A Biomechanical Comparison of the Fastball and Curveball in Adolescent Baseball Pitchers

Abstract

Background: The problem of shoulder and elbow injuries in adolescent baseball players is rapidly increasing in incidence. The etiology of this increase is unknown though several theories exist. One leading theory is that breaking pitches (such as the curveball) place increased stress on the dominant arm and thereby increase the risk of injury. A limited amount of research on the topic from a biomechanical point-of-view has been performed though some research does exist that refutes this hypothesis.

Hypothesis: We propose to evaluate the stress on the dominant arm of adolescent baseball pitchers comparing fastball to curveball pitches to determine the different stresses that exist. It is our hypothesis that there is no difference in the stress between the two types of pitches.

Study Design: Controlled Laboratory Study

Methods: Thirty-three adolescent baseball pitchers with a minimum of two years of pitching were identified from surrounding baseball leagues. All pitchers underwent three dimensional motion analysis using reflective markers aligned to bony landmarks. After a warmup pitchers threw either a fastball or curveball, randomly selected, from a portable pitching mound until three appropriate trials were collected of each pitch. Kinematic and kinetic data for the upper extremities, lower extremities, thorax, and pelvis were collected and computed for both pitch types.

Results: Our results showed that there is less stress on the shoulder and elbow when throwing a curveball than throwing a fastball. Speed for the two pitches was observed to be different as expected with the fastball measured at 65.78 ± 4.8 mph versus the curveball at 57.7 ± 6.2 mph (p< 0.001) Maximal shoulder internal rotation moment was 59.8 ± 16.5 Nm for the fastball but significantly lower for the curveball 53.9 ± 15.5 Nm (p<0.0001). Similarly, the maximum varus elbow moment was 59.6 ± 16.3 Nm for the fastball and significantly less for the curveball 54.1 ± 16.1 Nm (p< 0.001). Significant differences were also noted in the wrist moments. The wrist flexor moment was greater in the fastball 8.3 ± 3.6 Nm versus the curveball 7.8 ± 3.6 Nm (p < 0.001), but the wrist ulnar moment was greater in the curveball 4.9 ± 2.0 Nm versus the fastball 3.2 ± 1.5 Nm (p < 0.001) Relatively minor motion differences were noted at the shoulder and elbow throughout the pitching motion while significant differences were seen in forearm and wrist motion. The forearm remained more supinated at each point in the pitching cycle for the curveball but had less overall range of motion (61.6° ± 20.3) as compared to the fastball (69.2° ± 17.3) (p < 0.001) and the difference in the forearm pronation and supination moment between the pitches was not significant (p=0.104 for pronation and p=0.447 for supination). The wrist remained in greater extension during the fastball from foot contact through ball release and also had a significant but minimally greater total sagittal ROM (53.4° ± 11.1) when compared to the curveball (54.0° ± 14.8) (p < 0.0001).

Conclusions: We conclude that the curveball is not the cause of increasing shoulder and elbow injuries in adolescent baseball pitchers when using recommended technique.

Additionally, while significant differences are seen between the fastball and curveball, most are clinically insignificant.

Clinical Relevance: Further evaluation of adolescent and adult baseball pitchers is warranted to help determine and then reduce the risk of injury. This study does not mean to imply that incorrectly thrown curveballs are safe and the authors stress that proper pitching mechanics and the teaching thereof is important.

Key Terms: Baseball pitching, adolescent sports, Kinetics, Kinematics, Motion analysis

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Introduction

It is estimated that more than 6 million adolescents participate in organized baseball in the United States. During the course of their participation their bodies and specifically their dominant arms are subject to significant stresses during play. Shoulder and elbow injuries in particular are a common problem for pitchers of all ages and can limit or terminate participation in baseball and may ultimately impact activities of daily living as they grow older. If the specifics of the injury mechanisms which occur while throwing a baseball can be elucidated, the proper pitching techniques can be taught to limit use of potentially harmful techniques. Comprehensive three-dimensional motion analysis is an ideal tool to study in detail the biomechanics of the pitching motion.

As opposed to a single traumatic event, most baseball arm injuries are thought to be due to the accumulation of microtrauma from repeated pitching experiences(3)(9). Studies have also suggested an increased risk of shoulder and elbow pain in adolescent pitchers is secondary to pitch types, pitch counts, and pitch mechanics (7). Pitch mechanics have been looked at in detail by Fleisig et al., who showed that the curveball (CB) places higher loads across the shoulder and elbow in comparison to the fastball (FB) and can lead to increased risk of shoulder and elbow pain and disability(5)(6). These studies were limited to shoulder and elbow motion and did not include the important motions of the wrist in these two pitching techniques.

These and other studies have lead USA Baseball to make recommendations regarding the types of pitches thrown (i.e.: no curveballs before the age of 14) during a youth baseball game. These recommendations also include limits in the overall number of pitches that should be thrown in a game and over a week and season. This second set of recommendations is intuitively obvious. Recommendations have also been proposed regarding the types of pitches that can be thrown in relation to the player's age group (1).

More recently, however, Dun et al., in an analysis of the fastball, curveball, and the change-up techniques for 12.5 +/- 1.7 year old pitchers, found the opposite outcomes compared to previous studies and showed that the fastball places more stress on the adolescent pitcher's shoulder and elbow (2). In Dun's study, increased joint moments and forces were noted for the fastball in comparison to the curve ball at key points in the pitch cycle. These findings are not consistent with previous research and with general understanding in coaching circles. More studies are needed across a spectrum of ages to determine the biomechanical differences between fastball and curve ball pitching techniques to clarify this inconsistency.

Establishing the scientific data to support coaching practices will allow for more persuasive arguments that can be presented to young athletes and their coaches. In addition, the biomechanical data will provide a basis to avoid specific risky mechanics and assist in the teaching and coaching of proper pitching techniques leading to a reduction in pitching injuries (1). Therefore, the purpose of this study was to further evaluate the difference in pitching biomechanics between the fastball and curve ball pitching techniques for adolescent pitchers ranging in age from 14 to 18 years.

