal force that accelerates the ball in the desired direction. Efficient summation and transfer of core and lower-extremity potential energy to upper extremity kinetic energy is critical for high-level performance and injury prevention. The mechanism that facilitates that energy transfer has been termed the kinetic chain.[22]

A functional kinetic chain consists of 3 components: optimized anatomy, sequential generation of forces, and efficient motor patterns.[23] Optimized anatomy refers to strength, flexibility, and power of the many independent functional segments of the body, or kinetic links.[24] Important kinetic links for throwing include the feet, lower extremities, hip and pelvis, trunk, scapulothoracic articulation, shoulder and elbow, and distal extremity.[25] During a throw, forces are sequentially generated by the various segments of the kinetic chain and coordinated to accelerate the ball in the desired direction. Efficient task-specific motor patterns allow for minimal energy loss during transfer between independent segments of the kinetic chain.

Dysfunction of the kinetic chain can occur due to disruption of anatomy (e.g., loss of shoulder range of motion, lack of hip internal rotation), inappropriate distribution of forces between segments (relying too much on arm strength without lower-extremity activation), or inefficient motor patterns (scapular dyskinesis).[22] It has been reported that the legs and trunk account for 51% to 55% of the kinetic energy delivered to the hand during a throw.[26] When the kinetic chain is not functioning correctly, the upper extremity tries to "catch up," which increases the forces on the shoulder and elbow placing players at risk for injury.[27] This was highlighted by a recent study comparing professional pitchers with upper-extremity injuries with those who

completed the season without injury.[28] During both stride leg and drive leg balance tasks, injured pitchers were found to have significantly worse lumbopelvic control consistent with a dysfunctional kinetic chain.

Evaluation of kinetic chain dysfunction can be performed with a stepwise proximal to distal approach, which has been described by Kibler et al. and others.[22,26] Each link in the kinetic chain is separately evaluated for strength, range of motion, coordination, and internal derangements. Preventative training or postinjury rehabilitation can be tailored to address dysfunctional links in the kinetic chain and improve coordination between segments.[25] During modern throwing analysis, kinetic links are examined before the throwing task. Video motion capture is then used to examine the efficiency of the kinetic chain. Hip–shoulder separation (Fig 3) is a key indicator of this kinetic chain function, as it represents the loading of lower extremity into a torsion spring through the core. It has been demonstrated that hip–shoulder separation at front foot contact correlates with trunk rotation velocity, which in turn correlates with pitch velocity.[13,29]

Shoulder and Elbow Biomechanics

The upper extremity becomes active starting in the stride phase of throwing with initial external rotation and abduction of the humerus into a semicocked position.[16,27] With 6 degrees of freedom, the scapula protracts, tilts anteriorly, and rotates laterally.[11] The trunk and shoulder translate toward the target as the stride ends, but the elbow and hand lag behind resulting in extreme shoulder external rotation. Scapular position changes to accommodate this motion within the subacromial space. At maximum external rotation, the scapula is positioned in maximum retraction, lateral
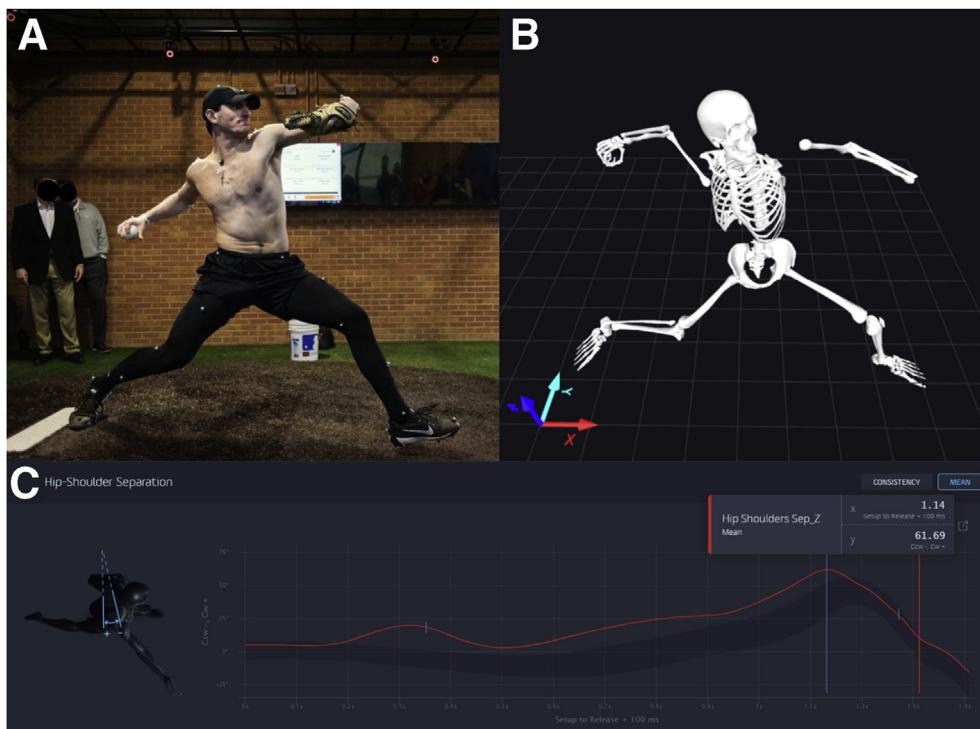
Fig 3. Example of a 3-dimensional (3D) biomechanical throwing analysis. (A) Right-handed pitcher wearing a 41 retroreflective marker set. (B) Skeletal model based on 3D marker data. (C) A graph of hip—shoulder separation, a measure of the rotational difference between the pelvis and the trunk, and just one of the kinematic metrics calculated in a 3D biomechanical analysis.

