

[Athletic Training]



Baseball Pitching Biomechanics in Relation to Injury Risk and Performance

Dave Fortenbaugh, MS, Glenn S. Fleisig, PhD,* and James R. Andrews, MD

Context: Baseball pitching kinematics, kinetics, ball velocity, and injuries at the shoulder and elbow are related.

Evidence Acquisition: PubMed and Sport Discus were searched for original studies published between 1994 and 2008. Relevant references in these studies were retrieved. Inferential studies that tested relationships between kinematics and kinetics were included, as were studies that tested relationships between kinematics and ball velocity. Descriptive studies that simply quantified kinematics and/or kinetics were excluded.

Results: Several kinematic parameters at the instant of foot contact were associated with increased upper extremity kinetics: front foot position, front foot orientation, shoulder abduction, and shoulder horizontal adduction. The timing of shoulder external rotation, pelvis rotation, and upper trunk rotation was associated with increased kinetics and decreased ball velocity. Low braking force of the lead leg and a short stride were associated with decreased ball velocity. Decreased maximum shoulder external rotation, shoulder abduction, knee extension, and trunk tilt were also associated with decreased ball velocity. As pitchers develop, kinematic values remain similar, their variability reduces, and kinetic values gradually increase. Slight kinematic variations were seen among pitch types, although the kinetics of fastballs and curveballs were relatively the same; changeup kinetics were the lowest. As pitchers fatigued, kinetic values remained constant, but increases in arm pain were reported.

Conclusions: Several kinematic parameters were related to joint kinetics and ball velocity. To enhance performance and reduce injury risk, pitchers need to learn proper fastball mechanics at an early age. A changeup is recommended as a safe secondary pitch to complement the fastball; the curveball can be added after fastball and changeup mechanics are mastered. Avoiding overuse and pitching while fatigued is necessary to minimize the risk of arm injury.

Keywords: shoulder; elbow; ball velocity; kinetics; mechanics

As with most other athletic movements, the biomechanics of baseball pitching is studied to improve performance and prevent and/or rehabilitate injury. As technology in the sports science field has developed over the past 20 years, the interest has skyrocketed in using these advancements to the benefit of athletes. The initial studies provided accurate descriptions of the pitching kinematics and kinetics,^{7,9-13,25} which helped athletes, coaches, medical professionals, and scientists understand the demands of pitching. Subsequent research has analyzed factors that correlate to performance enhancement and/or injury. The purpose of this review is to assimilate all the available scientific research on baseball pitching biomechanics related to performance and injury. This information is grouped into 5 areas: kinematics and its relationship to velocity; the association among kinematics, kinetics, and injury; the effects of

fatigue; the development of a pitcher from youth to adult; and the effect of pitch types on mechanics. Over the years, research has been collected from different institutions with assorted methodologies, thereby making it difficult to compare numbers directly. Despite variance in numbers, the commonalities among pathomechanical patterns are most interesting.

KINEMATICS AND VELOCITY

If you ask baseball coaches what elements make a pitcher effective, their responses will be “velocity” and “accuracy.” Pitching coaches and biomechanists have studied the motion of elite pitchers to discern how they consistently throw fast pitches in the strike zone. Limited scientific research exists on the biomechanical factors that affect accuracy, but a lot is known about

From the American Sports Medicine Institute, Birmingham, Alabama

*Address correspondence to Glenn S. Fleisig, PhD, 833 Saint Vincents Drive, Suite 100, Birmingham, AL 35205 (e-mail: glennf@asmi.org).

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kinematic measures that improve ball velocity. Implicit in higher ball velocity are higher kinetic values for the elbow and shoulder.⁹ Pitching kinematic variables affecting velocity are found in upper and lower body measures.