Materials and Methods

Thirty-three adolescent baseball pitchers between the ages of 14 and 18 were recruited from local youth and high school baseball programs. Each pitcher had at least two years of pitching experience, had been taught proper throwing mechanics of a curveball, and had thrown a curveball competitively. No pitcher had a current complaint of arm pain. The Institutional Review Board at xxxx approved the project. All subjects signed assent forms and informed consent was obtained from their parents prior to involvement in the study.

A medical and pitching history was obtained. A physical examination was performed and anthropomorphic measurements including height, weight, leg lengths, arm lengths, and joint range of motion were obtained from each subject. The subjects wore sneakers and shorts and were marked with a series of 38 reflective markers as previously described.(10) Subjects were then given time to stretch and warm-up until they felt ready to throw normally. Pitchers were then asked to throw a series of fastballs or curveballs, randomly chosen, into a netted target with a designated strike zone. An average of 16 pitches was thrown until three representative fastballs and three curveballs were obtained. Pitching motion data was captured via a 512 Vicon Motion Systems (Vicon Motion Systems, Lake Forest, CA) using 12 synchronized cameras collecting data at 250-Hz. Initial data processing was performed in Workstation (Vicon Motion Systems, Lake Forest, CA) generating kinematics using established Euler equations. A fourth order, zero-lag Butterworth digital filter was used to smooth the raw data with a 15 Hz cut-off frequency. Joint kinetics were then computed using customized Matlab codes using standard inverse dynamics.

Data was collected utilizing previously described critical phases of the pitching cycle(5) (Fig. 1) beginning with lead foot contact (FC), maximal glenohumeral external rotation (MER), ball release (BR), and finally maximal glenohumeral internal rotation (MIR). The entire cycle was time normalized to the pitch cycle with particular attention paid to FC, MER, BR, and MIR. The three trials for each type of pitch for each pitcher had its mean established and the standard deviation for each parameter computed. Mean kinematic and kinetic plots through the pitch cycle were computed for chosen parameters. The chosen parameters were evaluated using an unadjusted (pitch speed and player weight) regression analysis for each pitcher comparing their fastball to curveball measurements.

Statistical Analysis

The effect of fastball versus curveball was analyzed using a random intercept mixed effects regression model. This method properly accounts for the repeated measures from each pitcher, and provides better precision than averaging each subject's fast balls and curve balls and then using a paired sample t-test. Additionally the method readily extends to a multivariate model to account for ball velocity and a subject's weight. Occasionally fewer than 3 trials of each pitch type were available for analysis because of a marker not being captured by the cameras. The regression method is also robust to this variation and calculates proper standard errors to reflect the degree of precision available.

Means and standard errors were reported for a variety of kinematic and kinetic parameters.

The pre-study power analysis was performed on pilot data to determine the subject number needed to show a clinically meaningful difference (5 Nm) in elbow varus moment between the curveball and fastball. Pilot data on 7 subjects showed a standard deviation of 5 Nm for the difference between the FB and CB on a single pitch. Based on this data, thirty-three subjects are required to have 80% power to detect a 5 Nm difference with 95% confidence.

Results

The study subjects had an average age of 16.6 years, with a mean body weight of 76.2 kg. The mean height was 179.4 cm and body mass index (BMI) averaged 23.6 kg/m^2. (Table 1). The velocity of the fastball 65.78 ± 4.8 mph, was notably higher than the curveball 57.7 ± 6.2 mph, ($p<0.001$).

<u>Kinematics</u>

Wrist

As we have previously reported the wrist's greatest range-of-motion (ROM) occurred in the flexion – extension plane.(Table 2 and Fig. 2) The overall arc of motion averaged 53.4 ± 11.1 ° for the fastball and 54.0 ± 14.8° ($p<0.001$). Wrist extension at foot contact (FC) for the fastball and curveball was 29.2 ± 16.8° and 23.8 ± 11.8°($p<0.0001$), respectively and remained extended significantly more for the fastball throughout the pitching cycle (PC) ($p<0.001$). We also noted a greater radial-ulnar ROM for the wrist throwing a curveball (17.0 ± 7.0°) as compared with the fastball (13.7 ± 4.5°)($p<0.001$). The peak sagittal (flexion-extension) velocity of wrist motion occurred at 78 ± 8 % of pitching cycle (PC) for the fastball (1871.0 ± 431 °/sec) compared with 82 ± 3 % for the curveball (1857.1 ± 569 °/sec). While minimal radial and ulnar deviation was seen in either pitch type (Table 2 and Fig. 2) ulnar wrist angular velocity was significantly different between pitches at the point of BR and had an actual peak near the end of the PC (after BR and near MIR). (Table 4 and Fig. 6) At the point of BR, a statistically higher ulnar velocity was noted for the curveball (360.4 ± 217 °/sec vs. 153.9 ± 261 °/sec) ($p<0.001$). The ulnar velocity near the end of the PC remained somewhat constant for the curveball (392.5 ± 211 °/sec) and increased dramatically for the fastball (492.1 ± 266 °/sec) ($p=0.55$). (Fig.9)

Forearm

The difference in overall ROM for forearm rotation (supination-pronation) was significantly different ranging 69.2 ± 17.3° for the fastball and 61.6 ± 20.3° for the curveball.($p<0.001$) The forearm remained significantly more pronated at each point of the PC for the fastball as compared with the curveball. (Table 2 and Fig. 2) The peak forearm pronation velocity occurred at 85 ± 4 % and 88 ± 4 % of the PC for the fastball (2444.3 ± 522 °/sec) and curveball (2213.8 ± 390 °/sec), respectively, both occurring after BR. (Table 4 and Fig. 6 and 10)

