DETERMINING FACTORS OF SPIN ON PITCHED FASTBALLS IN BASEBALL – A LITERATURE REVIEW

A Thesis
by
ANDREW ZWART

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Abstract

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IN BASEBALL – A LITERATURE REVIEW

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Baseball is a popular sport that is often referred to as "America's game." Of all the pitches thrown in a Major League Baseball season, more than half of them are fastballs. Three forces (gravity, drag, and Magnus force) determine the movement of a pitched baseball. Magnus force is caused by spin and is the major modifiable force in pitching. By altering spin rates and the spin axis of a pitched fastball, pitchers are able to change the movement of their pitches. Pitchers who throw fastballs the closest to true backspin have been shown to be the most effective. Modifiable factors of spin include friction between the fingers and the ball, finger placement on the ball, and arm slot variation caused by trunk and arm kinematics. The purpose of this review was to determine modifiable factors of spin that improve pitching performance through increased vertical lift on fastballs. Future research should examined altered mechanisms to increase friction as well as changes to throwing kinematics in an effort to generate increased fastball lift.

Acknowledgments

I would like to thank all of those who played a role in my academic journey. First of all, my advisors at Bethel University, Dr. Paradis and Dr. Jackson who gave me my passion for science and for preparing me to attend graduate schooling. Without your support, I would not be where I am today.

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Finally, I would like to thank my advisor, Dr. van Werkhoven, for his constant support and endless proofreading. Without his constant feedback and encouragement, this review would not be the same.

Dedication

This thesis is dedicated to my parents who have supported me on my academic endeavors and been a source of inspiration over the years. Without them, I would never have had the skills necessary to undertake this academic journey.

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Chapter 1: The Fastball Pitch – A General Introduction

Introduction

Pitchers often throw multiple pitches that are generally categorized into two groups: fastballs and breaking balls. Fastballs are meant to overpower the hitter with high velocities and generally have little to no lateral movement. Breaking balls are thrown slower, with the goal of getting the hitter to miss the ball using both vertical and lateral movement. Nearly every major league pitcher throws a fastball, but the types of breaking balls thrown can vary from pitcher to pitcher. While fastball speeds on the whole have continually increased over the last decade, the rate at which fastballs are thrown has decreased (Foley, 2019). Throughout the 2018 MLB season, the average fastball from a starter was thrown at 92.3 mph, while the average reliever threw their fastball at 93.4 mph (Simon, 2019). Those speeds are up nearly 4 mph from the year 2000, yet fastballs have gone from being thrown 64 percent of the time in 2003, to 55 percent of the time in 2018 (Foley, 2019; Petriello, 2016). Despite the decrease in fastball usage over recent years, they are still thrown by MLB pitchers more than half the time.

Fastballs are thrown for a number of reasons. The first is to overpower the hitter with velocity. Instead of using a breaking pitch aimed to deceive the hitter both in terms of speed and movement, the pitcher will throw a fastball in an attempt to throw it past the hitter. Additionally, in situations where the batter has a favorable count, the fastball is generally a safer pitch. A fastball is much easier to throw accurately than a breaking ball. The pitching motion is simple, and the pitcher does not have to adjust their aim for significant lateral movement. This increases the likelihood of throwing a strike in situations where a walk is imminent.

The aim of this first section of the literature review is to discuss the general information regarding the fastball pitch and the factors associated with imparting lift on the ball. First, a general overview of the fastball pitching motion will be discussed, followed by the forces that affect the motion of a fastball during flight. Finally, specific information regarding spin will be reviewed.

The Fastball Pitching Motion

The fastball pitching motion has been broken down into between three and six distinct phases (Braatz & Gogia, 1987; Dillman et al., 1993; Escamilla et al., 2017; Pappas et al., 1985; Werner et al., 1993). For the purpose of this general introduction to a fastball pitch, we will focus on Braatz and Gogia who defined a five phase pitching motion consisting of the stance; wind-up; cocking; acceleration; and follow-through phases (1987). The stance position can vary from pitcher to pitcher but is often characterized by one of three positions (Braatz & Gogia, 1987). The first is standing with both feet across the pitching rubber and the shoulders square to the strike zone. The second is angling the body at a 45-degree angle pointing towards home plate. Both of these positions occur with no runners on base and the pitcher can take their time winding up (known as pitching from the wind-up). The third is to have the back foot on the pitching rubber with the body perpendicular to the strike zone. This is known as pitching from the stretch. Pitching from the stretch allows the pitcher to shorten the duration of the throwing motion which helps to prevent base runners from stealing the next base. An example of both stances is displayed in Figure 1.

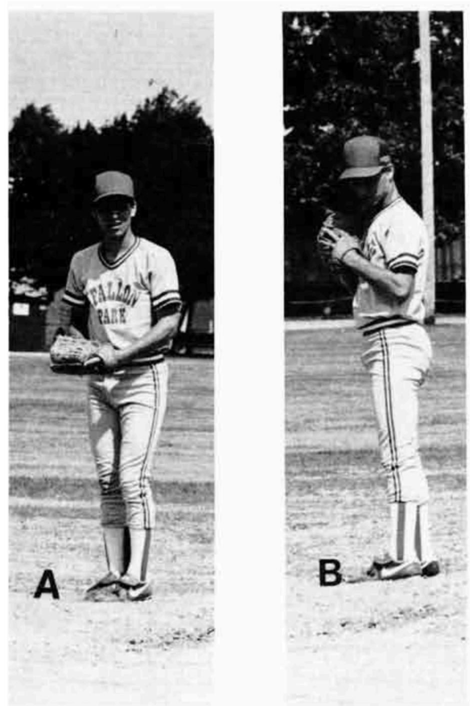

Figure 1. (A) Pitching from the wind-up at a 45-degree angle. (B) Pitching from the stretch with the back foot on the pitcher's mound. From Braatz & Gogia (1987).