rotation, and posterior tilt.[11] The elbow flexes and the hand is maintained on top of the ball. The rotator cuff activates in concavity compression to maintain the stability of the glenohumeral joint.[5,27] A "critical instant" occurs just before MER and the maximum elbow varus torque is reached.[8]

As the throw progresses from late cocking to early acceleration, there is a large transfer of potential energy to kinetic energy, which places a great deal of stress on the glenohumeral and elbow joints. In the shoulder, shear forces on the anterior and superior aspect of the joint must be resisted by the capsule, rotator cuff, and labrum.[26] In the elbow, a supraphysiologic valgus load is placed on the ulnar collateral ligament, which is partially shielded by the flexor pronator mass, biceps, and triceps.[26] At this stage, elbow flexion angle determines the perpendicular distance between the ball and the long axis of the humerus thereby controlling the axial torque on the humerus and glenohumeral joint.[16,26] Elbow extension begins slightly before

Table 1. Steps in a Pitching Evaluation at Our Institution

1. OnBaseU* functional movement screen
2. Assessment for scapular dyskinesis
3. Shoulder and hip passive range of motion (ROM)
4. Rotator cuff and grip strength
5. Player selected warm-up
6. 3D biomechanical evaluation (12 motion analysis cameras: surrounding the mound at approximately 12 feet; 4 high-speed video cameras: front, back, overhead, open side; 3 multi-axial force plates: 1 under the rubber, 2 in the "landing" zone)
   a) Place 41 retroreflective markers (Fig 4)
   b) Static standing trial
   c) Acclimation pitches without data collection
   d) Four pitches of each pitch type in the player's repertoire (4-seam fastball, sinker, slider, curveball, change up, etc.) with motion analysis, video, and force collected simultaneously