Elbow

Elbow ROM differed between the two types of pitches with the fastball having an overall greater arc (82.7 ± 14.2° vs. 80.9 ± 13.8°)($p=0.001$). (Table 5) The peak elbow extension velocity was greater for the fastball (fastball peak velocity of 1924.8 ± 354°/sec vs. 1841.1 ± 291°/sec for the curveball) ($p=0.09$) and occurred earlier in the PC than the curveball (70 ± 8% vs. 74 ± 5%). (Table 4 and Fig. 6 and 8)

Shoulder

The overall arc of motion for the glenohumeral joint was slightly greater for the fastball (fastball was 124 ± 12 ° vs. curveball 117 ± 17 °) ($p<0.001$). (Table 5 and Fig. 2)) Maximal external rotation (MER) of the glenohumeral joint was not statistically different with the fastball reaching a peak of 135 ± 20 ° and the curveball 135 ± 17 ° ($p=0.36$). The peak velocity of shoulder internal rotation was slightly higher for the fastball (3618.6 ± 656 °/sec) versus the curveball (3408.8 ± 722 °/sec) and statistically significant ($p=0.023$).

Kinetics

Wrist

Peak moments about the wrist as we previously reported in younger pitchers (10) are substantially lower than those about the elbow and shoulder. Peak wrist flexion moment was statistically slightly higher for the fastball than the curveball (8.3 ± 3.6 Nm vs. 7.8 ± 3.6 Nm) whereas the ulnar moment was higher for the curveball 4.9 ± 2.0 Nm versus the fastball 3.2 ± 1.5 Nm ($p < 0.001$) (Table 3) and both occur prior to MER (Fig. 5).

Forearm

The absolute values of the forearm moments were, similar to the wrist, significantly lower than those for the elbow and shoulder and comparable between the two pitch types. Forearm pronation moments were 1.7 ± 1.2 Nm for the fastball and 1.9 ± 0.9 Nm for the curveball ($p=0.10$). (Table 3)

Elbow

Elbow moments were significantly different between the fastball and curveball. The fastball peak varus moment was 59.6 ± 16.3 Nm compared to the curveball varus moment of 54.1 ± 16.1 Nm. ($p < 0.001$). (Table 6 and Fig. 4)

Shoulder

Kinetic calculations about the shoulder paralleled those of the elbow closely. The GH maximal internal rotation moment occurred just prior to BR for both the fastball and the curveball, was statistically different ($p<0.001$) and was 59.8 ± 16.5 Nm versus 53.9 ± 15.5 Nm, respectively. The GH flexion moment was 56.8 ± 18.3 Nm and 52.0 ± 17.4 Nm ($p<0.001$) for the fastball and the curveball, respectively. (Table 6 and Fig. 3)

Discussion

Fleisig et al (8) recently reported that there does not appear to be any significant differences on the stress placed on the medial elbow or anterior structures of the shoulder when throwing a curveball versus a fastball in elite level pitchers. Dun et al (2)subsequently found similar reduced stresses in adolescent pitchers when throwing a change-up or a curveball when compared to a fastball. These findings are contrary to the long held belief that throwing a curveball placed the arm at a higher risk of injury then throwing a fastball. This finding is not surprising when comparing the motion of the pitches and given the difference in ball velocity generated between the two pitch types. Using inverse dynamics, the force generated at the wrist, elbow and shoulder is directly related to the ball speed. We similarly found lower stresses and moments throwing the slower velocity curveball than the fastball in adolescent pitchers (aged 14-18). In fact we found the differences in varus elbow moment and glenohumeral internal rotation moments were statistically lower for the curveball then the fastball. When considering the calculations of these forces, not finding a corresponding lower moment for a slower thrown baseball would be concerning. At the same time we wonder, if the fact that the forces between the two pitch types is somewhat similar, that maybe some as of the yet undiscovered difference in either the kinematics or kinetics of these two pitches might exist explaining the similar overall results. This is an area of further research at our center.

Previous work in our lab has noted high variability between pitchers throwing similar pitch types. This variability is expected in younger, less experienced pitchers. We previously noted the variability in fastball pitches in 10 – 14 year old pitchers to be significant.(10) Our current group of pitchers was slightly older and more experienced. Given our interest in looking at biomechanical forces especially of the throwing arm the inclusion of these more experienced pitchers was intentional. The variability in these older pitchers was significantly less and has suggested to us the possibility that the less experienced pitchers with potentially incorrect technique, throwing a high number of pitches in a concentrated time frame, may be a risk factor for injury. One would theorize that if this was the case, however, that fatigue which would intuitively cause an increase in biomechanical variability, would also lead to an increased risk of injury. However, our lab and others (4) have been unable to induce a significant change in the biomechanics of pitching simply by fatiguing them.

One other suggested concern regarding the risk of throwing a curveball involves forearm pronation and supination during the pitch cycle. Some have suggested that rapid supination exposes the elbow to high valgus stresses and may lead to increased injury rates. Using our model we were able to look at both forearm rotation and wrist motion during the different motions. As mentioned, the differences between the pitches seen at the forearm and the wrist were more positional than motion related. The forearm remained more supinated and the wrist more flexed during the cocking and acceleration phases of each pitch (higher stress points of the PC). The forearm rotation moments were not statistically significant between the pitches and the differences noted were minimal and in our opinion of no clinical significance. The wrist ulnar and flexion moments were statistically significant between the pitches with the curveball showing a higher moment. Again, however, we do not believe that the absolute values of these moments are clinically significant though biomechanical data for risky wrist motion forces has not been established, to our knowledge.