The wind-up phase is important to establish a rhythm for the movement, begin the generation of energy, and hide the ball from the batter to improve deception (Pappas et al., 1985). To initiate the wind-up, the leg contralateral to the throwing arm pushes down into the ground to begin shifting the center of gravity forward towards home plate. The ipsilateral leg begins to rotate and extend while the contralateral hip and knee flex around 90 degrees. Arm movement can vary, but the elbows will be flexed at around 90 degrees with the upper arm next to the torso (Braatz & Gogia, 1987). Meanwhile, the ball is gripped in the glove by the throwing arm. At this point, the weight is fully shifted from the contralateral leg to the ipsilateral leg and the torso is positioned close to perpendicular from the pitching rubber. The entire wind-up phase lasts between 1.0 and 1.5 seconds from initiation of the movement to the start of the cocking phase (Braatz & Gogia, 1987). As the ball is separated from the glove by the throwing arm, the wind-up phase ends and the cocking phase begins. The wind-up phase is demonstrated in Figure 2.

Once separated from the glove just above the leading hip, the ball is quickly transitioned to behind and slightly below the trailing hip and then brought up to be cocked behind the head (Braatz & Gogia, 1987). The contralateral leg is then abducted, internally rotated, and extended forward towards home plate. The ipsilateral leg is slightly flexed as the center of gravity moves downward within the body. The contralateral leg travels forward until it plants on the ground with the toes pointed towards home plate. The leg should land on the contralateral side to the throwing arm of an imaginary line that bisects the pitcher's torso and home plate. The throwing arm finishes the cocking phase by abducting to 90 degrees, externally rotating to at least 90 degrees, and horizontally abducting to around 30 degrees behind the torso. The elbow is flexed around 90 degrees, the forearm is supinated, and the

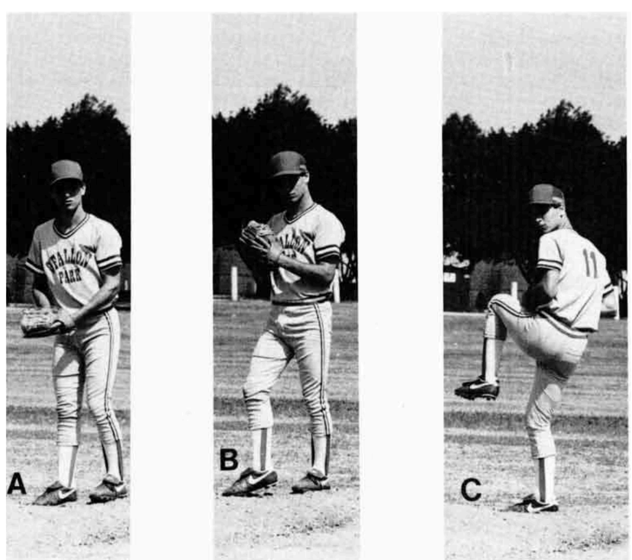

Figure 2. (A) Initiation of the wind-up phase by stepping backwards. (B) Right foot pivots parallel to pitching rubber. (C) Left knee raised and torso rotated perpendicular to target. From Braatz & Gogia (1987).

wrist remains in a neutral position. The torso will also slightly rotate towards the throwing arm. The contralateral arm is adducted and flexed to bring it alongside the torso on the home plate side of the body. Throughout the cocking phase, kinetic energy from the lower extremities is transferred upwards into the torso (Braatz & Gogia, 1987). This entire process occurs in just under half a second. The breakdown of the cocking phase is depicted in Figure 3. Following the completion of the cocking phase, the acceleration phase begins.

The beginning of the acceleration phase is where the throwing shoulder is maximally externally rotated (Pappas et al., 1985). Maximal external rotation of the shoulder joint allows for maximal stretching of the surrounding muscles as well as maximization of elastic energy in the joint capsule's fibrous tissues in the anterior shoulder (Braatz & Gogia, 1987). The arm and shoulder are pulled forward together as the elbow flexes to around 120 degrees. The elbow then extends as the arm is pulled forward, with extension ending at around 25

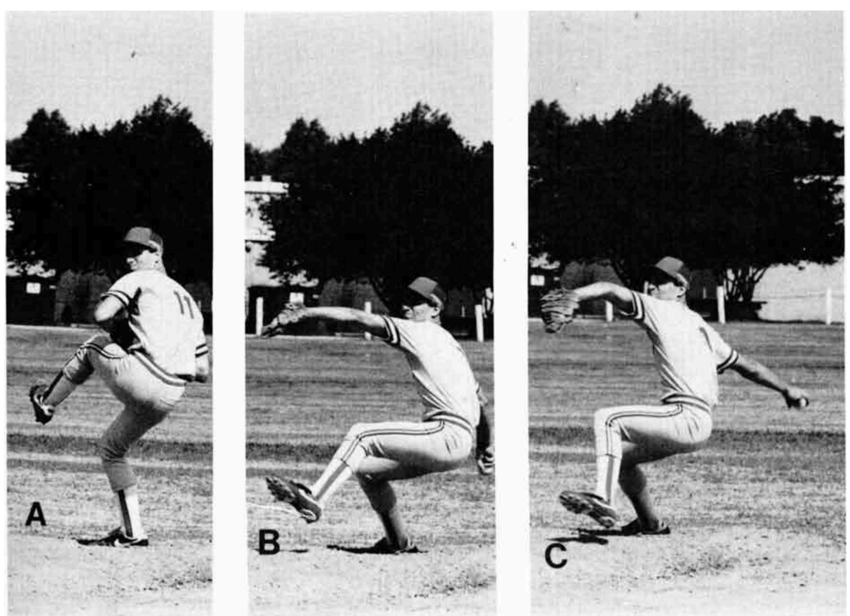

Figure 3. (A) Center of gravity is lowered. (B) Contralateral upper extremity action. (C) Right side drives forward. From Braatz & Gogia (1987).

degrees of elbow flexion. Slight wrist flexion begins about 20 ms before the ball is released, and forearm pronation occurs around 10 ms later (Pappas et al., 1985). Throughout the acceleration phase, the torso rotates to square up with the strike zone close to ball release. This entire process takes under 50 ms. In order to achieve that motion in a short period of time, the shoulder has been measured rotating up to around 9200 degrees/second. The end of the acceleration phase occurs at ball release. The release point varies from pitcher to pitcher, however, the harder the pitcher throws, the further posterior the ball will be released relative to the head (Braatz & Gogia, 1987). It has been suggested that this may be a result of increased forearm lag from faster arm movement (Atwater, 1979). Once the ball has been released, the follow-through phase occurs.