Much of the focus in the literature has been on the upper body, but the lower body is the foundation for baseball pitchers; pitching utilizes the kinetic chain to transfer energy from the lower body to the upper body. MacWilliams et al²⁵ performed one of the first biomechanical studies to examine the contributions of the lower body to pitching. They found that maximum linear wrist velocity (used as an indicator of ball velocity) correlated highly with the maximal push-off force of the throwing leg in the direction of the pitch. Montgomery and Knudson²⁹ demonstrated that decreases in stride length lowered velocity whereas increases in stride length increased velocity without affecting accuracy. The underlying mechanism was unknown. The push-off force supplies the initial forward momentum of the body, whereas the braking force that is applied by the lead leg during and after lead foot contact (FC) is actually the source of the energy that is transmitted up the body to maximize power output.²⁵ Matsuo et al²⁶ compared high- and low-velocity groups of pitchers and found significantly more lead knee extension angular velocity near the time of ball release (BR) in the high-velocity group. They hypothesized that a properly flexed lead knee at FC, approximately 38° to 50°,^{8,10,14,17,37} stabilizes the lead leg for trunk rotation.

Assuming that the lead leg adequately flexes at FC and extends thereafter, the next links in the kinetic chain are the rotations of the pelvis and upper trunk. Escamilla et al⁹ found that Americans had significantly greater maximum pelvis rotation velocity and ball velocity, compared to Korean pitchers. A critical component to maximizing the contribution of each link of the kinetic chain is the proper timing between the rotation of the pelvis and the rotation of the upper trunk. If too much lag or not enough occurs between the movements, the unique contributions of the 2 segments are lost.¹⁶ If pitch cycle time is normalized such that 0% represents FC and 100% represents BR, the instant of peak pelvis rotation velocity is between 28% and 35%, and the instant of peak upper trunk rotation velocity is between 47% and 53%, with a separation of approximately 18% to 22%.^{6,9,17,26} Although Matsuo et al did not directly measure this separation timing,²⁶ the high-velocity group had a separation-timing mean difference of 23%, whereas the low-velocity group had a mean difference of 17%. Stodden et al³⁸ also found, when analyzing pitcher variations, that the pelvis orientation at the times of maximum shoulder external rotation (MER) and BR and the proper rotational velocities of the pelvis and upper trunk translated into higher ball velocities.

The shoulder and elbow are the 2 joints that channel the significant power created by the lower body and trunk through the pitching arm. Because the shoulder complex has 3 degrees of freedom and the elbow, forearm, and wrist have 2 degrees of freedom, the throwing arm has many unique positional combinations. Finding the optimal arm path for a dynamic, explosive movement such as a baseball pitch becomes a

daunting task for any athlete. Ball velocity has been correlated with shoulder positioning at the instant of FC. Increased ball velocity correlates with increased horizontal abduction^{9,37} and decreased external rotation.^{9,42} These correlations apply only within a reasonable range. Excessive horizontal abduction puts additional strain on the anterior capsule of the glenohumeral joint, and late external rotation may disrupt the timing of the arm path. For the higher-velocity group in a study by Escamilla et al,⁹ horizontal abduction was $27^\circ \pm 10^\circ$ and external rotation was $45^\circ \pm 19^\circ$. As the delivery moves into the arm-cocking phase, the amount of MER is linked to increased ball velocity.^{9,26} During arm acceleration, pitchers with higher velocity reach peak shoulder internal rotation velocity closer to the instant of BR (102.3% time versus 104.4% time), optimizing the timing of arm acceleration and BR to maximize ball velocity.²⁶ At the instant of BR, the combination of shoulder abduction and lateral trunk tilt creates the pitcher's arm slot. Matsuo et al²⁸ conducted simulations based on biomechanical data to determine the optimal shoulder abduction angle at BR. It was traditionally taught that 90° maximizes functional stability.³³ Matsuo et al suggested a fairly narrow range centered on 90° that was self-optimized by selecting a comfortable lateral trunk tilt angle to maximize wrist velocity and, therefore, ball velocity.

KINEMATICS, KINETICS, AND INJURY

Performance enhancement and injury prevention often go hand-in-hand in biomechanics. Pitchers occasionally sustain groin and abdominal muscle strains, as well as knee and back soreness, but the overwhelming number of injuries have been at the elbow and shoulder.⁵ The instants of maximum shoulder external rotation and BR are critical for upper extremity kinetics analysis during pitching.¹³ At least 7 kinetic variables have been implicated as mechanisms of injury.¹³ During the arm-cocking phase, which ends at maximum shoulder external rotation, the throwing arm produces maximum anterior shoulder force, horizontal adduction torque, internal rotation torque, and elbow varus torque. During the arm acceleration phase (between MER and BR), maximum elbow flexion torque is achieved. Immediately after BR, when the arm begins to decelerate, maximum proximal shoulder force and proximal elbow force occur.¹³