Reviewing the pitching motion analysis, several positional differences between the pitch types were noted. The forearm was more supinated when throwing a curveball at each analyzed point in the PC as compared with the fastball while the wrist was more extended for the fastball then the curveball and the differences were statistically significant. These differences indicate that our adolescent pitchers were throwing different pitches when asked to and when they reported doing so. According to pitching coaches, a correctly thrown curveball creates spin using the wrist and not the forearm. A “12-to-6” curveball motion takes a radially deviated wrist that rapidly moves into ulnar deviation around the time of ball release, as noted in the wrist data collected in this study. Biomechanically, in order to position the wrist in a position to have this radial to ulnar motion, the forearm needs to be held in a roughly neutral position (minimal supination or pronation). Again, a supinated position at each point of the PC for the curveball as compared to the fastball was noted in the elbow transverse plane motion data. Interestingly we found similar flexion velocities for both pitch types which does not fit the long held belief that pitchers generate some velocity on their fastball with rapid wrist flexion.

Our study does have some limitations. The study was performed within a laboratory without a catcher or a batter in-the-box. Both situations as well as other distractions that might exist in a live game could result in alterations in the pitching motion that could create abnormal mechanics and thus high joint loads. We also realize that the age range of our pitchers covers a wide range of maturation. However, we report here a greater overall number of pitchers than elsewhere in the literature; the differences between stages of physical maturity were not analyzed and are a subject of ongoing research. An attempt was made to control for the physical differences as during our statistical analysis we controlled for pitcher weight.

Based on our study results, we conclude that throwing a curveball is not inherently risky for young (14 – 18 year old pitchers). We would not suggest, however, that curveballs or other breaking type pitches be thrown by pitchers who have not been taught the proper technique. If after being taught properly, the stress on the medial elbow and anterior shoulder is not different when throwing a fastball compared to a curveball then the increasing incidence of injuries, especially those resulting in the need for surgical intervention, still has an elusive etiology. This change in the perception biomechanical stresses in pitchers reflects what we believe is an appropriate increased awareness and concern over the number of pitches thrown per game, per week, per season, and perhaps most importantly per year. The number of pitches thrown coupled with appropriate rest periods appear to be a greater contributor to the increasing incidence in pitcher arm injuries. The ultimate description of the cause of pitcher injuries is an area of ongoing research both for us and others across the world.

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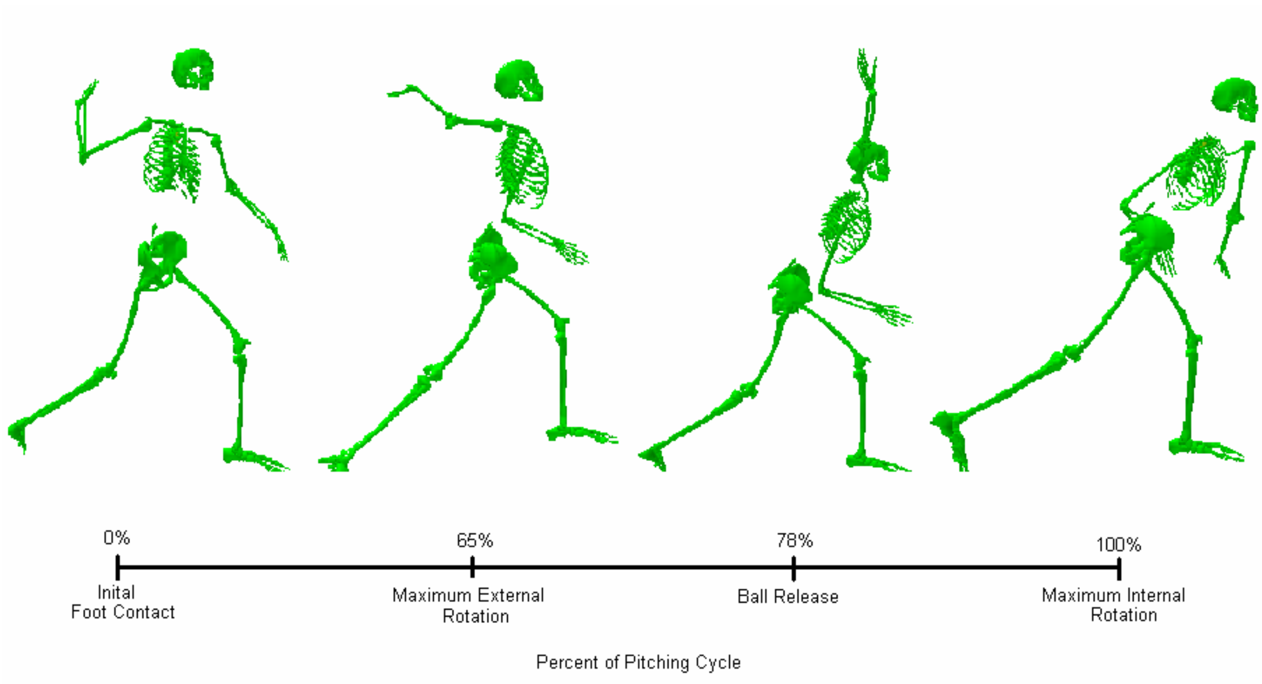