The follow-through phase is characterized by the deceleration of the throwing arm. The plant, or forward knee, flexes as the weight is shifted entirely to that foot for the purpose of decelerating the body (Braatz & Gogia, 1987). The throwing arm adducts across the body

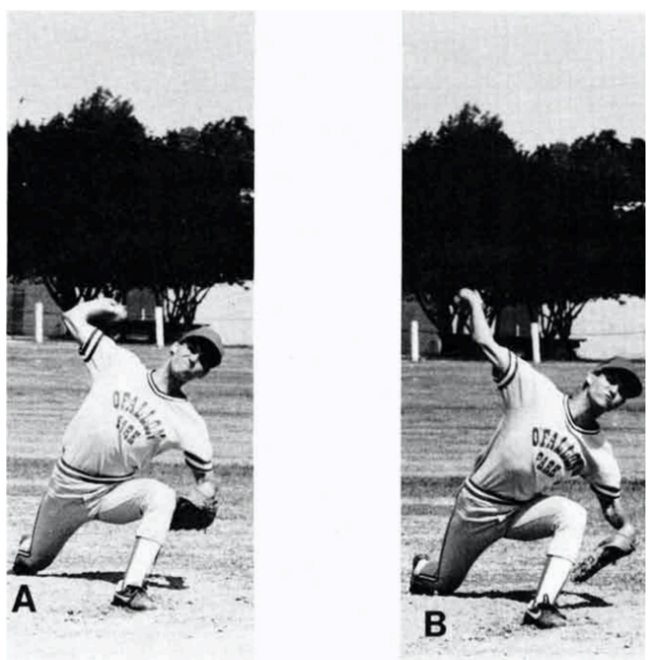

Figure 4. (A) Shoulders begin to square. (B) Arm rotates as elbow extends. From Braatz & Gogia (1987).

and the elbow will often flex to around 45 degrees as part of a recoil mechanism (Pappas et al., 1985). Coaches will often advise pitchers to maintain eye contact with the pitching target in an effort to maintain unilateral balance on the stride leg during the follow-through. The goal of the follow-through phase is to safely slow down the throwing arm without putting undue stress on the body, causing injury. Deceleration of the shoulder can occur at rates as fast at 500,000 degrees/second^2 (Pappas et al., 1985). Once the body catches up with the arm and the trail leg is planted once again, the pitching motion is complete.

Forces Acting on a Pitched Baseball

The movement of the baseball through the air is determined by the forces acting on the ball while airborne. There are three forces that can affect the trajectory of a pitched baseball (Nathan, 2008).

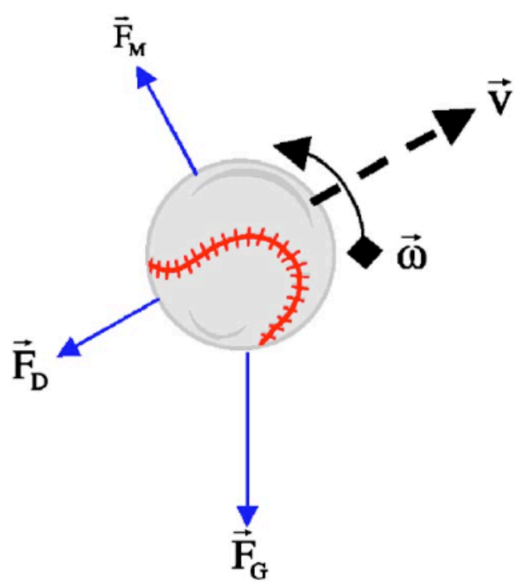

Figure 5. The forces acting on a spinning baseball in flight; Magnus Force(F_M), Drag Force (F_D), Gravitational Force (F_G). V is the direction of movement and ω is the direction of spin. From Nathan (2008).

Gravitational force

The force due to gravity pulls the baseball towards the ground at an acceleration of roughly 9.81 m/s^2. This gives the baseball an arced (parabolic) path as it travels from the pitcher's mound towards the plate. Newton's Universal Law of Gravitation states that the gravitational pull (force) between two objects can be calculated as:

$$(1)\ F_G = G\frac{m_{earth}m_{ball}}{r^2}$$

where G is the gravitational constant, m is the mass of the two objects, and r is the distance between their centers of mass. Since the distance between the surface of the earth and the ball is negligible, the r value is specified by the earth's radius. This equation is further simplified by:

$$(2)\ g = G\frac{m_{earth}}{r^2}$$

where g = acceleration due to gravity, on average 9.81 m/s^2. Finally the force on the ball can then be calculated as:

$$(3)\ F_G(or\ Weight) = 9.81m_{ball}$$

Therefore

$$(4)\ F_G = 9.81 \times 0.145$$

$$= 1.42 \text{ N}$$

It should be noted that the value for g = 9.81 m/s^2 is an average value. This value varies depending on the earth's radius at different locations. For example, g = 9.78 m/s^2 in Mexico City and 9.82 m/s^2 in Oslo. This has a small effect on the downward force acting on the ball. Of course, this is not something that can be manipulated by a pitcher.