Injuries are most likely when high forces and/or torques are repeatedly applied to vulnerable tissue and when the pitcher transitions through susceptible positions. Fleisig¹² hypothesized 8 mechanisms that increase kinetic values and the risk of injury. Five of these mechanisms had significant correlations to increased kinetics. An open lead foot angle (for a right-handed pitcher, foot pointing toward left-handed batter) or an open foot position (for a right-handed pitcher, foot landing toward first-base side) at FC can cause the pelvis to rotate too soon. At FC, the normative mechanics are $19^\circ \pm 11^\circ$ closed for foot angle, 19 ± 14 cm closed for foot position, and $30\% \pm 17\%$ for the timing of maximum pelvis rotation velocity.¹⁷ These improper lead foot mechanics and pelvis rotation produce

additional anterior shoulder force and medial elbow force. The timing of shoulder rotation is also important. If there is insufficient or excessive shoulder external rotation at FC, the throwing arm may not be in correct position (thereby adding shoulder stress), or it will lag behind stressing the elbow. In either case, compensations can increase shoulder and elbow kinetics. During arm cocking, a pitcher who excessively adducts the shoulder horizontally (ie, leads with the elbow) increases anterior shoulder force, medial elbow force, and horizontal adduction shoulder torque. This pathomechanical pattern is seen in pitchers who have a compromised ulnar collateral ligament. Increased varus torque leads to increased ulnar collateral ligament strain.^{2,20,21} As such, leading with the elbow lowers varus elbow torque, effectively reducing such strain. These elements may explain the development of shoulder injuries in pitchers with previous elbow injuries.

Although Newton's second law of motion dictates that increasing the acceleration of a constant mass will require an application of more force, the temporal sequencing of the kinetic chain during pitching makes this simple concept much more complex. Ascertaining the safe limit for each kinetic value is also difficult because many factors are dependent on one another (eg, anthropometrics, strength, flexibility, medical history). When assessing kinetic changes due to kinematic variability, the most reasonable approach is to determine which kinematic variables unnecessarily increase kinetic values. Changes in kinematics can increase or decrease velocity or not affect it at all. Clearly, any kinematic pattern that significantly increases kinetic values without increasing velocity is pathomechanical.

A simulation of shoulder abduction and lateral trunk tilt (the pitcher's arm slot) showed that if the values deviated from approximately 10° of lateral trunk tilt and 100° of shoulder abduction, maximum varus elbow torque increased.²⁷ With a shoulder abduction of 90°, linear wrist velocity was maximized and varus torque stayed relatively low.²⁸ Aguinaldo et al¹ showed that professional pitchers generated significantly less normalized shoulder internal rotation torque than that of college, high school, and youth pitchers. The researchers hypothesized that the professional pitchers were able to maximize their efficiency by rotating their upper trunks at the appropriate time, allowing the energy to pass from the trunk to the shoulder at precisely the right sequence. Although both pathomechanical patterns (pelvis and upper trunk rotation) make intuitive sense, Fleisig et al¹⁴ did not find significant differences in the timing of the maximum pelvis or upper trunk rotation velocity. However, there were clinically significant separation timing differences between pelvis and upper trunk rotation: 11% and 12% in youth and high school pitchers, 17% and 18% in college and professional pitchers.

In a study comparing American and Korean pitchers,⁹ there were no significant differences in shoulder and elbow force and torque, despite the fact that Americans threw the ball significantly faster (38.0 m/s to 34.6 m/s). The Koreans displayed 2 significant pathologic kinematic differences: greater shoulder

external rotation at FC (68° to 45°) and less forward trunk tilt at BR (26° to 36°).

FATIGUE

The game of baseball has evolved in many ways, including the use of pitchers. In the early days of baseball, pitchers threw the entire game, regardless of score, inning, or number of pitches thrown. After generations of this approach, managers realized that it was counterproductive to continue to use a pitcher who was fatigued. Epidemiological and biomechanical studies have analyzed pitching to determine the effects of fatigue on performance and injury. The former have focused on pitch counts, whereas the latter have focused on kinematics and kinetics. Combining these 2 factors may be an effective strategy to determine exactly when a pitcher is fatigued.