   e) Removal of markers
7. Calculations, feedback, and intervention
   a) Full body kinematics, kinetics, and spaciotemporal variables are calculated (Table 2 lists some key performance indicators)
   b) Web-based reports are generated
   c) Biomechanical, ROM, strength, and mobility feedback added to reports
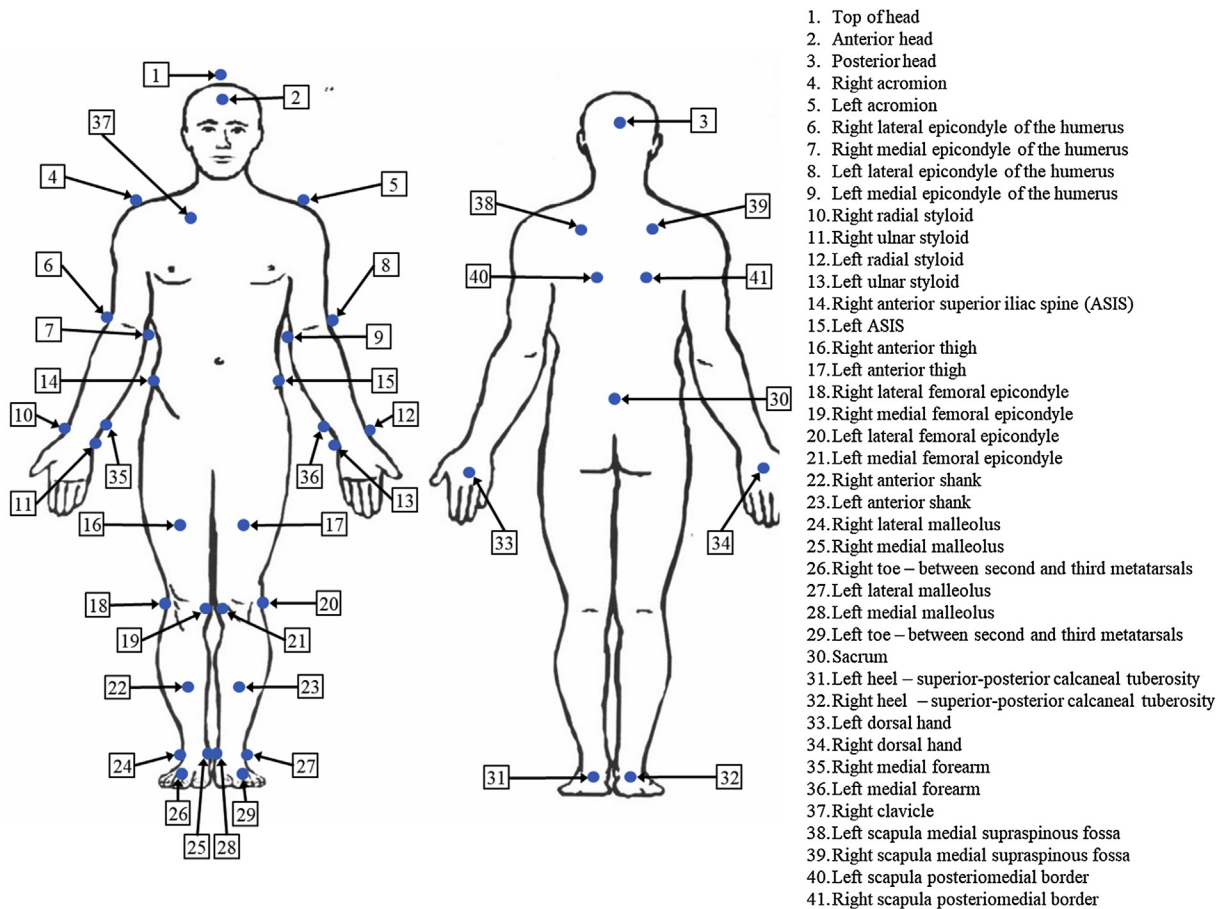   d) Follow up session to discuss correctives based on feedback

*OnBaseU (Oceanside, CA).

1. Top of head
2. Anterior head
3. Posterior head
4. Right acromion
5. Left acromion
6. Right lateral epicondyle of the humerus
7. Right medial epicondyle of the humerus
8. Left lateral epicondyle of the humerus
9. Left medial epicondyle of the humerus
10. Right radial styloid
11. Right ulnar styloid
12. Left radial styloid
13. Left ulnar styloid
14. Right anterior superior iliac spine (ASIS)
15. Left ASIS
16. Right anterior thigh
17. Left anterior thigh
18. Right lateral femoral epicondyle
19. Right medial femoral epicondyle
20. Left lateral femoral epicondyle
21. Left medial femoral epicondyle
22. Right anterior shank
23. Left anterior shank
24. Right lateral malleolus
25. Right medial malleolus
26. Right toe – between second and third metatarsals
27. Left lateral malleolus
28. Left medial malleolus
29. Left toe – between second and third metatarsals
30. Sacrum
31. Left heel – superior-posterior calcaneal tuberosity
32. Right heel – superior-posterior calcaneal tuberosity
33. Left dorsal hand
34. Right dorsal hand
35. Right medial forearm
36. Left medial forearm
37. Right clavicle
38. Left scapula medial supraspinous fossa
39. Right scapula medial supraspinous fossa
40. Left scapula posteriomedial border
41. Right scapula posteriomedial border