Drag force

Drag force resists the movement of an object moving through a fluid medium, in this case, slowing the ball down as it moves through the air (Hall, n.d.). This force can be calculated as:

$$(5)\ F_D = \frac{1}{2}\rho v^2 A C_D$$

where ρ is the density of air, v is the velocity of the ball, A is the cross-sectional area of the ball, and C_D is the coefficient of drag. The drag coefficient, determined using a wind-tunnel model, is found by solving Eq (5) for C_D where F_D, ρ, v, and A are all known variables under experimental conditions (Hall, n.d.). When examining the drag force on a fastball, it does not remain constant throughout a pitch (Sarafian, 2015). Given that drag force is directly tied to velocity, as the velocity changes, so does the drag force. While the coefficient of drag can also change as velocity slows, it is considered negligible when calculating drag force on a pitch (Jinji & Sakurai, 2006).

The drag coefficient is critical in estimating the amount of drag force experienced by a pitched baseball. The drag coefficient is a measure of a specific object's resistance to flow in a fluid medium and it is mainly determined by factors associated with air flow around the ball. As a baseball travels through space, air flows past it at the same speed the baseball is moving. The air molecules along the surface on the ball stick to the outer layer of the baseball, creating a boundary layer (Hall, n.d.). For a baseball moving through air, the major source of drag force is due to this boundary layer of air separating from the ball. Whether this separation and associated wake occurs closer to the front of the ball or closer to the back of the ball, is the main determining factor of the coefficient of drag magnitude, and it is related to the Reynolds number. The Reynolds number is calculated by:

$$(6)\ Re = \frac{\rho v R}{\mu}$$

where ρ is the density of air, v is the velocity of the object, R is the radius of the ball, and μ is the viscosity of the air. When the Reynolds number is low, there is mostly laminar airflow (smooth layers of air) around the ball. When the Reynolds number is high, the flow is turbulent, which is associated with a mixing of adjacent fluid layers. Research suggests that at low Reynolds numbers, laminar flow generates a large wake, which results in increased drag forces (Sharp & Adrian, 2004). At higher Reynolds numbers, when turbulent flow occurs, the result is a smaller wake and therefore a smaller drag force. Smooth objects typically have laminar flow, while objects with perturbations on the surface often present with turbulent flow. The seams on a baseball function to change the flow from laminar to turbulent which reduces the drag force acting on the ball.

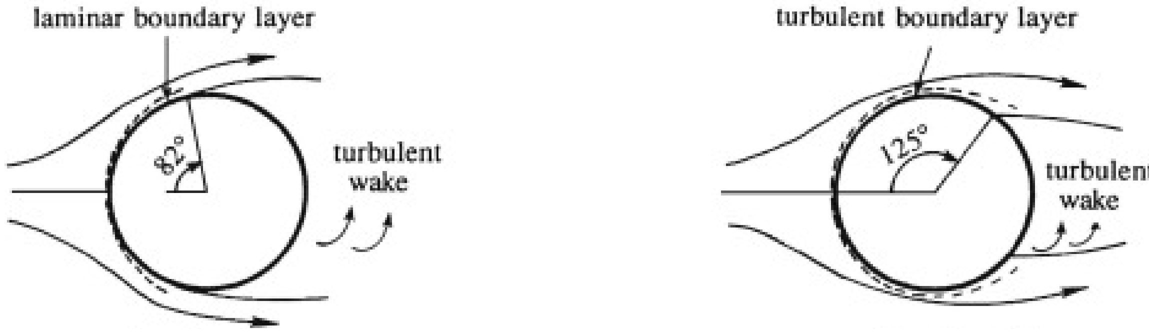

Figure 6. Laminar flow vs turbulent flow. A laminar boundary layer causes a larger wake, whereas a turbulent boundary layer reduces the size of the wake. From Kundu et al. (2012).

When a baseball is pitched at sea level with standard atmospheric conditions, the Reynolds number is around 2.2×10^5 (Hall, n.d.). Under these conditions, if a smooth ball was thrown at 100 mph, the coefficient of drag would be 0.5, while a baseball would have a drag coefficient of only 0.3. The reduced drag coefficient of the baseball would allow it to move through the air at faster velocity.

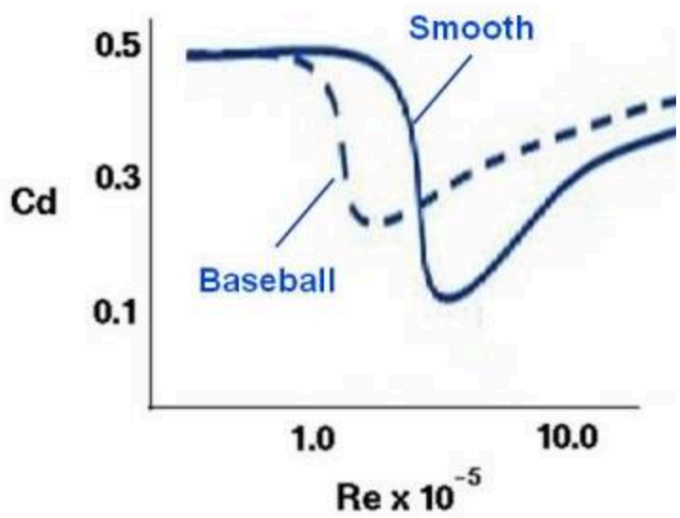

Figure 7. The relationship between the coefficient of drag and the Reynolds number between a smooth ball (solid line) and a baseball (dashed line). From *Hall, n.d.*

Magnus force

The third and final force acting on a baseball is the Magnus force. Magnus force is caused by changes in pressure surrounding a spinning ball as governed by Bernoulli's principle. Bernoulli's principle states that as a fluid moves faster, the pressure in that fluid decreases relative to the pressure in a slower moving fluid. The airflow on one side of the ball is in the same direction as ball spin, causing the velocity of the airflow to increase while on the opposite side of the ball, the ball spins against the airflow causing the velocity of the airflow to decrease. This difference in velocity causes a pressure differential, and the ball moves towards the side with lower pressure, or the faster air flow. The Magnus force of a baseball can be expressed in an equation as

$$(7)\ F_M = \frac{1}{2} C_L \rho A v^2$$

where C_L is the coefficient of lift, ρ is the density of air, A is the cross-sectional area of the ball, and v is the linear velocity of the ball.

