

ASSESSING THROWING BIOMECHANICS TO INJURY RISK IN THE BASEBALL PITCHER

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INTRODUCTION

Baseball pitching arm injuries are a significant problem, with injuries rates and surgery continuing to increase across all levels^{5,6,9,25,37}. Pitching injuries have been associated with high volumes of pitch counts³⁰, pitching velocity³, and pitching while fatigued¹⁵. To properly assess pitching arm injury risk, clinicians must evaluate arm (i.e., shoulder and elbow) stress. Pitching arm stress refers to the strain placed on the muscles and joints during the act of pitching³⁸. Evaluation requires a mixture of multifaceted evaluations, across clinical test⁴⁷ and measures and pitching biomechanics^{20,44}.

Sports medicine clinicians must use a mixture of qualitative³⁰ and quantitative⁵ assessments to holistically evaluate⁴⁴ and prescribe interventions to reduce arm injury stress³⁵. These evaluations are necessary for general injury prevention³⁹ and/or assessing a pitchers' ability to return to sport following an injury and/or surgery⁴⁴. In the modern context, sports medicine

clinicians have a plethora of technological tools at their fingertips to evaluate and synthesize these data, allowing for a more data driven evaluation and intervention prescription. While technological tools such as inclinometers²⁸ and dynamometers³¹ can be used to improve range of motion and strength measurement precision, within baseball, the majority of technological evaluations will be focused on pitching mechanical evaluations³²⁻³⁴. This could include qualitative assessment through video³⁹, quantitative markered or markerless biomechanical analyses²⁰, or wearable biomechanical technologies⁴⁵.

In this clinical commentary, we describe the clinical steps and processes involved in evaluating a baseball pitcher. We proceed to describe the various technological tools available to enhance data driven assessments, and how best to properly integrate these tools in clinical and performance contexts. Finally, we will describe two case studies to help provide real world perspectives.

COMMON THROWING MECHANICAL ISSUES THAT PREDISPOSE TO ARM INJURIES

The pitching motion is a complex series of steps that include the windup, stride (early cocking), late cocking, acceleration, deceleration, and follow-through²⁰. Pitching motion pathomechanical adaptations can have implications on increased stress to the elbow and shoulder^{3,33}, which can ultimately lead to injury⁴³. In a prospective cohort of 23 professional pitchers, pitchers that sustained an elbow injury over the course of a season demonstrated greater elbow torque compared to pitchers that did not sustain an elbow injury (91.6 Nm, non-injured: 74.7 Nm)³. In a cross-sectional study of 19 youth baseball pitchers, pitchers that reported shoulder pain demonstrated for every 1 Newton increase in peak proximal shoulder force, there was a corresponding 4.6% increase in the likelihood of shoulder pain²⁷. These data demonstrate that increased forces to the elbow and/or shoulder can predispose



Illustration

baseball pitchers to increased arm injury risk.

There are specific points within the pitching motion to be related to increased arm stress, pain, and/or injury.⁵ Specifically, the proximal to distal sequencing of the lower extremity, following by the timing and positioning of the trunk between stride through late cocking and release^{12,26}, plays a critical element in reducing elbow and shoulder forces while maintaining velocity. In a cross-sectional study of 168 high school and college pitchers, lower extremity ground reaction force was the most influential variable when predicting elbow and shoulder forces³³. Early rotation prior front foot contact has been associated with greater risk of sustaining an elbow or shoulder surgery (Hazard Ratio: 1.69 (95% CI 1.02–2.80))¹². Professional pitchers with a history of elbow or shoulder surgery demonstrated greater lateral trunk tilt at release (surgery: 29.3°, controls: 23.4°)²⁶. These study findings demonstrate the role the lower extremity and trunk play in transferring force to the arm²². Generating ample force through the

lower extremity is an important first step in creating pitch velocity. However, premature trunk rotation contributes to greater arm lag, leading to an overall increase in upper extremity torque^{2,14}. Early trunk rotation may be used as a strategy to increase pitching velocity, allowing for greater time to peak trunk acceleration,² and ultimately pitching velocity⁴². Greater lateral trunk tilt is another compensation strategy, relating to generating greater pitch velocities and arm forces³⁶. Differences in trunk and pelvic pitching kinematics emphasize how proximal-to-distal sequencing, along with increased rotational velocity and joint positioning, impact upper extremity joint loads⁵.

