Pitching Arm Injuries: Biomechanical, Physical, and Training-related Factors

Abstract

Background: Biomechanics can be broken into kinetics and kinematics. Kinetics refer to forces and torques on joints, while kinematics refer to positions, velocities, and accelerations of different body parts. Elbow valgus torque is of particular relevance to arm injuries, many of which occur on the ulnar collateral ligament (UCL). Fastballs, changeups, and curveballs are different types of pitches that a pitcher can throw, and there are many other types as well that will not be considered here for the sake of simplicity.

Purpose: To investigate what biomechanical, physical, and training-related variables are correlated with arm injuries in baseball pitchers, and consider how to approach training with this in mind.

Study design: 10 papers were examined through Google scholar.

Methods: N/A

Results: Various biomechanical variables in the elbow and shoulder are related to injury risk. The triceps, biceps, and flexor-pronators are used during the pitching delivery to protect the structures in the elbow, most notably the UCL, and so must be trained to be sufficiently strong to handle these demands. Shoulder kinematic positions at different stages in the pitching delivery play also a major role in preventing injury. Biomechanical variables in other areas of the body are of interest as well, particularly in the torso and landing leg. Pitch velocity and throwing volume are also of interest, and as one might expect both are positively correlated with injury risk. Lastly, several training modalities, such as long toss (throwing the ball for maximal distance) and weighted ball training (throwing balls that are heavier or lighter than a regulation 5 oz. baseball) can be used to improve performance and minimize injury risk when used properly.

Conclusion: Pitching injuries are complex and depend on a large number of variables, some of which are out of the pitcher's control. However, by accounting for all of the factors examined here (as well as many others), pitchers can greatly minimize their risk for injury, while also optimizing performance. Recently, there has been a shift towards these more progressive training methodologies in baseball. As more and more pitchers and coaches begin to implement these progressive training approaches, less and less pitchers will sustain arm injuries.

Keywords: Biomechanics; pitching; baseball; injuries.

Introduction

Baseball pitchers are getting hurt now more than ever before. In the year 2015 alone, over 140 professional pitchers underwent Tommy John surgery[10], an all-too-common surgery to repair ligament tears in the elbow. Baseball fans in the early 2000's remember pitchers like Mark Prior or Kerry Wood, who had promising careers derailed by arm injuries that they just couldn't bounce back from. It is clear that this is a major problem in baseball, but what can be done to solve it? Specifically, what biomechanical, physical, and training-related variables can be optimized in order to minimize injury risk?

In order to better understand the problem of arm injuries and what causes them, some background information is necessary. First, note that elbow valgus torque is the peak torque on the throwing elbow during the delivery. A portion of this torque acts on the Ulnar Collateral Ligament, or UCL, a ligament in the elbow that is commonly sprained or torn by pitchers. Some authors speak of elbow varus torque instead, which is torque in the opposite direction. Valgus torque and other torques and forces (as in figure 1) on the elbow, shoulder and various other parts of the body are *kinetic* variables, whereas *kinematic* variables reflect (linear and angular) positions and velocities of different body parts.