Research has shown that several factors increase the risk of pain and injury in pitchers. Much of this work has focused on youth pitchers because arm pain is common at that level. In fact, roughly one-half of the 476 participants in a 2002 study of youth pitchers²³ reported elbow or shoulder pain at least once during a season. Lyman et al²⁴ found an increased risk of elbow and shoulder pain by pitchers with self-reported fatigue (5.94 times the risk for the elbow and 4.14 times the risk for the shoulder). The risk of pain increased if they threw more than 75 pitches per game (2.48, shoulder) and more than 600 pitches per season (3.44, elbow). This study supports the theory that high pitch counts lead to fatigue, which can in turn lead to injury. Olsen et al³² reported compelling results of a direct comparison between adolescent pitchers who had elbow/shoulder surgery and those who did not. In this study, pitchers who averaged more than 80 pitches per appearance were nearly 4 times likely to require surgery. Those who pitched competitively more than 8 months per year were 5 times more likely to require surgery. Last, those who occasionally pitched with a fatigued arm were 4 times more likely to undergo surgery, whereas those who regularly pitched with a fatigued arm were 36 times more likely to have an injury that required surgery. Olsen et al concluded that overuse was the overriding factor in the development of arm pain.

Like most athletes, pitchers are generally reluctant to tell coaches that they feel fatigued, even when not telling might be detrimental to both the team and the player. A pitching coach's observational skills and judgment may be best suited to detect fatigue in the pitcher's mechanics and performance. A decline in ball velocity is typically seen in fatigued pitchers.^{8,31} Specific mechanical flaws are also usually present in a fatigued pitcher. Murray et al³¹ filmed pitchers during the first and last innings of games. In the last inning, pitchers achieved significantly less maximum shoulder external rotation and knee flexion at BR, and they threw 2 m/s slower (5 mph). Significantly less shoulder and elbow proximal force and shoulder horizontal abduction torque were applied. Escamilla et al⁸ found that during simulated games, fatigued pitchers had a slightly more upright trunk position at BR. No significant differences in kinetics

were found, although there was a drop in velocity of 1 m/s (2 mph) from the first inning to the last. During simulated pitching, Hirayama et al (unpublished data, 2008) found (1) a negative correlation between the number of pitches thrown in a game and lead hip extension work and (2) a positive correlation between the number of pitches thrown and shoulder horizontal adduction work—all of which suggests that pitchers rely less on the lower body and more on the arm as they fatigue.

Fatigue can affect motor control with losses in proprioception visualized by a significantly different arm path while throwing a baseball.⁴¹ Significant losses of arm strength have been seen after pitching approximately 7 innings and throwing 100 pitches (shoulder flexion, 10%; internal rotation, 14%; humeral adduction, 12%; and grip strength, 8%).³⁰ Like pain, fatigue is generally difficult to quantify because it is a subjective measure that varies among persons. Therefore, pitch counts, ball velocity, ball location, pitching mechanics, and strength may be better guides in determining fatigue.

DEVELOPMENT

A majority of baseball players in the United States are younger than 18 years.³⁶ Therefore, the study of baseball pitching mechanics should be rooted in the development of youth pitchers from the time that they first pick up a baseball through high school. Collegiate and professional pitchers represent the most advanced in both skill and talent. Stodden et al^{39,40} demonstrated that the initial acquisition of the overhead throwing skill is progressive, advancing from a single movement to a sequence of movements utilizing the body as a kinetic chain, which suggests that coordination is essential for developing throwing talent. Ishida et al¹⁹ studied youth aged 6 to 12 years and demonstrated that players 9 and older displayed many of the biomechanical features of adult throwers. The researchers recognized that one possible limitation for the young thrower may be the weight of the baseball. Fleisig et al,¹⁸ however, did not find significant differences between the arm paths of youth pitchers between 9 and 12 years who used lightweight and standard-weight baseballs. But the researchers' study did report significantly lower kinetic values with lightweight balls, suggesting that they may lessen the risk of an overuse injury. In another study, Fleisig et al¹⁴ found few kinematic and temporal differences among youth, high school, college, and professional pitchers. Nearly all the kinetic values increased at each level of development.