Following lower extremity and trunk sequencing, where the arm is in space during cocking and acceleration can increase elbow and shoulder forces¹⁹. Decreased shoulder abduction below 90 degrees at release has been attributed to greater elbow forces and an increased risk of elbow injuries^{19,23}. In the previously referenced cross-sectional study of 168 high school and college baseball

pitchers, decreased shoulder abduction was an influential variable in predicting elbow and shoulder forces³³. Shoulder horizontal abduction is also attributed to increased elbow and shoulder forces, with greater shoulder horizontal abduction at release increasing strain specifically to the rotator cuff^{13,19}.

CLINICAL ASSESSMENT

Clinical Assessment for the baseball pitcher follows the basic examination plan for all injured athletes. Some modifications are applied based on patient age, physical development, and sport specific risk factors. As with all evaluations, the assessment begins with a medical screening, history, description of the mechanism of injury, pitch type, participation, and context around the specific impetus to seek care (i.e., pain, degrading performance, inability to continue to pitch)^{17,29}.

The information reported in the subjective examination influences the order and content of the objective assessment. The initial assessment serves as the baseline for patient recovery. Subsequent examinations inform knowledge of tissue status, recovery and proximity to return to participation. In youth athletes, serial monitoring of anthropometric measures is critical to determine the influence of morphologic changes impacting healing, recovery, and safe loading throughout the rehab process. Physical examination often begins with an assessment of kinetic chain function including examination of lower extremity and core functional mobility, muscle performance, and balance⁸. Specific to shoulder and elbow assessment, a cervical screen preceding glenohumeral humeral torsion and shoulder mobility including straight plane and total rotational range of motion (ROM) are evaluated in patients with shoulder and elbow pain^{40,41}. Muscle performance testing helps to determine the athletes strength and endurance to safely generate the forces required to pitch, repeatedly. Special tests are used to rule in or out specific shoulder or elbow pathology⁴⁷.

Functional tests and re-examination are critical for monitoring the athletes recovery and ability to adapt to functional, sport specific activities. Return to play and competition are dependent on the outcome of the athletes functional testing, tolerance and successful completion of the interval throwing programs, and early

return to throwing in practice, bullpens and simulated games³⁷.

BIOMECHANICAL AND TECHNOLOGY FACILITATED ASSESSMENT

Ideally, we'd like to have some solution which allowed us to know how strong a tissue was (e.g. the anterior band of the ulnar collateral ligament of the elbow, the biceps anchor at the superior labrum) and then match this up with the actual amount of force going through that tissue when in order to throw a baseball as fast as 100mph. Engineers calculate how much force goes through a structure like a building, and based on these calculations, they then tell the builders what material it needs to be constructed from to make sure the building doesn't fall down. The basic principles the engineers use to do this is largely based on laws described hundreds of years ago by Newton and others, and they have also been applied to humans working in the dark art of "biomechanics". To understand the strengths and limitations of different approaches available to us, we first need to understand a little bit of background to better interpret the accuracy of the numbers these analyses generate.

Figuring out the loads in different tissues during a movement like throwing without embedding sensors in those tissues can be done with some accuracy as long as we can track the movement of the body, and the forces going through the body. This includes things like muscle activity (internally), and reaction forces (externally). Traditionally this required biomechanical laboratories with dedicated staff who had a lot of time on their hands as well as some extremely expensive and often temperamental equipment. Now that we all have a combined high-speed camera and computer in our pockets, you may have heard that the barriers to doing these sorts of analyses have been resolved, however this is not exactly true. Our phone cameras can capture video at very high resolution and very high frame rates, but to even begin estimating the force going through the body, for example, the ulnar collateral ligament at the late cocking phase of throwing, we need to know the exact joint angles, limb and segment masses (and ball weight), as well as muscle forces during that specific throw.