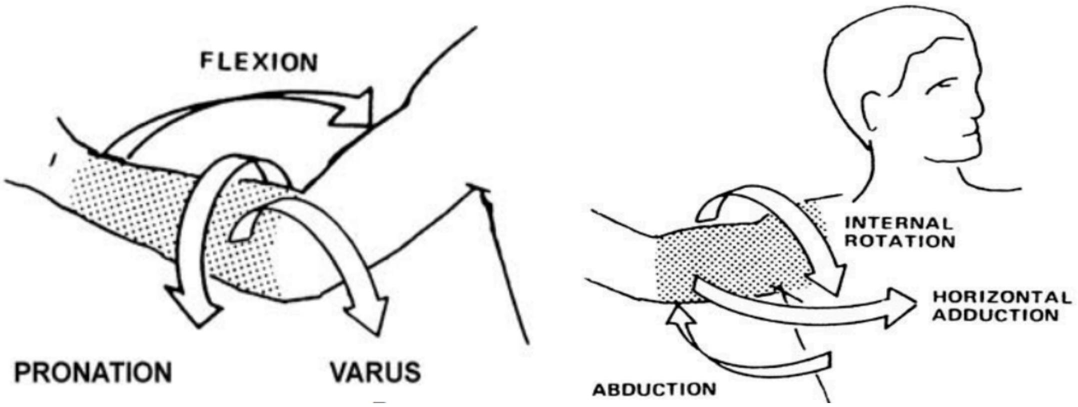


Figure 1: Some of the relevant kinetic and kinematic variables in the arm[8]. Each of the above movements represents a kinematic angular position, with a corresponding kinetic torque. For example, one could speak of an elbow flexion angle, the angle between the forearm and bicep, and an elbow flexion torque, which is the torque perpendicular to the plane of the forearm and bicep.

There are a few specific kinematic variables to be aware of when it comes to pitching biomechanics other than the ones shown in figure 1. Shoulder internal and external rotation reflect whether the shoulder is rotating towards or away from the front of the body, respectively. Hip/shoulder separation is the maximum angle that the line of the shoulders makes with the line of the hips. Lastly, lead leg blocking reflects the angle the landing leg's calf makes with the thigh.

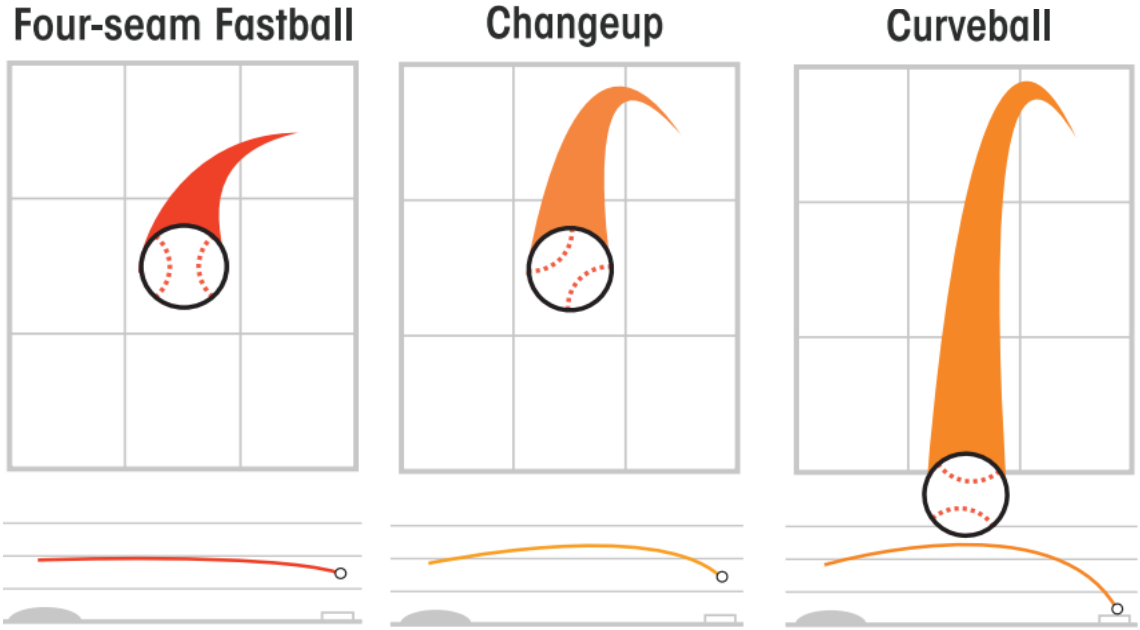


Figure 2: Front- and side-view movement profiles of pitch types examined in the review[2]. In professional baseball four-seam fastballs are generally thrown at 90-100 miles per hour (MPH), changeups at 80-90 MPH, and curveballs at 70-80 MPH. Many other pitch types exist, but these are three of the most common.