Most complex skills such as baseball pitching take years of practice and thousands of repetitions to master. Fleisig et al¹⁵ measured the change in variability in pitching biomechanics at different levels of development by comparing the standard deviations of relevant parameters. Their study found that variability of several kinematic parameters decreased as the level of development increased: foot placement, knee flexion at FC, maximum upper torso angular velocity, maximum elbow flexion, maximum shoulder external rotation, and forward trunk tilt at BR. Differences in kinetic parameters, however, were not significant. The researchers concluded that

there was no increased risk of arm injury due to variability in pitching mechanics. They also noted that the largest changes occurred between youth and high school pitchers, and they emphasized the importance of teaching proper mechanics at an early age.




As youth pitchers approach physical maturity, their growing bodies are susceptible to a multitude of pathologies; therefore, the need to refine mechanics through repetition remains constant. During puberty, bones grow rapidly at the physes, which are weaker and therefore more susceptible to avulsion fractures. These fractures are most common during youth because ligaments and tendons are stronger than bones at the attachment sites.³⁴ Sabick et al³⁴ examined the stress that the adolescent proximal humeral epiphysis endures during the pitching motion. Their biomechanical testing suggested that the humeral epiphysis may experience more than 4 times the tolerable load of epiphyseal cartilage.

An extremely common diagnosis in young throwers is "Little League elbow." This inflammation at the medial epicondyle apophysis is the result of repetitive valgus overload during the cocking phase of pitching.⁴ The medial epicondyle is the proximal attachment site for the ulnar collateral ligament, which can tear from repetitive stress.³⁵ These injuries have led youth organizations to adopt strict pitching policies to reduce the risk of injury to athletes.²²

PITCH TYPES



Baseball legend Ted Williams is credited with saying that hitting a baseball is the most difficult thing to do in sports. One factor that makes hitting so challenging is the variety of pitches that a hitter must recognize—fastballs, cutters, curves, sliders, sinkers, changeups, and knuckleballs, to name a few. Theoretically, each has a unique trajectory that is controlled by pitching mechanics. Researchers in recent years have attempted to differentiate kinematic patterns among pitch types, as well as assess the kinetic values associated with each. A few studies compared the kinematics of common pitches in collegiate pitchers.^{3,10,17} The largest differences were found between the fastball and the curveball, and the fewest were between the fastball and the slider. The curveball had significantly more forearm supination (32°) than that of the fastball (17°) and the changeup (18°).³ Fastballs had significantly greater pelvis and upper trunk rotation velocities (600 and 1120 degrees per second, respectively) than curveballs (560 and 1070 degrees per second) and changeups (540 and 1020 degrees per second).¹⁷ The lead knee extended 9° from FC to BR in the fastball and 5° in the curveball, flexing 4° during the changeup deliveries. Pitchers landed with their lead foot 4 cm more closed (for a right-handed pitcher, toward the third-base side of the mound) when throwing curveballs versus fastballs. Maximum elbow extension and shoulder internal rotation velocity (ie, arm speed) were similar between the fastball (elbow, 2210 degrees per second; shoulder, 6520) and curveball (2160 and 6480 degrees per second) but significantly slower in the changeup (1970 and 6360 degrees per second).

Table 1. Summary of pathomechanics associated with increased kinetics and decreased ball velocity.^a

Phase / Event	Proper Mechanics	Pathomechanics → Consequences
Windup	Lift front leg.	
Maximum knee height 	Pitcher is balanced.	
Stride	Front leg goes down and forward. Arms separate, swing down, and up.	↓ Push off rubber → ↓ Ball velocity ²⁴
Foot contact 	Front foot is planted slightly to third-base side (for a right-handed pitcher). Front foot is pointed slightly inward. Shoulder is abducted approximately 90°, with approximately 60° of external rotation.	↓ Stride length → ↓ Ball velocity ²⁸ Front foot open (position or angle) → ↑ Shoulder and elbow force ¹² Improper shoulder external rotation → ↑ Shoulder and elbow kinetics ¹² Excessive shoulder external rotation → ↓ Ball velocity ^{9,40} ↓ Shoulder horizontal abduction → ↓ Ball velocity ^{11,36}
Arm cocking	Pelvis rotation, followed by upper trunk rotation. Shoulder externally rotates, and trunk arches.	Early pelvis rotation → ↓ Ball velocity ^{25,40} Late pelvis rotation → ↑ Shoulder and elbow kinetics ⁴⁰ ↓ Pelvis rotation velocity → ↓ Ball velocity ^{9,40} Poor timing between pelvis rotation and upper trunk rotation → ↓ Ball velocity ^{23,35} Poor timing between pelvis rotation and upper trunk rotation → ↑ Shoulder internal rotation torque ¹
Maximum external rotation 	Shoulder external rotation is approximately 180°. Elbow flexion is approximately 90°.	↓ Shoulder external rotation → ↓ Ball velocity ^{9,23,29} Excessive shoulder horizontal adduction and elbow flexion → ↑ Shoulder kinetics ¹²
Arm acceleration	Elbow extends, followed by shoulder internal rotation. Front knee extends.	