Thinking firstly about the joint angles, if you are only interested in, say, knee flexion angle while someone is walking, then one

camera placed at exactly 90 degrees to the direction of gait will probably be accurate enough to give you an answer within a degree or two. If, however, the limb is moving through more than one plane, as the elbow is during throwing, then we need at least 2, probably more, synchronised cameras to be able to ensure we don't make errors when the arm moves "out of plane".

There are no phone-based apps which can accurately measure muscle activity. There are some algorithms which can make guesses at what are the likely muscle

forces for a given movement, but these will never be able to account for within- and between- athlete differences in muscle activity in executing the same movement. Thus, the forces these models estimate will inherently be less accurate than a solution which captures muscle activity using the 'gold standard' of electromyography (EMG).

While it is considered the "gold standard" for motion capture, there are a lot of assumptions in marker-based motion capture in throwing athletes that may not be valid; principal among these being the

TABLE 1

<i>Method</i>	<i>Strengths</i>	<i>Weaknesses</i>
<i>EMG-driven, marker-based, inverse kinetic (computational) model</i>	<i>Most accurate estimation of actual tissue loads throughout the entire throwing motion (see caveats above)</i>	<i>Tens of thousands of dollars in equipment cost Highly specialised staff required for analyses Marker and EMG set-up will take a minimum of 15 minutes (likely longer) analysis will take much longer - up to days, even weeks. Almost certainly done in a lab, not on a field</i>
<i>EMG-driven, IMU-based inverse kinetic model</i>	<i>Quicker set-up using IMUs - minutes typically Less expensive than marker-based</i>	<i>Probably less accurate for shoulder rotation and elbow extension than marker-based alternatives Need to deal with integrating EMG into the analyses</i>
<i>Marker or IMU-based kinematic model</i>	<i>Very accurate joint estimation captured at high frame rates</i>	<i>No force or muscle activity information so these need to be inferred based on population averages</i>
<i>Markerless kinematic model (multiple cameras)</i>	<i>Quick set-up and relatively quick analyses Quick feedback and visualisation</i>	<i>Not accurate enough for fast moving events like shoulder rotation and elbow extension during throwing to accurately estimate forces</i>
<i>Single camera kinematic analysis</i>	<i>Fast, inexpensive, high-quality images Rapid reporting of key events assuming cameras placed correctly</i>	<i>Can't measure any angles out of plane Need to repeat the analyses with different camera placement for each event of interest (e.g. stride foot contact, shoulder maximum external rotation, ball release, etc.)</i>
<i>Coaches eye</i>	<i>No validity, so you can say whatever you want about the athlete to justify anything you want</i>	<i>No reliability, so you have to remember whatever it was you said last time you "analysed" the athlete to ensure you are not identified as a fraud</i>

Table 1: Options for biomechanical analyses of throwing arranged from most accurate to least accurate. Note that the current time and financial constraints of the more expensive options have reduced substantially over the last decade and are expected to continue to do so as sensor and computing technology continues to improve. EMG=Electromyography; IMU=Inertial measurement unit.

difficulty in tracking the scapula's position. In perhaps the biggest understatement of this issue, this problem may not be trivial.

With these caveats in mind, our options, from "most valid" to "least valid" are shown in the Table 1.

PRACTICAL APPLICATIONS - CASE STUDIES

Case 1. Return to pitching following arm injury

Early in the return to the throwing process, many clinicians opt for simpler, low-cost tools, ranging from coach's eye and drills to slow motion capture with software analytics. Before starting these assessments, athletes must meet all prerequisites: healing time, restored range of motion and strength, and successful completion of a plyometric program. Once these are achieved without issues, throwing drills and programs can begin, focusing on safe and repeatable mechanics^{17-19,46,47}.