Fig 4. Marker locations for video motion capture throwing analysis.

humeral internal rotation to reduce the moment of inertia of the upper extremity kinetic link and allow for greater angular velocity with less torque.[16]

The completion of the throw involves humeral internal rotation and elbow extension as the ball accelerates towards the target. Once the ball is released, the arm experiences a second "critical instant" where the maximum glenohumeral distraction force occurs.[8] The shoulder must be safely decelerated, compressed, and stabilized by forceful contraction of the infraspinatus, teres minor and major, latissimus dorsi, and posterior deltoid.[11] Elbow extension must also be decelerated by way of eccentric contraction of the elbow flexors. The scapula decelerates and derotates back to its resting position through action of the trapezius, rhomboids, and serratus anterior.[30] Finally, the follow through dissipates the remaining kinetic energy of the throw through the stride leg as the arm reaches its terminal position of internal rotation and adduction.

Modern Throwing Analysis

Modern throwing analysis is designed to capture a wide breadth of the biomechanical variables discussed previously from a series of recorded throws. These variables are referred to as key performance indicators (KPIs) and are compared with population norms throughout the phases of throwing for a given level of competition (i.e., youth, high school, collegiate, or professional). The steps for a complete video motion capture pitching assessment at our institution are outlined in Table 1 (Fig 4).

In brief, players present initially for a physical examination and functional movement evaluation. This is followed by a warm-up, which is left to player preference. Motion-capture markers are then applied followed by acclimation of video motion capture equipment. Finally, players will throw a series of pitches that are subsequently analyzed for KPIs, which are outlined in Table 2. Once this analysis is performed, a follow-up session is scheduled to discuss the results and educate the player on biomechanical factors that may increase their risk for poor performance or injury. While it has been used in prior throwing analysis research,[5,6,10,31,32] electromyography is not routinely performed at our institution.

Pathomechanics

From a clinical standpoint, there are 2 key questions regarding throwing analysis: (1) Can biomechanical

Table 2. Key Performance Indicators (KPIs) Measured at Our Institution

Ball Speed	Shoulder Abduction/horizontal Abduction at Foot Strike
Stride length	Shoulder abduction at release
Back leg GRF max	**Maximum shoulder external rotation (MER)**
Lead leg GRF max	**Elbow angle at MER**
Pelvis rotation at MER	Elbow angle at release
Hip-shoulder separation at foot strike	Elbow angle at foot strike
Trunk lateral tilt at foot strike	**Max elbow varus torque**
Trunk forward flexion at foot strike	Thorax angular velocity max
Knee flexion angle at release	Humerus angular velocity max
Trunk forward flexion at release	Elbow extension velocity max
Trunk lateral tilt at release	Pelvis angular velocity max
Trunk rotation at release	Lead knee angular velocity max
Time between max pelvis rotation velocity and max trunk rotation velocity	

NOTE. Bolded font indicates the most clinically relevant KPIs.

GRF, ground reaction force; MER, maximum shoulder external rotation.

measurements (KPIs) predict injury, and (2) can we modify abnormal mechanics to prevent injury? There has been extensive research investigating musculoskeletal health in baseball, but relatively few papers that directly address these questions. In a scoping review of 583 articles relating to musculoskeletal health and baseball, only 24 studies (5%) compared attributes of injured and uninjured players, and only 11 studies (2%) were identified that directly investigated injury prevention.[1] Nevertheless, some throwing parameters have been identified in the literature as risk factors for injury. Chalmers et al.[33] reviewed the relationship between throwing mechanics and injury and noted that the most significant factors included elbow varus torque, elbow flexion at ball release, altered knee flexion at ball release, fatigue, shoulder external rotation torque, and early trunk rotation (i.e., loss of hip−shoulder separation).