(continued)

Table 1. (continued)

Phase / Event	Proper Mechanics	Pathomechanics → Consequences
Ball release 	The throwing shoulder is abducted approximately 90°	↓ Knee extension velocity → ↓ Ball velocity ²³ Improper shoulder abduction → ↓ Ball velocity ²⁵ Improper shoulder abduction → ↑ Elbow varus torque ²⁶ ↓ Forward trunk tilt → ↓ Ball velocity ^{8,9}
Arm deceleration	Shoulder internal rotation and front knee extension continue. Trunk tilts forward.	
Maximum internal rotation 	Shoulder external rotation is approximately 0°.	
Follow through	Arm crosses in front of body. Trunk flexes forward.	

^a Definition of symbols in chart: ↓, decreased; ↑, increased; →, correlates with.

The forces and torques experienced by the elbow and shoulder joints during various pitch types are important for understanding the mechanics and potential injury risk of each pitch type. In collegiate pitchers, unique kinetic patterns for the fastball, curveball, changeup, and slider have been detected.¹⁷ Six of the 9 kinetic variables were significantly lower in the changeup versus the fastball. The fastball was kinetically similar to the curveball; only proximal elbow force was significantly higher in the fastball. Kinetics were also similar between the fastball and the slider, although sliders were thrown with significantly higher horizontal shoulder adduction torque. These kinetic investigations were partially based on anecdotal evidence targeting the curveball as a dangerous pitch for younger pitchers. Dun et al⁶ analyzed the kinematics and kinetics of 10- to 14-year-olds throwing fastballs, curveballs, and changeups. The fastball had significantly higher values than those of the curveball for elbow varus torque (35 to 32 N·m), shoulder internal rotation torque (35 to 32 N·m), elbow flexion torque (16 to 14 N·m), proximal elbow force (462 to 428 N), and proximal shoulder force (466 to 433 N). Neither the curveball nor the changeup had significantly higher values than those of the fastball, implying that curveballs were not more stressful than fastballs.

At all levels of competition, a good fastball is the foundation for successful pitching; thus, the young baseball pitcher should master the fastball first. The changeup seems to be a good choice for a second pitch, given that it produces lower kinetics in the elbow and shoulder.

SUMMARY

Knowledge of the mechanics that can improve performance and prevent injury is an invaluable resource for doctors, athletic trainers, therapists, coaches, and athletes. Increased ball velocity has been seen with proper separation timing between the pelvis and upper trunk,^{26,38} with greater maximum shoulder external rotation,^{9,26,31} with greater knee extension velocity,²⁶ and with more forward trunk tilt at BR.^{8,9} Some of the mechanics that lead to additional stress on the arm include an open foot position or angle,¹² too much or too little shoulder external rotation at FC,¹² poor timing between the separation of the pelvis and upper trunk rotations,^{26,38} and shoulder abduction angle deviating from 90° at BR.²⁷

Complementing this knowledge of mechanics with the known effects of fatigue, growth and development, and pitch

types enhances our understanding of the demands of pitching. Executing proper, repeatable fastball mechanics is the fundamental skill that all pitchers must learn first. Although curveballs have not been shown to have increased kinetic values over fastballs, it may be wisest to teach the changeup as a second pitch because of the reduced amount of stress that it places on the arm.^{6,10} Pitchers need to be conscious of their fatigue and pain levels at all times and make a concerted effort to avoid pitching when either of these become uncomfortable. Resting between 3 and 4 months between seasons is also advised.³²