Figure 1: Pitching cycle

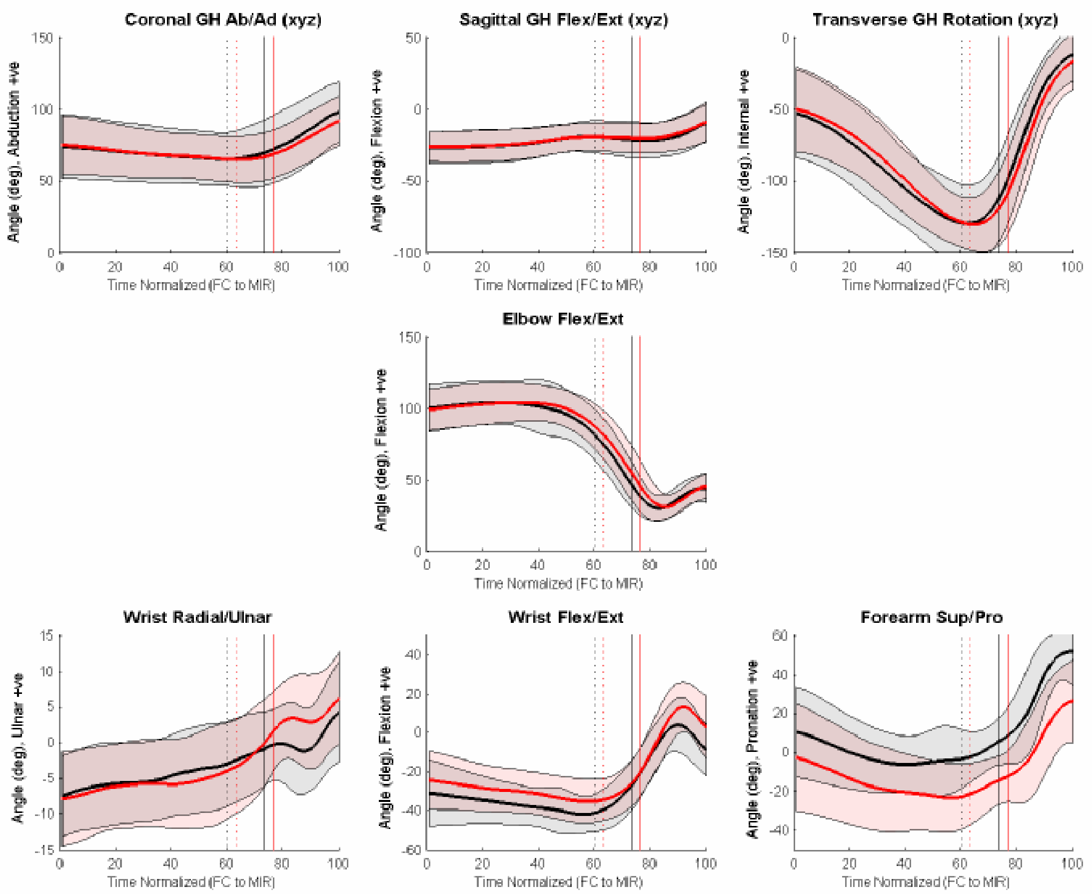

Figure 2: Kinematics mean +/- 1 standard deviation: Fastball=black/grey Curveball=red/pink N=33, n=33. Dotted vertical line- MER, Solid vertical line-BR

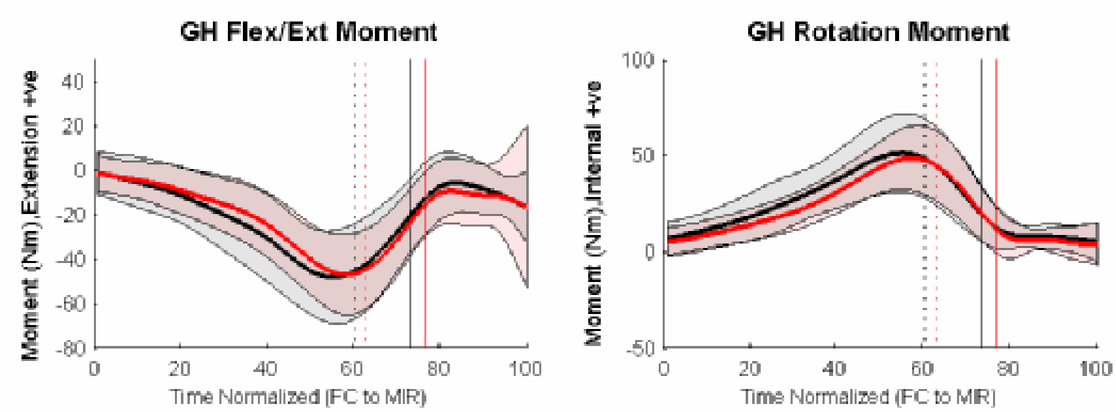

Figure 3: GH Kinetics (Nm) mean +/- 1 standard deviation: Fastball=black/grey Curveball=red/pink. N=33, n=33. Dotted vertical line- MER, Solid vertical line-BR

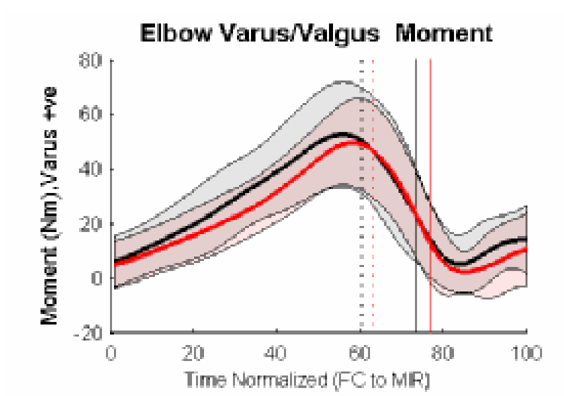

Figure 4: Elbow Kinetics (Nm) mean +/- 1 standard deviation: Fastball=black/grey Curveball=red/pink. N=33, n=33. Dotted vertical line- MER, Solid vertical line-BR