Younger athletes tend to struggle more with consistency of mechanics, which can be

attributed to growth and body control issues putting them at risk for injury^{11,16,18,21}. For young athletes, initial throwing drills may involve a towel drill or flag drill, which offer the assessor the ability to see and hear throwing mechanics but also allows the athlete to focus on mechanics verse where's the ball going. The ball with a flag or towel in hand enhances the clinician's ability to visualize the hand position during the throwing motion. (Figure 1).

During the towel drill, you may notice a lagging arm and early elbow extension. With the ball easy to track, you may coach the athlete on a better hand break to help achieve better arm action throughout the motion and throw out in front. The ability to provide a simple cue, such as "shoot for out in front" or "arm up a bit higher" along with positioning a young athlete can help them learn the new position. Providing an object to hit with the towel that is out in front will give visual cue and make it more fun. As throwing

mechanics improve with age, simple techniques are effective for creating safe, repeatable mechanics that reduce injury and stress on growing adolescents.

Towel drills and the coach's eye can be good for global movement faults, but they can miss smaller ones. While you cue for hand break and ball release out in front, a subtle hip drop affecting the stride and kinetic chain can be missed.²⁴ By adding slow-motion capture from your phone camera, it becomes easier to detect faults in balance, stride length, and trunk and arm position during key moments of the throwing motion.

For older adolescent throwers, such as those in high school, basic cues and drills may not be sufficient to refine their throwing mechanics. If the returning athlete experiences performance issues or residual soreness, drawing a line on the image can assist in adjusting mechanics. For example, a pitcher during their return to pitching program reports back soreness. Using a video from behind the athlete, you observe excessive trunk lean to the glove side and can show this to the athlete. Now by drawing a line from the initial direction of setup to the catcher helps to assist in determining where a potential issue may come from. Observing the pitcher's stride foot landing position, the pitcher is landing too closed, leading to upper body compensation (Figure 2). Simple lines help illustrate specific directions of movement, expected planes of movement, or ideal positions at key points.

Depending on their willingness to invest, a clinician may provide more data-driven throwing instructions and adjustments by utilizing specialized programs, multiple synchronized cameras, or marker-less systems. This enables precise guidance on stride length, arm position, and joint load management for athletes who continue to struggle with throwing soreness or pain.

Case 2. Risk Mitigation

To mitigate the risk of injury for a pitcher, employing a combination of sensors and cameras for comprehensive evaluations is conducive for both prevention and return from injury. The most accurate analysis is derived from extensive marker-based or marker-less systems (see biomechanical and technology facilitated assessment section); however, these can be impractical for many users due to cost and space required. Clinicians may therefore utilize a variety

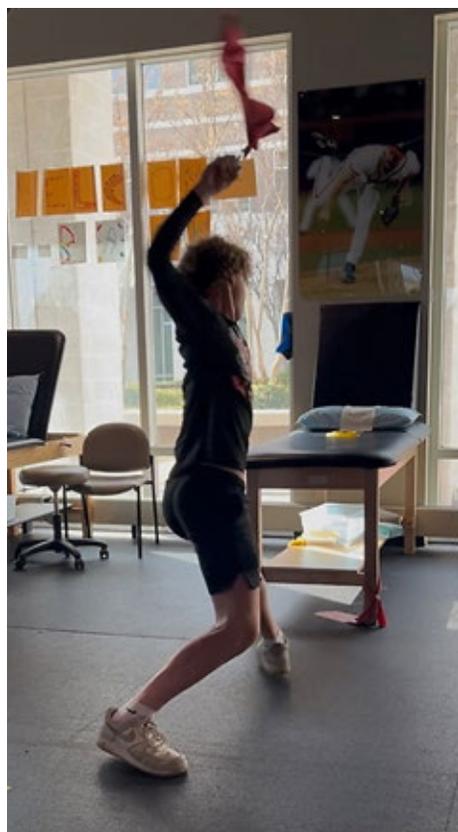


Figure 1: Athlete is demonstrating the towel drill with a flag attached to the ball. The towel allows for the clinician or coach to have both visual and auditory feedback. In this image, you can see the open foot position of the stride leg, and shortened stride length.