Briggs was one of the first to examine Magnus forces caused by spin (Briggs, 1959). Briggs attached a baseball to a rod on the ceiling of a wind tunnel and held it in place using a suction device. The ball was spun, and then dropped vertically through the horizontal wind tunnel. Lateral deflection was measured, and Briggs found the Magnus force to be proportional to the product of the wind tunnel speed and the rate of rotation on the ball. Watts and Ferrer expanded on these results by using a more complex set up (Watts & Ferrer, 1987). They attached a baseball to a spinning rod mounted on Plexiglas and strain gauges in a wind tunnel. Air was pushed through the tunnel and baseline measurements were taken with a stationary ball to factor out drag force. The rod was then spun at different constant rates and the strain measurements were once again measured. By subtracting the previously recorded drag forces, all that was left was the Magnus force. The Magnus forces collected did not appear to agree with previous research (Briggs, 1959). Watts and Ferrer concluded that the lift coefficient was best represented by

$$(8)\ C_L = \pi D\omega/v$$

where D is diameter of the sphere, ω is the rotation rate, and v is the velocity of the ball. More recent examination of lift forces has utilized high speed cameras to measure the relationship between spin and lift force in more detail (e.g., Alaways, 1998; Alaways & Hubbard, 2001; Jinji et al., 2011; Nagami et al., 2011; Nathan, 2008).

Between 2018 and 2020, MLB pitchers threw a total of 606,523 four-seam fastballs with an average spin rate of 2280 revolutions per minute (rpm) (baseballsavant.com). This spin is an important determinant of a pitcher's performance, as spin causes Magnus force. Magnus force causes the ball to deviate from the expected parabolic path which causes hitters to swing and miss. Many researchers have studied the relationship between spin and linear velocity (e.g., Alaways, 1998; Alaways & Hubbard, 2001; Nagami et al., 2011, 2013; Nathan, 2008). The relationship between spin and velocity is known as the spin factor or spin parameter (Nagami et al., 2013; Nathan, 2008). The spin factor of a baseball can be calculated as

$$(9)\ S = R\omega/v$$

where R is the radius of the ball, ω is the rate of spin of the ball (radians/s), and v is the linear velocity of the ball (m/s) (Nathan, 2008). Since the radius of a baseball is constant, Driveline Baseball coined the term "Bauer Unit" which is calculated by simply dividing the angular velocity (in rpm) by the linear velocity (in mph) (Driveline Baseball, 2017a). An understanding of the relationship between spin and velocity helps to further describe lift force acting on a baseball.

Alaways and Hubbard placed 4 markers onto a baseball and tracked the spin and movement of a baseball launched from a pitching machine as it neared home plate. The results demonstrated that previous research describing the relationship between spin parameter and lift were accurate, and reinforced the idea that at low spin parameters, small changes in the spin parameter cause larger changes in lift (Alaways & Hubbard, 2001). They also concluded that at the same spin parameters, four-seam fastballs have greater coefficients of lift than two-seam fastballs. Jinji and Sakurai examined the spin on baseballs thrown by collegiate pitchers using high speed cameras just after ball release. They concluded that previous research examining the aerodynamic forces on baseballs in wind tunnels were not appropriate for determining the aerodynamic forces on a pitched baseball, as the spin direction on a pitched baseball is different from a wind tunnel due to what has become known as the spin axis (Jinji & Sakurai, 2006).

Nathan's examination of the relationship between spin factor and the coefficient of lift confirmed previous work done by Alaways (Alaways, 1998; Alaways & Hubbard, 2001; Nathan, 2008). Recall that the coefficient of lift, as well as linear velocity, are major

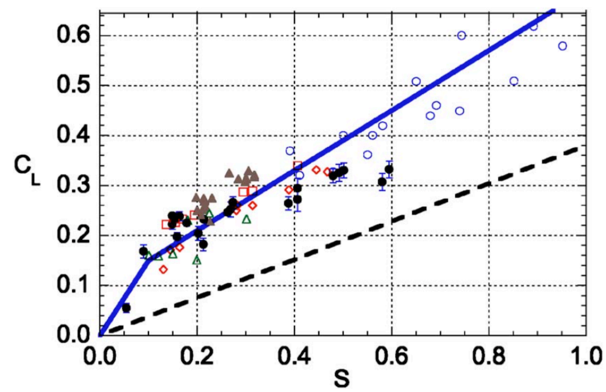

Figure 8. Experimental results of the coefficient of lift (C_L) as depicted by Nathan. Different shapes and lines show experimental C_L from differing researchers. From Nathan (2008).

determining factors of Magnus force experienced by a pitched baseball. For spin factors below 0.15, a small change in spin factor results in a significant change in the coefficient of lift. For spin factors above 0.15, the same change in spin factor results in a smaller change in the coefficient of lift, although it remains proportional at least through a spin factor of 1.0. Across multiple levels of baseball, the spin parameter of a pitched baseball ranges between 0.15 and 0.25. Within the fixed value $0.15 < S < 0.25$, Nathan also found that changing velocity between 50 mph and 100 mph does not have a significant impact on the coefficient of lift (Nathan, 2008).