It is also important to know the differences between different types of pitches. A fastball is a pitch that is generally thrown at around 90-100 miles per hour (MPH) in professional baseball, and typically does not deviate very much from a straight trajectory. Curveballs, sliders, and other *breaking pitches* are pitches that move either laterally, vertically, or both as they travel towards home plate. They are typically thrown at least 10 MPH slower than fastballs. Lastly, a changeup is a pitch that “looks” like a fastball but is deliberately thrown 5-10 MPH slower, with the intent of making the hitter swing early, and may or may not also break laterally and/or vertically. There are also many other pitches and variations of those discussed above, but for the sake of simplicity, only the pitch types shown in figure 2 will be considered.

Arm injuries are often multi-factored and complex, and nailing down exactly what caused a particular injury is an impossible task in most practical cases. Nevertheless, a review of the literature published in the last 30 years indicates that certain biomechanical, anatomical, and workload-related variables are correlated with injury. Optimizing these variables in a training or competition environment can maximize a pitcher’s chance of both staying healthy and performing at his/her best.

On the biomechanics side, any discussion of arm injuries begins with the elbow and the shoulder, and the associated kinematic variables. Specifically, elbow extension, shoulder abduction, and shoulder internal rotation are all related to elbow and shoulder injuries[5,11], and the ways in which they relate will be examined below. There are other biomechanical variables throughout the body that are of interest as well, and it is known that torso rotation timing and lead-leg blocking, among others, have implications for injury risk[1,12]. Additionally, there are certain anatomical variables, such as joint laxity and mobility, that are relevant to elbow and shoulder pathology[6].

The way that different pitch types (for example, fastballs, curveballs, sliders, etc.) are related to injury risk is also an important point. Recent research contradicts the long-held idea by coaches and parents that curveballs and other breaking pitches are more dangerous than fastballs, particularly for younger athletes. Even though these pitches produced kinematic differences in some athletes, they did not produce *kinetic* differences[8,12], which is what ultimately matters.

Another common idea among coaches and parents is that higher throwing velocities and higher throwing volumes are positively correlated with arm injuries. These notions are backed up by the literature[3,4], and any good throwing program must keep these considerations in mind.

There are several training tools that can be used to optimize performance (i.e., velocity), while still minimizing injury risk, such as overload and underload throwing training and long toss. In conjunction with a well-rounded training program, overload and underload throwing (better known as "weighted ball training") has been shown to be a safe and effective method for increasing velocity[9], and long toss (throwing the ball for maximal distance) is a safe method for building up increased tolerance in the muscles surrounding the UCL[7]. With all of these biomechanical, physical, and training-related variables in mind, it is possible to design a training program that maximizes both arm health and performance simultaneously.

Body

One major factor when it comes to pitching injuries is the biomechanics of the elbow and shoulder. The literature suggests that certain kinetic and kinematic variables in these regions are associated with injury. Therefore, by optimizing these variables, an athlete's injury risk can be minimized. For example, Werner *et al*.[11] note that the UCL is not strong enough on its own to handle the stresses of a pitching motion without tearing. Essentially, the varus torque needed to counter the valgus extension needs to be attenuated by the surrounding musculature near the UCL. Using electromyography (EMG) sensors to measure muscle activity at different times during the delivery, Werner *et al*. were able to determine which muscles were used when in order to protect the UCL.

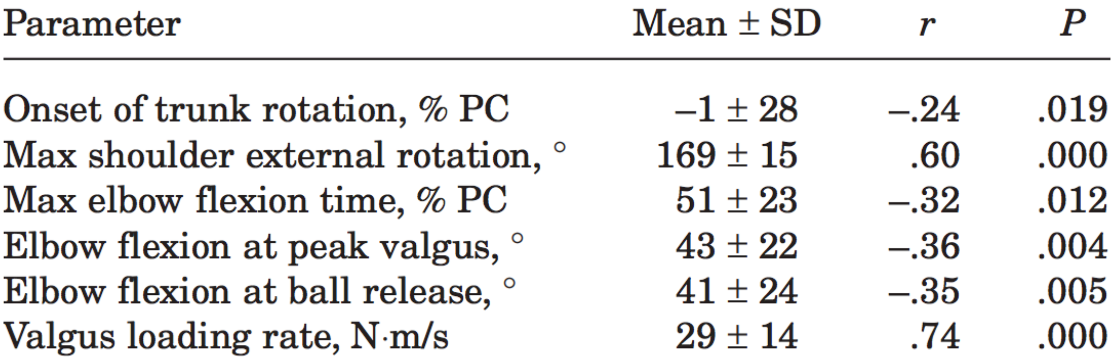
The triceps, flexor-pronator, and anconeus muscles were most responsible for providing this varus torque as the arm goes into maximum external rotation, which is when the peak amount of stress is placed on the elbow. From here, the triceps activity increased as the ball was accelerated forward, which prevented the elbow from extending and experiencing excess forces and torques. Finally, all of the muscle groups studied (triceps, biceps, wrist extensors, wrist flexor-pronators, and anconeus) were active in decelerating the arm. The training implications of this are interesting: not only do these muscle groups need to be strong enough handle the force placed on them during the pitching motion, they also must be able to move in an efficient manner so that the arm is in the right places at the right times.