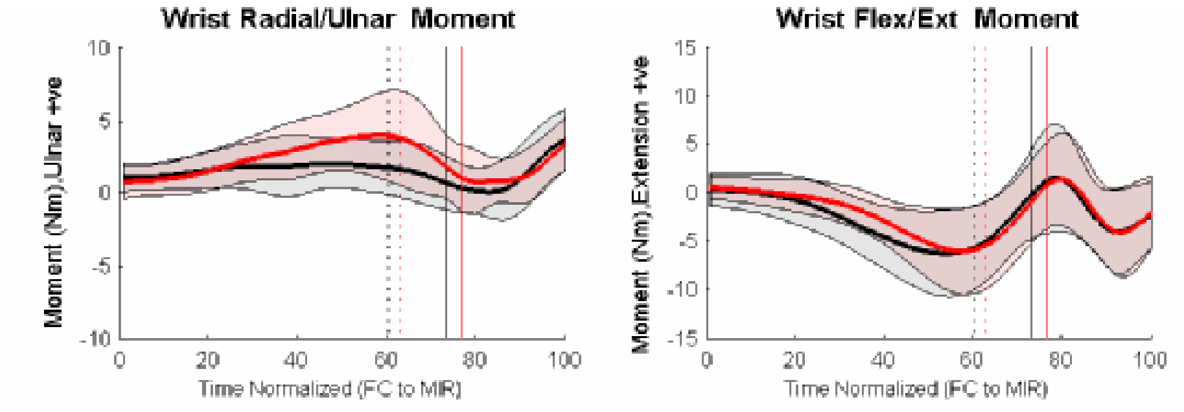

Figure 5: Wrist Kinetics mean +/- 1 standard deviation: Fastball=black/grey Curveball=red/pink. N=33, n=33. Dotted vertical line- MER, Solid vertical line-BR

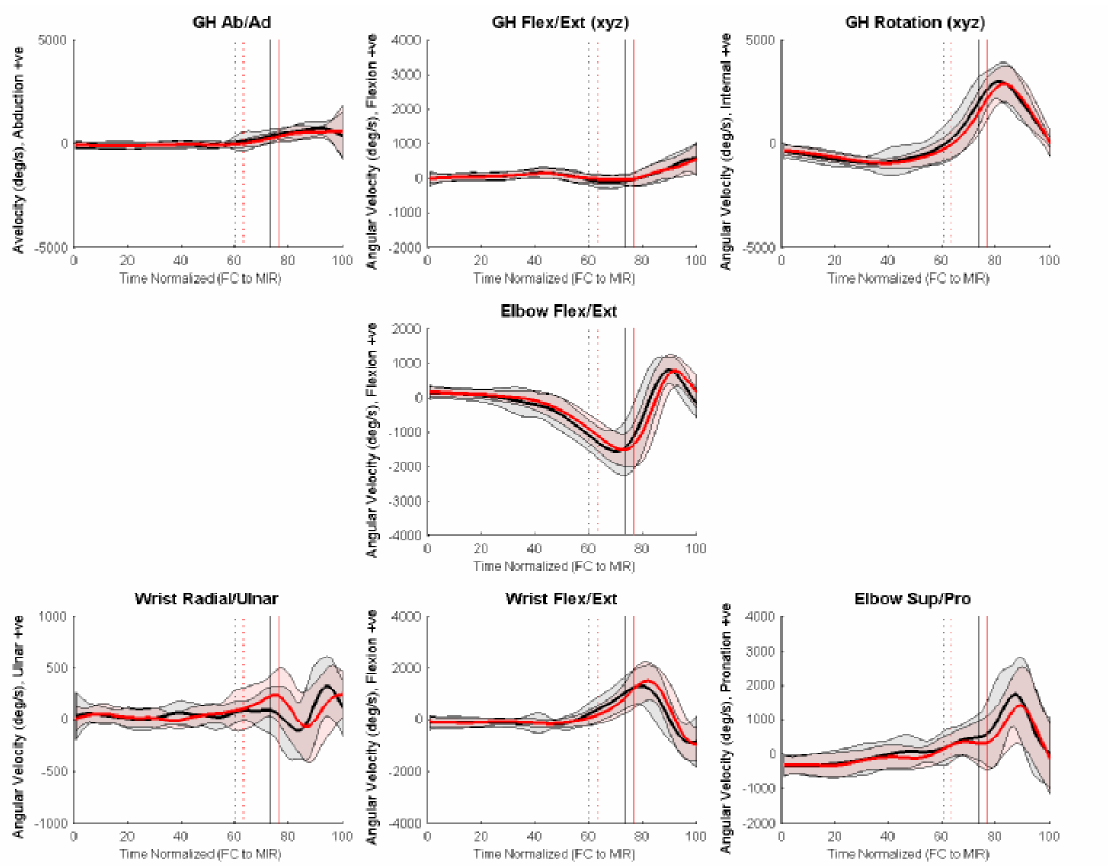

Figure 6: Velocity curves mean +/- 1 standard deviation: Fastball=black/grey Curveball=red/pink. N=33, n=33. Dotted vertical line- MER, Solid vertical line-BR

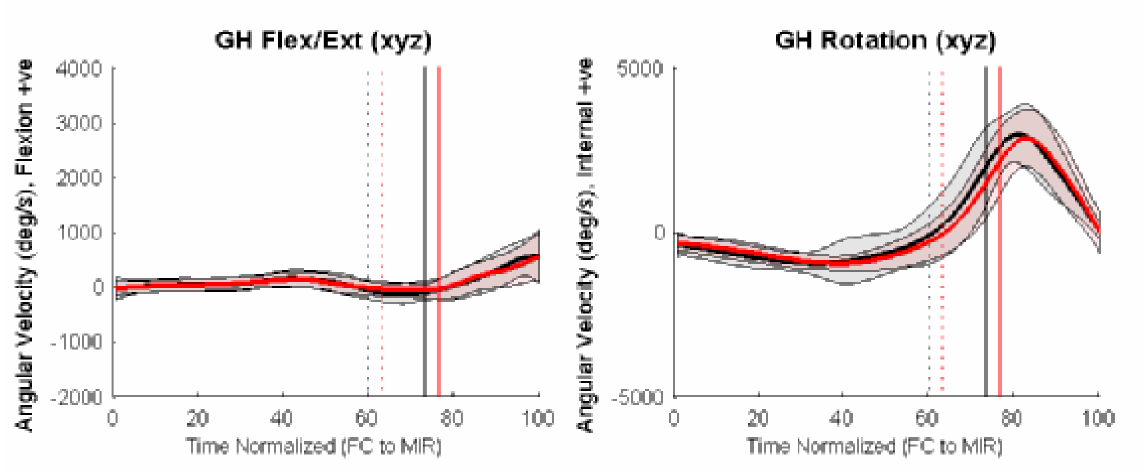

Figure 7: Velocity graphs for GH mean +/- 1 standard deviation: Fastball=black/grey Curveball=red/pink. N=33, n=33. Dotted vertical line- MER, Solid vertical line-BR