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REFERENCES

- Aguinaldo AL, Buttermore J, Chambers, H. Effects of upper trunk rotation on shoulder joint torque among baseball pitchers of various levels. *J Appl Biomech*. 2007;23:42-51.
- Andrews JR, Heggland JH, Fleisig GS, Zheng N. Relationship of ulnar collateral ligament strain to amount of medial olecranon osteotomy. *Am J Sports Med*. 2001;29:716-721.
- Barrentine SW, Matsuo T, Escamilla RF, Fleisig GS, Andrews JR. Kinematic analysis of the wrist and forearm during baseball pitching. *J Appl Biomech*. 1998;14:24-39.
- Benjamin HJ, Briner WW. Little league elbow. *Clin J Sport Med*. 2005;15:37-40.
- Conte S, Requa RK, Garrick JG. Disability days in Major League Baseball. *Am J Sports Med*. 2001;29:431-436.
- Dun S, Loftice J, Fleisig GS, Kingsley D, Andrews JR. A biomechanical comparison of youth baseball pitches: is the curveball potentially harmful? *Am J Sports Med*. 2008;36(4):686-692.
- Elliott B, Grove JR, Gibson B. Timing of the lower limb drive and throwing limb movement in baseball pitching. *Int J Sports Biomech*. 1988;4:59-67.
- Escamilla RF, Barrentine SW, Fleisig GS, et al. Pitching biomechanics as a pitcher approaches muscular fatigue during a simulated baseball game. *Am J Sports Med*. 2007;35(1):23-33.
- Escamilla RF, Fleisig GS, Barrentine SW, Andrews JR, Moorman C. Kinematic and kinetic comparisons between American and Korean professional baseball pitchers. *Sports Biomech*. 2002;1(2):213-228.
- Escamilla RF, Fleisig GS, Barrentine SW, Zheng N, Andrews JR. Kinematic comparisons of throwing different types of baseball pitches. *J Appl Biomech*. 1998;14:1-23.
- Escamilla RF, Fleisig GS, Zheng N, Barrentine SW, Andrews JR. Kinematics comparisons of 1996 Olympic baseball pitchers. *J Sports Sci*. 2001;19:665-676.
- Fleisig GS. *The biomechanics of baseball pitching*. Birmingham, AL: University of Alabama; 1994.
- Fleisig GS, Andrews JR, Dillman CJ, Escamilla RF. Kinetics of baseball pitching with implications about injury mechanisms. *Am J Sports Med*. 1995;23(2):233-239.
- Fleisig GS, Barrentine SW, Zheng N, Escamilla RF, Andrews JR. Kinematic and kinetic comparison of baseball pitching among various levels of development. *J Biomech*. 1999;32:1371-1375.
- Fleisig GS, Chu Y, Weber, A, Andrews J. Variability in baseball pitching biomechanics among various levels of competition. *Sports Biomech*. 2009;8(1):10-21.
- Fleisig GS, Escamilla RF, Andrews JR. Biomechanics of throwing. In: JE Zachazewski, DJ Magee, WS Quillen, eds. *Athletic Injuries and Rehabilitation*. Philadelphia, PA: WB Saunders Co; 1996: 332-353.
- Fleisig GS, Kingsley DS, Loftice JW, et al. Kinetic comparison among the fastball, curveball, change-up, and slider. *Am J Sports Med*. 2006;34(3):423-430.
- Fleisig GS, Phillips R, Shatley A, et al. Kinematics and kinetics of youth baseball pitching with standard and lightweight balls. *Sports Engineering*. 2006;9:155-163.
- Ishida K, Murata M, Hirano Y. Shoulder and elbow kinematics in throwing of young baseball players. *Sports Biomech*. 2006;5(2):183-196.
- Kamineni S, ElAttrache NS, O'Driscoll SW, et al. Medial collateral ligament strain with partial posterior olecranon resection: a biomechanical study. *J Bone Joint Surg Am*. 2004;86(11):2424-2430.
- Levin JS, Zheng N, Dugas J, Cain EL, Andrews JR. Posterior olecranon resection and ulnar collateral ligament strain. *J Shoulder Elbow Surg*. 2004;13:66-71.
- Little League Inc. Protecting young pitching arms. 2008 ed. http://www.littleleague.org/Assets/old_assets/media/Pitch_Count_Publication_2008.pdf. Accessed October 2, 2008.