Shoulder biomechanics are similarly important when it comes to preventing injury and maximizing performance. Dillman *et al.*[5] discuss how the kinematic variables of shoulder abduction, horizontal abduction, and internal rotation are related to injury risk. The shoulder should maintain between 90 and 110 degrees of abduction from stride foot contact (the time at which the front foot hits the ground) to ball release in order to optimize for arm health and velocity, and ideally stay at some (roughly) constant value within that range. Anything too far outside of this range can result in injury or decreased mechanical efficiency.

Shoulder horizontal abduction follows a bit of a different pattern among elite throwers (healthy college and professional pitchers). At stride foot contact, their shoulders are horizontally abducted by about 30 degrees, but by maximum external rotation they are actually *adducted* by about 14 degrees. However, as the humerus internally rotates, the shoulder of a high-level thrower horizontally abducts again, and the arm winds up at around 0 degrees by the time the ball is released. The shoulder then continues into an adducted position as it begins to decelerate. The shoulder externally rotates from foot contact until near the time of ball release, and then very quickly internally rotates to throw the ball forwards, reaching angular velocities of 6940 degrees/second, one of the fastest known human movements!

Given that elite pitchers from both an arm health and performance standpoint exhibit these kinematic “checkpoints” of shoulder abduction, horizontal abduction, and internal rotation, aspiring pitchers should be trained with these “checkpoints” in mind. Strength and mobility also play a large role in determining shoulder and overall arm health, but given that healthy and high-performing athletes follow these biomechanical patterns, a pitcher who strays too far away from them is not only less likely to maximize performance, they also may increase shoulder torques and put the structures of their shoulder at risk.

Figure 3: Kinematic and kinetic parameters with significant correlations to elbow valgus torque[1]. %PC refers to the time when it occurs as a percentage of the entire “pitching cycle.”



Parameter	Mean ± SD	*r*	*P*
Onset of trunk rotation, % PC	–1 ± 28	–.24	.019
Max shoulder external rotation, °	169 ± 15	.60	.000
Max elbow flexion time, % PC	51 ± 23	–.32	.012
Elbow flexion at peak valgus, °	43 ± 22	–.36	.004
Elbow flexion at ball release, °	41 ± 24	–.35	.005
Valgus loading rate, N·m/s	29 ± 14	.74	.000

Outside of the elbow and shoulder, there are other biomechanical variables associated with injury risk. Aguinaldo and Chambers[1] note the importance of trunk rotation timing, and how it can play a role in decreasing elbow valgus stress. Specifically, athletes who began trunk rotation later in the delivery (after stride foot contact) had lower peak valgus torques than athletes who initiated trunk rotation prior to stride foot contact (see figure 3). There was also no statistically significant difference between ball velocity in the early and late trunk rotation groups, indicating that there is no performance benefit to be had from rotating early. Thus, it is advantageous for pitchers to avoid early trunk rotation as much as possible. Aguinaldo and Chambers also noted that maximum shoulder external rotation, peak elbow flexion (and timing), shoulder abduction, and shoulder horizontal abduction were associated with injury in a way similar to what Dillman *et al*. suggest.