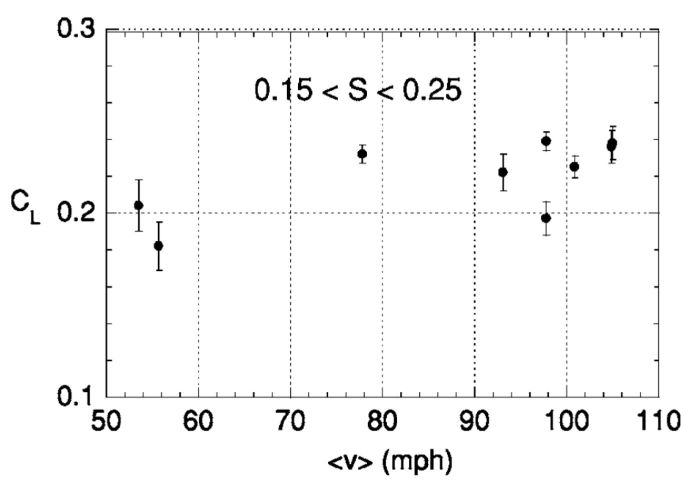

Figure 9. Coefficient of lift from the testing done by Nathan (2008) for a fixed S between 0.15 and 0.25.

Therefore, MLB pitchers must rely on spin, and not velocity, to generate movement on a four-seam fastball.

Spin Axis

While every professional pitcher generates movement on their pitches, that movement varies from pitch to pitch as well as between different pitchers. This is a result of the direction of the Magnus force. The direction of movement depends on what researchers have termed “spin axis” (Jinji et al., 2011; Jinji & Sakurai, 2006; Nagami et al., 2011, 2013). Spin axis is the imaginary axis that the ball rotates around. For example, a ball with pure backspin would have a spin axis that is parallel to the ground through the middle of the ball and perpendicular to the direction the ball is moving. When a baseball has a spin axis orthogonal to the pitching direction, the right hand rule can be used to describe the direction of movement (Nagami et al., 2013). The thumb points in the direction of the spin axis and the index finger points in the pitching direction. The middle finger is then pointed perpendicular to both the thumb and index finger where it represents the direction of the spin-induced deflection.

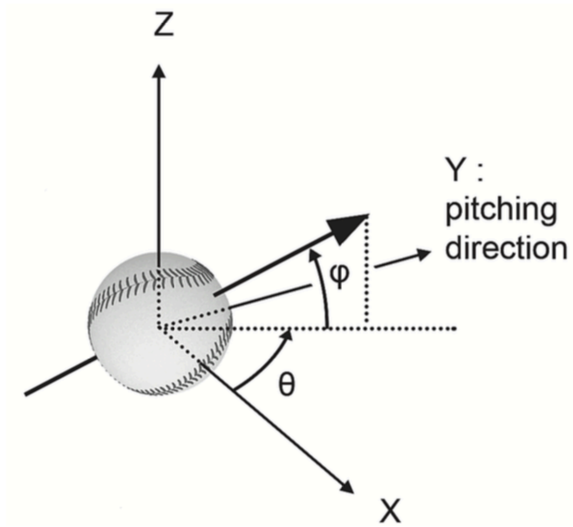

Figure 10. The spin axis of a pitched baseball. The spin axis is denoted by the thick black arrow running through the center of the ball. The y-axis is the pitching direction, and the z-axis is straight up in the air. From (Nagami et al., 2013).

The magnitude of this deflection is calculated using the Magnus force described in Eq (7). This rule only works if the spin axis is orthogonal to the pitching direction. When this is not the case, a more complicated calculation is required to determine the direction of movement.

When the spin axis is not orthogonal to the pitching motion, the magnitude and direction of the Magnus force is calculated as the cross product of the force acting in both the vertical (F_{lift}) and horizontal ($F_{lateral}$) directions. Each of these can be calculated using their respective formulas:

$$(10)\ F_{lift} = \frac{1}{2}\rho\pi\omega r^3 v \sin\theta_{VS} \sin\theta_{SD}$$

$$(11)\ F_{lateral} = \frac{1}{2}\rho\pi\omega r^3 v \cos\theta_{VS} \sin\theta_{SD}$$

where ρ is air mass density, ω is the spin rate of the ball, r is the radius of the ball, v is the velocity of the ball, θ_{VS} is the angle between the vertical axis and the spin axis, and θ_{SD} is the angle between the spin axis and the direction of motion (Bahill & Baldwin, 2007). The θ_{SD} may also be referred to as the angle of attack. As the ball is pulled downwards by gravity throughout the ball flight, the spin axis remains unchanged, however the direction of the linear motion changes as the ball drops. This causes θ_{SD} to increase which can result in up to a 10% increase in F_{lift} and $F_{lateral}$ (Bahill & Baldwin, 2007). In situations where the spin axis is parallel to the line of motion, a unique phenomenon, known as a gyroball, occurs (Nagami et al., 2013). When the spin axis and the direction of motion align, the θ_{SD} is 0 degrees. When plugged into the F_{lift} and $F_{lateral}$ equations, the sin (0) = 0, and there is no vertical or lateral force acting on the baseball. However, as the ball falls due to the force of gravity, the angles change and the resulting lateral and lift forces generate late movement on a pitch.

To simplify our understanding of the effects of spin on lift force, the spin can be broken down into two components (Nathan, 2020). The "transverse spin" is the component of spin perpendicular to the direction of motion. The "gyrospin" is the component of spin that is parallel to the direction of motion. As previously mentioned, gyrospin does not have an impact on the movement of the ball. The remaining portion of spin, the transverse spin, is solely responsible for the lift force and movement on a baseball. The transverse spin can be referred to as "effective" or "active" spin while the gyrospin can be referred to as "ineffective" or "inactive" spin.