Figure 2: Slow motion capture with line drawing. The athlete is presenting with persistent pain. Blue line is drawn from initial foot direction to the catcher. As you can see, the athlete demonstrates excessive glove side lean due to being overly closed at foot contact.

To get a good overall picture with minimal investment, clinicians may use inertial measurement units (IMUs) and video motion capture devices.

of combined systems to assist in reducing injury risk.

Consider a collegiate pitcher undergoing injury risk assessments who has a history of youth and high school injuries but has not suffered an injury in college. Normal screens for upper and lower extremities reveal no mobility or strength deficits. The addition of a biomechanical assessment can help identify dynamic mobility or synchronization problems. To get a good overall picture with minimal investment, clinicians may use inertial measurement units (IMUs) and video motion capture devices. If stride issues are suspected, the athlete can test various stride distances and foot placements to observe joint forces³⁰. However, this minimal setup can miss variables like shoulder-hip separation angles, arm position at foot contact, and rotational speed, which all can affect pitching mechanics and ultimately the forces sustained in the shoulder and elbow³²⁻³⁴.

Currently, this athlete is evaluated using either a marker-based or marker-less system, allowing for precise tracking of every pitch and accurate estimation of forces^{17,19}. When the athlete is demonstrating excessive elbow stress while pitching, the advanced systems can identify what may be causing the issue. A plain stationary camera may show the arm as being in an acceptable spot at foot contact, but when examined with an advanced system the athlete may demonstrate a low external rotation position of the hand in loading prior to max external rotation. By determining the

precise arm slot at foot contact, adjustments to the athlete's hand break technique or changes in stride technique can be made to optimize pitching mechanics to reduce stress on the elbow and shoulder.⁴⁴

Having the athlete pitch on a mound with ground force reaction plates can further enhance clinical and player feedback.³³ This allows the assessor to determine the direction and force of stance and stride legs giving the assessor the ability to cue for longer push-off or more explosive stride knee extension. Improved lower extremity evaluation and feedback can influence the ability to decelerate, improve performance, and assist with injury risk management. For our pitcher who is struggling with increased arm stress and demonstrates a poor stance leg stability and power, the pitcher can be cued to drive the foot down and knee towards second base. Instructing the athlete to push down and drive the knee toward second may help to increase push time down the mound leading to better stride foot position and distance. This can positively influence his ability to get layback and improve his arm lag. If the arm lag and kinetics are not affected from lower half cueing, then looking at other key time frames in the pitching mechanics and help identify risk. The athlete may be staying in hyperabduction too long and can be cued to fix this mechanical flaw. The ability to freeze an athlete's motion captured image with all body angles and forces provides enhanced feedback for the assessor allowing for more input and helping to reduce risk of injury.

CONCLUSION

The sports medicine practitioner should consider both clinical and sport specific assessments when evaluating a baseball pitcher either from an injury risk or performance perspective. Investigating on the table assessments such as range of motion at the shoulder, trunk, hips, shoulder strength, and humeral torsion provides a comprehensive clinical assessment. Sport specific assessments should consider the entire pitching motion, with emphasis at the lower extremity to trunk sequencing, and where the trunk and arm are in space during the cocking and release phases. In the modern context, it is advisable to include both qualitative and quantitative data, with quantitative data informed by the burgeoning technologies across phone, laboratory, and wearable technologies. The two case studies described provide real world context that can be used as templates to guide sports medicine practitioners in evaluating prevention assessments and return to sport following injury.

References

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