Lead leg kinematics are also of relevance when it comes to injury risk and performance. Specifically, according to Whiteley[12], lower rates of knee flexion at stride foot contact, and subsequent higher rates of lead knee extension are correlated with increased ball velocity. This agrees with the cue of “firming up the front side” taught by many pitching coaches. The magnitude of the ground reaction force (essentially, the peak force put into the ground by the lead leg) is also shown to be correlated with ball velocity, as is the time at which this peak force occurs; later peak forces resulted in higher ball velocities. In Whiteley’s review, there was no mention of any kind of an association between lead leg kinematics and elbow or shoulder pathology. This doesn’t rule out the possibility, but more research may need to be done in order to determine whether or not an association exists. At any rate, it appears that improving lead leg mechanics in the manner described above can result in increased ball velocity without changing elbow or shoulder kinetics, and therefore without increasing injury risk.

In addition to these kinetic and kinematic factors, there are also mobility considerations in pitching biomechanics. Flesig *et al*. note that the way shoulder mobility enters into the equation is complex[6]. On one hand, high-level throwers need to have sufficient shoulder laxity in order to safely reach the extreme positions necessary for maximal velocity (for example, maximum external rotation). On the other hand, any elite thrower also needs to have sufficient stability in the shoulder joint in order to handle all of the forces placed on the joint during the pitching delivery and minimize the risk for injury. The shoulder therefore must not only be strong enough to accept these forces without tearing any ligaments or muscles, but also mobile enough to get into positions conducive to generating velocity, and should be trained with this in mind. Flesig *et al*. also note that, in agreement with the other studies already mentioned, the instants of maximum internal rotation torque and maximum compressive force were the “critical points” where shoulder injuries were most likely to occur.

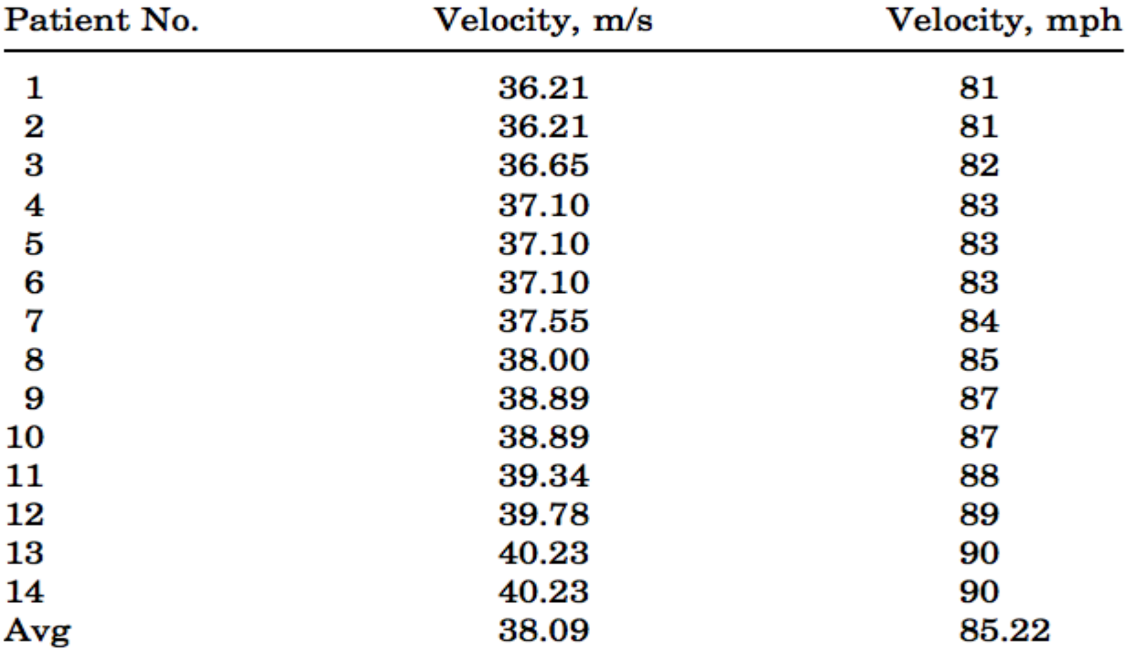
The way that different pitch types are related to elbow and shoulder biomechanics is also of interest. Flesig *et al*.[8] observed significant kinematic differences between fastballs, changeups, and curveballs. Specifically, fastballs and curveballs differed in forward and lateral trunk tilt, wrist extension, and foot position, whereas fastballs and changeups differed in knee and elbow flexion angles, as well as shoulder abduction and horizontal abduction. Changeups and curveballs also differed in almost all of these kinematic variables.