- Lyman S, Fleisig GS, Andrews JR, Osinski ED. Effect of pitch type, pitch count, and pitching mechanics on risk of elbow and shoulder pain in youth baseball pitchers. *Am J Sports Med*. 2002;30(4):463-468.
- Lyman S, Fleisig GS, Waterbor JW, et al. Longitudinal study of elbow and shoulder pain in youth baseball pitchers. *Med Sci Sports Exerc*. 2001;33:1803-1810.
- MacWilliams BA, Choi T, Perezous MK, Chao EYS, McFarland EG. Characteristics ground-reaction forces in baseball pitching. *Am J Sports Med*. 1998;26(1):66-71.
- Matsuo T, Escamilla RF, Fleisig GS, Barrentine SW, Andrews JR. Comparison of kinematic and temporal parameters between different pitch velocity groups. *J Appl Biomech*. 2001;17:1-13.
- Matsuo T, Fleisig GS, Zheng N, Andrews JR. Influence of shoulder abduction and lateral trunk tilt on peak elbow varus torque for college baseball pitchers during simulated pitching. *J Appl Biomech*. 2006;22:93-102.
- Matsuo T, Matsumoto T, Mochizuki Y, Takada Y, Saito K. Optimal shoulder abduction angles during baseball pitching from maximal wrist and minimal kinetics viewpoints. *J Appl Biomech*. 2002;18:306-320.
- Montgomery J, Knudson D. A method to determine stride length for baseball pitching. *Appl Res Coaching Athletics*. 2002;17:75-84.
- Mullaney MJ, McHugh MP, Donofrio TM, Nicholas SJ. Upper and lower extremity muscle fatigue after a baseball pitching performance. *Am J Sports Med*. 2005;33(1):108-113.
- Murray TA, Cook TD, Werner SL, Schlegel TF, Hawkins RJ. The effects of extended play on professional baseball pitchers. *Am J Sports Med*. 2001;29(2):137-142.
- Olsen SJ, Fleisig GS, Dun S, Loftice J, Andrews JR. Risk factors for shoulder and elbow injuries in adolescent baseball pitchers. *Am J Sports Med*. 2006;34(6):905-912.
- Poppen NK, Walker RS. Forces at the glenohumeral joint in abduction. *Clin Orthop Rel Res*. 1978;135:165-170.
- Sabick MB, Kim YK, Torry MR, Keirns MA, Hawkins RJ. Biomechanics of the shoulder in youth baseball pitchers: implications for the development of proximal humeral epiphysiolysis and humeral retrotorsion. *Am J Sports Med*. 2005;33(11):1716-1722.
- Schwartz ML, Thornton DD, Larrison MC, et al. Avulsion of the medial epicondyle after ulnar collateral ligament reconstruction: imaging of a rare throwing injury. *Am J Roentgenol*. 2008;190:595-598.
- Sporting Goods Manufacturers Association. *U.S. Trends in Team Sports*. Washington, DC: Sporting Goods Manufacturers Association; 2007.
- Stodden DF, Fleisig GS, McLean SP, Andrews JR. Relationship of biomechanical factors to baseball pitching velocity: within pitcher variation. *J Appl Biomech*. 2005;21:44-56.
- Stodden DF, Fleisig GS, McLean SP, Lyman SL, Andrews JR. Relationship of pelvis and upper torso kinematics to pitched baseball velocity. *J Appl Biomech*. 2001;17:164-172.
- Stodden DF, Langendorfer SJ, Fleisig, Andrews JR. Kinematic constraints associated with the acquisition of overarm throwing, part I: step and trunk actions. *Res Q Exerc Sport*. 2006;77(4):417-427.
- Stodden DF, Langendorfer SJ, Fleisig, Andrews JR. Kinematic constraints associated with the acquisition of overarm throwing, part II: upper extremity actions. *Res Q Exerc Sport*. 2006;77(4):428-436.
- Tripp BL, Boswell L, Gansneder BM, Shultz SJ. Functional fatigue decreases 3-dimensional multijoint position reproduction acuity in the overhead-throwing athlete. *J Athl Train*. 2004;39(4):316-320.
- Wight J, Richards J, Hall S. Influence of pelvis rotation styles on baseball pitching mechanics. *Sports Biomech*. 2004;3(1):67-84.