Elbow varus torque has been extensively studied. Elbow varus torque is correlated with pitch velocity, MER, and arm slot at ball release.[34] Relationships have been reported between elbow varus torque and increased risk of elbow injuries. In a study of 23 professional pitchers monitored for 3 years after throwing analysis, those with increased shoulder and elbow torque values had higher rates of elbow injury.[35]

Early trunk rotation and loss of hip−shoulder separation are other pathologic KPIs that are measured during throwing analysis. As discussed, these factors are measured to evaluate the thrower for kinetic chain dysfunction. Improper trunk rotation sequences have been shown to increase shoulder forces by 9.2% body weight.[36]

While most throwing analyses occur during a short pitching session with few pitches, this may fail to identify pathomechanics that develop with fatigue. In a study of 28 adolescent pitchers, Erickson et al.[37] identified deterioration of kinetic chain mechanics as pitch count increased during a simulated game. Specifically,

hip−shoulder separation decreased while upper-extremity variables remained unchanged. Hip−shoulder separation is critical for energy transfer through the core muscles.[9] With less efficient core muscle energy transfer, there is increased demand on the throwers shoulder and elbow if the same energy at ball release is to be achieved.[33] Consequently, pitchers in this study lost velocity and had increased reports of arm pain as pitch count increased. In another simulated game study of 11 pitchers, the impact of fatigue on elbow varus torque was examined specifically.[38] After the third inning, medial elbow torque began to increase by 0.84 Nm each inning.

Static shoulder range of motion is also relevant due to the increased risk of injury noted with external rotation motion restriction. In a systematic review and meta-analysis of 15 studies, throwing athletes with preseason external rotation limitation (defined as throwing arm $<5°$ greater than non-throwing arm) had an increased risk of injury with an odds ratio of 1.90.[39] It should be noted that this study pooled all throwing athletes, and results may not be generalizable to just baseball athletes specifically. In a more focused meta-analysis of 3 studies investigating range of motion in baseball throwers, internal rotation and total range of motion were found to be significant predictors of injury but external rotation was not.[40]

While the associations between KPIs and injury risk have become increasingly clear to clinicians, a second question remains: are the KPIs measured in throwing analysis modifiable in a way that prevents injury? This represents a research gap in the literature[1] and is an area that requires further research. Data thus far suggest that throwing mechanics are indeed modifiable. In a study of 46 pitchers with serial throwing assessments at an average of 12 months apart, 44% of flaws identified at the index assessment had been corrected.[41] It remains to be shown whether this translates to injury prevention. Challenges in this pursuit include the

Fig 5. Return-to-sport protocol with kinematic assessments, video motion capture throwing analyses, and incorporation of next-generation technology (including wearable devices and marker-less motion capture). This protocol is adapted from Sgroi and Zajac[42] with additions to reflect the role of biomechanics assessments and emerging technologies. (KPI, key performance indicators; ROM, range of motion.)

necessity of longitudinal throwing analysis data and injury reporting, the ethical limitations of a control group without modification of throwing pathomechanics, selection bias in pitchers presenting to throwing analysis centers and the multitude of confounding factors that contribute to athletic injuries.

Return to Sport

The role of throwing analysis in determining safe return to sport is another key area of interest that is under-represented in the literature to date. Sgroi and Zajac[42] proposed a return to throwing protocol after shoulder and elbow injury with a stepwise, criteria-based approach: (1) no pain or swelling in the affected joint, (2) restore baseline range of motion, (3) restore baseline strength, (4) assess for normal scapular position, (5) asymptomatic plyometric strength progression, (6) interval throwing and workload monitoring, (7) mechanics assessment, and (8) return to full competition. Biomechanical throwing analysis may have an important role in both the assessment of scapular position and throwing mechanics assessment, which are two steps along the return to sport cascade. Recognition of persistent pathomechanics (i.e., abnormal KPIs) at these stages has the potential to prevent reinjury, but this has yet to be shown in prospective studies. In addition, routine preinjury baseline throwing assessments can establish an athlete's true baseline for ROM, strength, and mechanics which can be used for comparison during the recovery protocol. Our recommended return to throwing protocol, adapted from Sgroi and Zajac, incorporates video motion capture throwing analysis, wearable technology, and marker-less in-game monitoring as outlined in Figure 5.