Interestingly enough, there were almost no significant kinetic differences between fastballs and curveballs, although changeups had lower overall kinetics than fastballs and curveballs did. This indicates that, all else being equal, fastballs and curveballs have similar injury risk, whereas changeups might be slightly safer. These findings are in accordance with Whiteley's review[12]: he concluded that the frequency at which different pitch types are thrown is not associated with injury risk (although total volume of pitches thrown is, which will be discussed below). Flesig et al. also studied another type of pitch called a slider, but due to the small sample size of sliders thrown it was difficult for them to make any kind of a conclusion about their kinetics or kinematics.

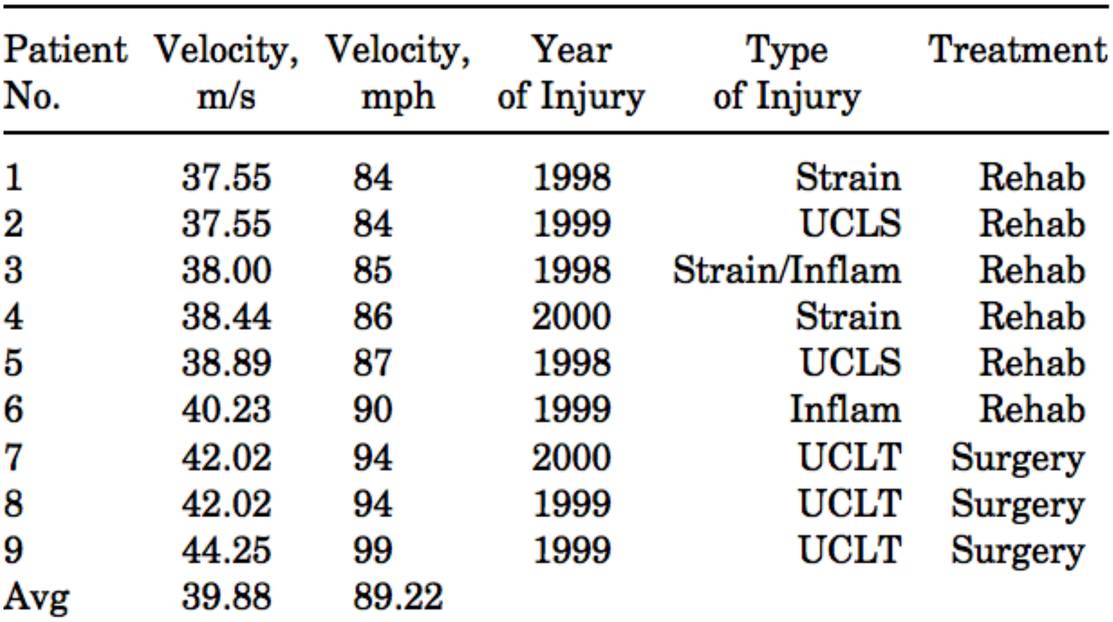
There are several implications of these results. First off, the fact that kinetics between fastballs and curveballs were more or less identical dispels the long-held notion that curveballs are "bad for your arm," particularly at a young age. An important caveat to this is that the elbow torques measured by Flesig *et al*. are the *total* torques on the elbow joint. This is not necessarily the torque actually felt by the UCL (since the surrounding musculature will attenuate some of the torque), although based on their results it is unlikely that the UCL torques differ significantly between the different pitches.