Recent data collection suggests that pitchers who have spin factors that deviate from the average are the most effective at their jobs (Alaways & Hubbard, 2001). Additionally, it is believed that while different pitches will achieve different spin rates at the same velocities, each pitcher has his own linear relationship between velocity and spin on a single pitch that is difficult if not impossible to modify (Driveline Baseball, 2016). However, the specific factors that affect the amount of spin imparted on the ball is not clear. Previous studies have suggested spin is impacted by the linear velocity of the pitch and pitch orientation (Driveline Baseball, 2016; Kanosue et al., 2014; Nagami et al., 2011, 2013; Watts & Ferrer, 1987).

In general, there are two types of fastballs thrown by pitchers, and they rely on the orientation of the seams on a baseball (Driveline Baseball, 2016). The two-seam fastball is thrown so that with each revolution of the ball, two seams rotate around the spin axis. On the other hand, the four-seam fastball is thrown so that each revolution of the ball produces four seams rotating about the axis. The four-seam fastball is more likely to rise, while the two-seam fastball will often drop and have side-to-side movement. See section on Finger Position for more details.

Perception of Fastballs

Elite baseball pitchers often throw pitches, typically fastballs, that are described as having “hop.” While it is physically impossible to throw a fastball that rises, a hitter’s perception of a pitch can deceive the hitter into believing the ball rose. A major league fastball is too fast to be tracked continuously from release to home plate. In order for a hitter to make contact, they must interpret the path of the ball based on the initial velocity and the immediate movement following release (McBeath, 1990). As the ball nears home plate, the batter must make a decision on where the ball is going to cross home plate. If the hitter

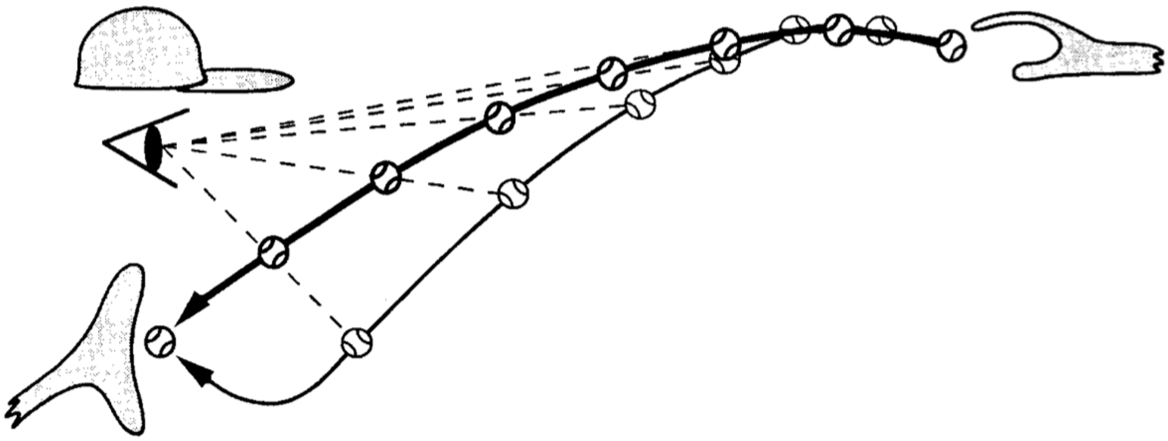

Figure 11. The top (thicker line) trajectory shows the actual path of a fastball. The bottom (thin line) shows the path the batter perceives the fastball to travel if he incorrectly estimates the initial velocity. The baseballs demonstrate where the ball is relative to where the batter believes the ball to be along the path. Once the ball reaches home plate, the batter reconciles his incorrect estimation of position with the actual position (far right baseball) and the ball appears to hop. From McBeath (1990).

underestimates the initial velocity of the ball, the perceived trajectory will be ahead of and above the actual trajectory (Figure 11). When the ball crosses home plate, the perceived trajectory and actual trajectory align which results in the ball appearing to rise at the last possible moment (McBeath, 1990).

Hitters often report four-seam fastballs appearing to have more rise (Bahill & Baldwin, 2004). While a portion of that can stem from the spin axis causing more upward lift, there is another proposed explanation that relies on perception of spin. Human vision refreshes between 40 and 50 times per second (40-50 Hz). A two-seam fastball thrown at 1200 rpm will rotate at around 20 rps (revolutions per second). Each revolution will show two seams, which means the seams will appear at around 40 Hz. This can be perceived by the human eye, and with practice, spin direction can be interpreted. When spin direction is interpreted, the perception of rising is less likely to occur given the hitter can better estimate the movement of the ball. On a four-seam fastball thrown with the same spin rate, the seams will appear four times per revolution for a seam appearance of 80 Hz. In this case, the spin would be imperceptible, and the seams would appear as a blur. Therefore, although mechanical factors are critical in determining the 'rise' or reduction in downward movement of a four-seam fastball, the batter's perception does play a role in the success of the pitch.

Chapter 2: Potential Modifiable Factors Affecting Fastball Spin

Introduction

The first section of the literature review considered basic information on the common fastball pitch as well as specific information pertinent to the forces causing a pitched ball to move the way it does. The main purpose of this literature review is to identify potential modifiable factors that could affect the lift force acting on a pitched fastball. This lift force relates specifically to the ability of the pitcher to reduce the downward movement as the ball moves toward the batter. As described in the previous section, lift force is a function of spin, and upward lift force is created when a ball is pitched with some degree of backspin. Therefore, the aim of this section will be to consider factors that could potentially maximize backspin, or spin about the horizontal axis, and therefore vertical lift force on a pitched fastball.