Future Directions

While throwing analysis still relies on video motion capture, which was performed as far back as the 1980s, the precision of measurement and complexity of analysis has continuously evolved. One area of recent progress has been the analysis of scapular mechanics. Scapular motion is challenging to accurately model with motion capture instruments.[43] Increasing the number of calibration stages for scapular marker clusters placed on the acromion can improve accuracy, but this is not practical for all applications.[44] A recent study sought to improve modeling of scapular kinematics using machine learning algorithms to better predict scapular motion based on 3D video motion capture.[45] Scapular position predicted by the model was within $10°$ of the positions measured by biplanar fluoroscopy. Further refinement of these models using similar computational techniques is an ongoing area of research.

Another topic of recent interest has been wearable technology for throwing analysis, which has the potential for more widespread use and could be incorporated into in-game throwing analysis. It also may have a role in guided rehabilitation particularly after ulnar collateral ligament reconstruction, as elbow varus torque can be monitored in real time.[46] In a study using a wearable inertial device, elbow varus torque increased with long toss distance, a rehab variable that can be easily modified.[47] One question with these devices has been the validity of their measurements. Camp et al.[48] compared a wearable inertial measurement unit (MotusBASEBALL; Motus Global, Inc., Massapequa, NY) with gold-standard video motion capture in 10 varsity-level high school pitchers. While the wearable unit had good-to-excellent reliability with repeated measurements, significant differences between the gold standard and wearable unit were noted for arm slot, arm stress, and shoulder rotation. There was no difference in arm speed between the 2 measurement techniques. In a similar study, Boddy et al.[49] used the same device and found strong correlations between the wearable technology and gold standard, but with significant differences in the magnitude of measurement for arm slot, arm speed, arm stress, and shoulder rotation. Taken together, these results suggest that there may be a role for wearable device measurements but that these measurements cannot be directly compared with video motion capture values reported in the literature. Further research is required to clarify the role of this device and others.

Of all measurements discussed so far, a common theme is some degree of wearable or marker-based attachment to a player's body to assist in measurements. A possible new frontier exists in marker-less tracking. Studies have begun to apply this technology for analysis of gait,[50-52] jumping,[53] and baseball

swinging.[21] Application of marker-less technology to throwing has not been sufficiently validated to date, but research is ongoing, In a study comparing marker-based to marker-less motion capture during gait, differences between the 2 techniques were only 2.1 cm, 2.4 cm, and 1.1 cm for segment locations at the shoulder, elbow, and wrist, respectively.[50] In 2020, Major League Baseball also introduced a motion capture system for in-game use. This system (Hawk-Eye Statcast; Hawk-Eye Innovations Ltd., Basingstoke, UK) relies on 12 cameras positioned around an MLB ballpark. Five cameras are used for pitch tracking and operate at 100 frames per second, whereas 7 others are dedicated to player and batted ball tracking at 50 frames per second.[54] Reported measurement capabilities include pitcher mechanics, release point, spin rate, spin axis, ball speed, and ball trajectory in addition to potential hitting and fielding-based metrics. Other systems with similar capabilities include KinaTrax (KinaTrax, Inc., Boca Raton, FL), SIMI (Simi Reality Motion Systems, Unterschleißheim, Germany), Theia3D (Theia Markerless, Inc., Kingston, Ontario, Canada), and DARI Motion (DARI Motion, Overland Park, KS). There is no peer-reviewed literature available to date to determine these systems' relative validity or injury-prevention capabilities, but the potential is exciting and future research is warranted.

Conclusions

Biomechanical analysis of the throwing athlete is most often performed with marker-based 3D video motion capture. This method allows for the noninvasive measurement of as many as 26 in vivo performance indicators. These measurements allow clinicians to identify pathomechanics that increase the risk of injury or poor performance. While video motion capture has remained the gold standard for throwing analysis for more than 3 decades, there have been recent advances in computational data analysis that may improve measurement precision. In addition, newer technologies are on the horizon including wearable devices and marker-less motion capture. It is important to rigorously validate these evolving technologies with the goal of widespread injury prevention for throwing athletes.

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