The fact that there were significant kinematic differences also has some interesting implications when it comes to training. For one, it makes the skill of developing multiple pitches all the more difficult, given that certain kinematic variables will likely be different from pitch to pitch. This result also implies that it may not be possible for pitchers to "repeat their mechanics" perfectly between different pitches, due to the underlying kinematic differences necessary to throw them. Flesig *et al*. suggest that pitchers who reach higher levels of the game (e.g., professional baseball) likely have smaller kinematic differences between pitches than pitchers at lower levels have, although based on their study it seems like some kinematic differences are impossible to avoid. Lastly, it is possible that the lower changeup kinetics relative to the other pitches are a result of pitchers “slowing their arm down” (i.e., deliberately throwing changeups with lower arm kinematics) in order to decrease the velocity of the ball and try to generate early swings from the hitter, which is the point of the pitch to begin with.

Figure 4: Information about the professional pitchers examined by Bushnell *et al*.[3] The top table is the noninjured group, and the bottom table is the injured group. The types of injuries sustained by the injured group were strains, inflammations (Inflam), UCL sprains (UCLS), and UCL tears (UCLT). As the tables indicate, the injured group threw harder on average than the noninjured group.



Patient No.	Velocity, m/s	Velocity, mph
1	36.21	81
2	36.21	81
3	36.65	82
4	37.10	83
5	37.10	83
6	37.10	83
7	37.55	84
8	38.00	85
9	38.89	87
10	38.89	87
11	39.34	88
12	39.78	89
13	40.23	90
14	40.23	90
Avg	38.09	85.22



Patient No.	Velocity, m/s	Velocity, mph	Year of Injury	Type of Injury	Treatment
1	37.55	84	1998	Strain	Rehab
2	37.55	84	1999	UCLS	Rehab
3	38.00	85	1998	Strain/Inflam	Rehab
4	38.44	86	2000	Strain	Rehab
5	38.89	87	1998	UCLS	Rehab
6	40.23	90	1999	Inflam	Rehab
7	42.02	94	2000	UCLT	Surgery
8	42.02	94	1999	UCLT	Surgery
9	44.25	99	1999	UCLT	Surgery
Avg	39.88	89.22			

It is often suggested that higher-velocity pitches place more torque on the elbow and shoulder, and are thus more dangerous from an arm health standpoint than lower-velocity ones. The literature backs this intuition, as well as another commonly held notion that higher volumes of throwing are also associated with increased injury risk. Bushnell *et al.*[3] looked at elbow injuries in professional baseball pitchers, and found a statistically significant association between maximum pitch velocity and injury (see figure 4). The injured pitchers threw about 4 MPH harder on average than the noninjured pitchers did (89.22 ± 5.36 MPH compared to 85.22 ± 3.24 MPH), and also had a significantly longer average career (9.7 years to 6.5 years). Given that elbow injuries (and UCL injuries in particular) are either acute events, events related to the accumulation of fatigue (microtears), or both, it makes sense that maximum velocity and career length were both associated with increased risk for injury in this study.

Bushnell *et al*. note that many other factors, such as a pitcher's height, weight, age, strength, and mobility can all play a role in injury risk, and that velocity alone will never be able to predict a pitcher's injury risk. They also note that part of the reason the injured group had a longer average career length was likely because they threw harder, and thus had more opportunities to play, than pitchers who didn't throw as hard. These associations of velocity and throwing volume to injury risk are backed up by Chalmers *et al.*[4], who also point out that there is a similar trend in youth pitchers. Chalmers *et al*. also note that providing pitch count guidelines for varying age groups could be an effective solution to limit pitching volume at a young age and prevent injuries.

The implications of these findings are interesting, because pitchers obviously want to avoid injury, but can gain a competitive advantage over their peers by training for high velocity. This just makes it all the more important that pitchers training for increased velocity manage all of their other training variables effectively. Harder-throwing pitchers can make sure that they are adequately mobile to safely get into the extreme ranges of motion associated with the pitching delivery, yet strong enough to handle the physical demands associated with throwing thousands of pitches over the course of a season. Harder throwers can also make sure that their mechanics are efficient so that they can avoid many of the "red flags" for potential injury discussed above. Finally, they can design their training and throwing programs in order to make sure that there isn't too much fatigue buildup at any one time, while also making sure that they are prepared to handle the throwing volume associated with a season of competition. There are also several training modalities that can be useful from a performance and injury prevention standpoint, which will be discussed below.