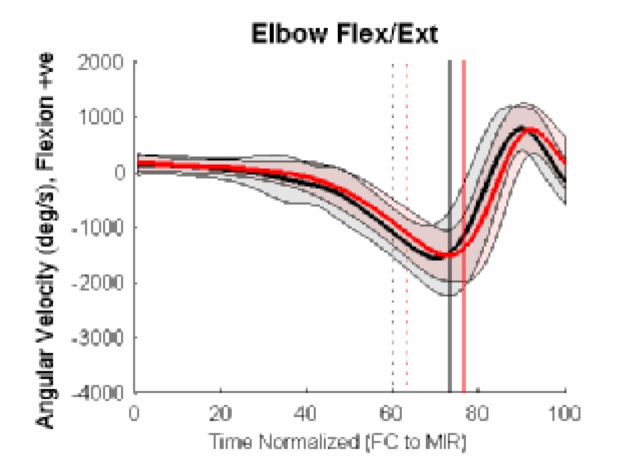

Figure 8: Velocity graphs for Elbow mean +/- 1 standard deviation: Fastball=black/grey Curveball=red/pink. N=33, n=33. Dotted vertical line- MER, Solid vertical line-BR

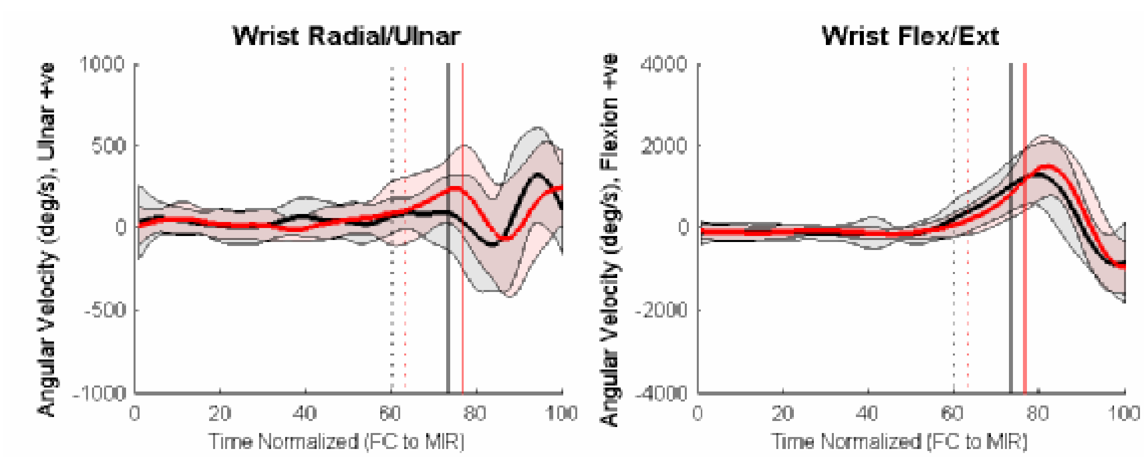

Figure 9: Velocity graphs for Wrist mean +/- 1 standard deviation: Fastball=black/grey Curveball=red/pink. N=33, n=33. Dotted vertical line- MER, Solid vertical line-BR

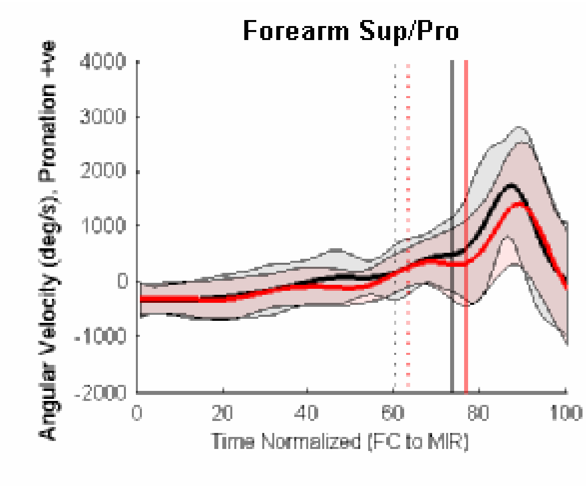

Figure 10: Velocity graphs for Forearm mean +/- 1 standard deviation: Fastball=black/grey Curveball=red/pink. N=33, n=33

Table 1
Subject Information (N=33)

Age (years and months)	16.6 ± 1.5
Weight (Kg)	76.2 ± 12.5
Height (cm)	179.4 ± 6.8
BMI	23.6 ± 3.1
Fastballs Pitched	8 ± 2
Fastball Velocity (m/s)	29.5 ± 2.1
Fastball Velocity (mph)	65.78 ± 4.8
Curveballs Pitched	8 ± 2
Curveball Velocity (m/s)	25.9 ± 2.8
Curveball Velocity (mph)	57.7 ± 6.2