Figure 5: Long toss setup used by Flesig *et al.*[7]. In long toss, pitchers throw a ball on an arc at various distances, much like the athlete shown here is doing.

One training modality that (when used effectively) can increase performance and reduce injury risk is *long toss*, which involves throwing the ball on an arc at increasing distances (see figure 5). Flesig *et al.*[7] found that maximal effort long toss does in fact increase elbow and shoulder torques relative to maximal effort pitching off a mound. They also found that certain kinematic positions were different between long toss and the mound, most notably elbow flexion, (forward) trunk tilt, lead knee flexion, and foot position. Lastly, they found that pelvis, trunk, and elbow extension angular velocities increased with distance.

The key for long toss to be an effective training tool, then, is using it in a responsible manner. Knowing that long toss will increase elbow and shoulder kinetics, it can be used to prepare pitchers to handle throwing maximal effort pitches off a mound, which will then be "easier" on the ligaments in the elbow and shoulder by comparison. The difficulty is determining the correct amount of long toss to incorporate into training, because obviously long tossing too much can put pitchers at an increased risk for injury. When used responsibly, however, long toss can help prepare pitchers to handle the elbow and shoulder torques experienced during mound work.

Flesig *et al*. view the differences in kinematics as a negative, but these differences can also be used as a training tool. By experiencing different trunk, elbow, knee, and foot positions in training, an athlete gains adjustability to different conditions in a game (e.g., different mound heights or slopes). Obviously, an athlete should spend time throwing off a mound under game-like conditions in training, but this doesn't mean that this is the *only* way an athlete should train. However, as Flesig *et al*. point out, more research is needed on the effectiveness of different long toss protocols.

Weighted ball throwing training is another training modality that is commonly used to improve performance. Several studies have been done suggesting the effectiveness of weighted ball training in increasing pitching velocity without increasing elbow or shoulder kinetics. A six-week study done by Marsh *et al*.[9] partially supports the hypothesis, finding that elbow and shoulder kinetics were indeed unaffected by the weighted ball throwing program. However, they also did not find a statistically significant increase in velocity as a result of the program, which contradicts the previous research. One major caveat to this lack of velocity increase is the fact that many of the participants had experience with weighted ball training before. Thus, putting these participants on a six-week program might not produce the same kind of training stimulus that it would for athletes who have never done weighted ball training in the past.

Marsh *et al*. also found no increase in shoulder external rotation at the conclusion of the program in any of the athletes. When participants were broken up into those who gained and lost velocity over the course of the program, the velocity-gaining group actually *increased* shoulder internal rotation, and neither group lost internal rotation. Both of these are good signs for arm health, as internal rotation losses and external rotation gains have been linked to arm injuries in previous research. With these results in mind, as well as the existing literature that Marsh *et al*. cite, weighted ball training is a safe training method, so long as the throwing volumes and intensities are well managed. More research may need to be done to determine the effects of weighted ball training on velocity, although there is still a high chance that it can be used to increase velocity given the existing literature on the subject.

Conclusion

This review has looked at several biomechanical, physical, training-related, and other factors that could potentially be related to pitching injuries in baseball. Specifically, it looked at how elbow and shoulder biomechanics; biomechanics and anatomy in other areas of the body; different pitch types; velocity and throwing volume; and different training methodologies are related to injury risk. Thankfully, more and more athletes and coaches are becoming aware of how to train with these variables in mind, and in 2018 there were only 75 Tommy John surgeries among professional pitchers[10] (as of September 12th, compared to over 140 in 2015). For example, weighted ball training and long toss were barely used at all as recently as 10 years ago, but now are becoming more and more prevalent in today's game. Additionally, coaches are becoming more and more aware that strength, mobility, and throwing training are not separate entities, and that a well-integrated program combining all three can greatly minimize an athlete's injury risk. Hopefully, as these progressive training methodologies become more integrated into baseball, fewer pitchers will lose their careers to injuries.

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