Table 2
Wrist and Forearm Kinematics

		Fastball (°)	Curveball (°)	p
Forearm Rotation Angle (pronation + / supination-)	@ FC	10.3 ± 21.5	-5.1 ± 21.8	<.0001
	@ MER	-2.5 ± 14.2	-19.7 ± 11.6	<.0001
	@ BR	6.3 ± 13.3	-13.2 ± 10.6	<.0001
	@ MIR	47.5 ± 24.8	28.6 ± 18.6	<.0001
	ROM	69.2 ± 17.3	61.6 ± 20.3	<.0001
Mean Forearm Pronation	*FC to BR*	*7.2 ± 11.3*	*-9.88 ± 14.6*	*<.0001*
Wrist Sagittal Angle (flexion + / extension -)	@ FC	-29.9± 16.8	-23.8 ± 11.8	<.0001
	@ MER	-41.8 ± 8.0	-35.6 ± 8.7	<.0001
	@ BR	-26.8 ± 6.2	-21.6 ± 7.4	<.0001
	@ MIR	-8.2 ± 13.1	2.6 ± 12.6	<.0001
	ROM	53.4 ± 11.1	54.0 ± 14.8	0.91
Wrist Coronal Angle (ulnar + / radial -)	@ FC	-7.2 ± 5.7	-7.6 ± 6.4	0.832
	@ MER	-2.06 ± 6.1	-3.0 ± 6.3	0.136
	@ BR	-0.35 ± 4.7	1.2 ± 5.1	0.0001
	@ MIR	3.8 ± 5.96	5.92 ± 5.4	0.017
	ROM	13.7 ± 4.5	17.0 ± 7.0	<.0001
N=33 average of repeated trials for each subject *				

* Fastball- 3 trials = 23, 2 trials= 6, 1 trial =4 Curveball- 3 trials =22, 2 trials =9, 1 trial= 2

Table 3
Wrist and Forearm Kinetics
(Maximum Moments, Nm)

	Fastball	Curveball	p
Forearm Pronation	1.70 ± 1.2	1.90 ± 0.9	0.104
Forearm Supination	2.34 ± 1.6	2.39 ± 1.04	0.447
Wrist Flexion	8.30 ± 3.6	7.76 ± 3.6	0.0008
Wrist Radial	0.73 ± 1.9	0.235 ± 1.6	0.062
Wrist Ulnar	3.20 ± 1.46	4.87 ± 2.0	<.0001
N=33 average of repeated trials for each subject *			

* Fastball- 3 trials = 23, 2 trials= 6, 1 trial =4 Curveball- 3 trials =22, 2 trials =9, 1 trial= 2

Table 4
GH, Elbow, Forearm, and Wrist Angular Velocity and Timing
(Maximum Angular Velocity, deg./sec)
(Timing- percent of Pitch Cycle)

	Fastball	Curveball	p
GH Internal Rotation	3618.6 ± 656	3408.8 ± 722	0.023
GH Internal Rotation % pc	77 ± 8	81 ± 4	0.008
Elbow Flexion	976 ± 347	890 ± 371	0.087
Elbow Flexion % pc	88 ± 7	84 ± 14	0.570
Elbow Extension	1924.8 ± 354	1841.1 ± 291	0.091
Elbow Extension %pc	70 ± 8	74 ± 5	0.010
Forearm Pronation between BR and 100%	2444.3 ± 522	2213.8 ± 390	0.053
Forearm Pronation %PC	85 ± 4	88 ± 4	0.005
Wrist Ulnar Velocity at BR	153.9 ± 261	360.4 ± 217	<.0001
Wrist Ulnar Velocity between 65% and 85%	271.6 ± 166	415 ± 220	0.0007
Wrist Ulnar Velocity %PC	74 ± 6	75 ± 6	0.456
Wrist Ulnar Velocity between 90% and 100%	492.1 ± 266	392.5 ± 211	0.054
Wrist Ulnar Velocity %PC	94 ± 3	97 ± 3	0.001
Wrist Flexion	1871 ± 431	1857.1 ± 569	0.841
Wrist Flexion % pc	78 ± 8	82 ± 3	0.004
N=33 average of repeated trials for each subject *			

* Fastball- 3 trials = 23, 2 trials= 6, 1 trial =4 Curveball- 3 trials =22, 2 trials =9, 1 trial= 2

Table 5
GH and Elbow Kinematics

		Fastball (°)	Curveball (°)	p
GH Rotation Angle (internal + / external-)	@ FC	-51.7 ± 30.8	-55.8 ± 30.2	0.019
	@ MER	-135 ± 20	-135 ± 17	0.361
	@ BR	-110 ± 23	-111 ± 17	0.071
	@ MIR	-12.9 ± 18.3	-18.5 ± 20	<.0001
	ROM	124 ± 12	117 ± 17	<.0001
GH Coronal ROM	*FC to MIR*	21.6 ± 9.5	19.9 ± 9.2	0.009
GH Sagittal ROM	*FC to MIR*	35.3 ± 7.8	31.7± 7.7	<.0001
Elbow Sagittal Angle (flexion + / extension -)	@ FC	99.8 ± 14.7	100.1 ± 14.0	0.978
	@ MER	73.2 ± 17.5	74.7 ± 19.3	0.579
	@ BR	40.4 ± 15.5	43.9 ± 18.1	0.077
	ROM	82.7 ± 14.2	80.9 ± 13.8	0.001
N=33 average of repeated trials for each subject *				

* Fastball- 3 trials = 23, 2 trials= 6, 1 trial =4 Curveball- 3 trials =22, 2 trials =9, 1 trial= 2

Table 6
GH and Elbow Kinetics
(Maximum Moments, Nm)

	Fastball	Curveball	p
GH Internal Moment	59.8 ± 16.5	53.9 ± 15.5	<.0001
GH Flexion Moment	56.8 ± 18.3	52.0 ± 17.4	<.0001
Elbow Varus Moment	59.6 ± 16.3	54.1 ± 16.1	<.0001
N=33 average of repeated trials for each subject *			

* Fastball- 3 trials = 23, 2 trials= 6, 1 trial =4 Curveball- 3 trials =22, 2 trials =9, 1 trial= 2