When throwing a fastball, the fingers flex within a few milliseconds of when the ball is released to prevent the ball from rolling off the top of the hand prematurely and falling backwards due to back force from the baseball (Hore & Watts, 2011; Matsuo et al., 2018). Keeping the ball in the hand longer allows the pitcher to impart backspin onto the ball during the milliseconds leading up to ball release (Matsuo et al., 2018). The magnitude of the spin generated, and the orientation of the spin axis, then determine the Magnus force acting on the ball. To maximize the upward force on the ball, the spin axis needs to be oriented horizontal to the ground and perpendicular to the direction of movement (Nagami et al., 2013). There are two angles to consider when examining spin axis (Jinji & Sakurai, 2006). The azimuth angle is the angle between the x-axis, which runs off towards first and third base, and the projection of the spin axis onto the horizontal plane. The elevation angle is the angle between the spin axis and the horizontal plane. Research suggests that the most effective pitchers, in terms of strikeout per nine innings, have as little azimuth and elevation angles as possible (Nagami et al., 2013). Ideally, a pitcher would have no azimuth or elevation angle meaning the spin axis would be horizontal and perpendicular to the line of motion. This is true backspin (Nagami et al., 2013). The topics below discuss different factors that are potentially modifiable that would have an effect on the ability to produce optimal backspin during fastball pitching.

Forces

The forces applied to a baseball by a pitcher act on a baseball to determine 1) the direction and velocity of ball release as well as 2) the amount of spin imparted on the ball. The resultant force is the root of the squared sum of all force components (Kinoshita et al., 2017), and determines the direction of motion of the ball. The shear force however, which is the sum of the tangential forces applied to the ball, generates angular rotation, or spin. It is accepted that this shear force is caused by friction. While the ring finger and thumb make minor contributions to force production, the index and middle fingers produce a majority of the resultant and shear force (Kinoshita et al., 2017). While both types of forces have been discussed in recent literature, there is no clear definition of the relationship between resultant and shear forces.

The ability to generate shear force is largely tied to friction. Friction can be controlled for in a number of ways (Kinoshita et al., 2017). Changing the finger placement on the baseball could likely affect the amount of frictional force produced. Differences in the material that the fingers touch on the baseball, for example, seam versus no seam, would affect the friction coefficient between the fingers and the baseball. Further, any interference in the tactile sensation of the ball from the fingers can alter gripping force, and therefore the resulting force of friction (Kinoshita, 1999). Moisture can play a significant role on the coefficient of friction on finger pads (Adams et al., 2013). When the finger pads are too dry or too moist, the coefficient of friction will be suboptimal. The optimal level of friction heavily relies on a number of factors including the material of the baseball, sliding velocity of the movement, magnitude of the loading, and the surface design of the individual finger pad among others (Pasumarty et al., 2011). While the exact moisture level varies from pitcher to pitcher, moisture can be controlled by adding rosin, wiping the fingers off, or even blowing on the fingers. Rosin powder has been shown to increase the coefficient of friction during wet conditions, while it may reduce the coefficient of friction under dry conditions (Yamaguchi et al., 2020). The increase in the coefficient of friction under wet conditions has only been shown to occur at normal forces over 10 N. While a majority of the ball rolling phase has forces over 10 N, as the ball is released, the force drops to 0 N (Figure 12). Once the force drops to below 10 N, the rosin powder can cause ball slippage. This would suggest that it may be beneficial to only add rosin powder to the lower part of the pad of the fingers and below, allowing for the late contact (below 10 N) to occur on skin without rosin powder in an attempt to avoid any slippage and maximize spin. Finally, it should be noted that each individual's fingertips will have slightly different features that can alter the coefficient of friction, as well as change the optimal moisture level for maximizing friction (Adams et al., 2007; Spinner et al., 2016).

Roughing up the surface of the fingers or the ball could potentially increase friction between the two, and therefore increase spin. There is currently limited data looking at the

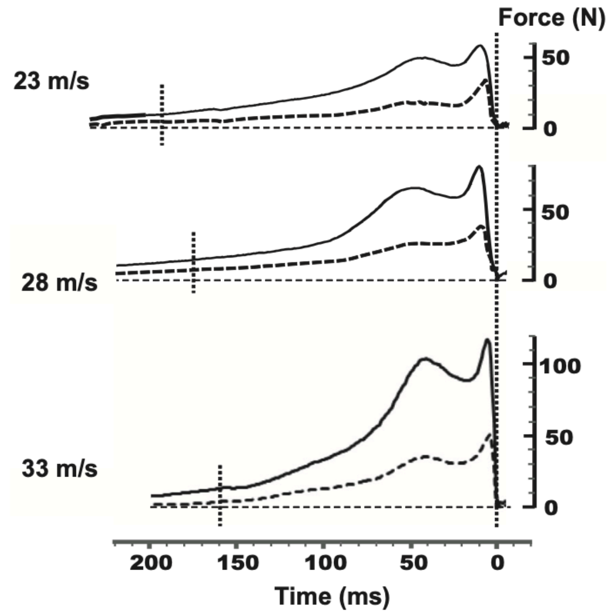

Figure 12. The resultant (solid line) and shear (dashed line) forces for a single pitcher throwing pitches at three different speeds. The short vertical dashed line indicates the moment of stride foot contact and the long vertical dashed line indicates the moment of ball release. From Kinoshita et al. (2017).

relationship between friction of the ball and fingers, but research on finger pad coefficients of friction suggests that roughing up one of the surfaces may actually reduce friction (Pasumarty et al., 2011). At loads of around 0.2 N, the coefficient of friction between the finger pad and filter paper was only 0.2, while it was 4 between a finger pad and a smooth glass. This suggests that roughing up the surface of the finger or ball would actually reduce shear force, and therefore spin. However, it must be noted that this study occurred at extremely low normal forces, and much less than the 10 N suggested by the rosin study. Therefore, future research should examine increasing the surface roughness of the finger pad and baseball and the effects on friction. The main challenge to this argument is a potential relationship between blisters and repetitive finger friction, which would require further examination (Dawson et al., 2004).

Before proceeding, it must be acknowledged that adding substances, aside from rosin, to the fingers of pitchers is currently illegal in professional baseball. Batters routinely use pine tar to get a better grip on the bat. As previously mentioned, pitchers have rosin bags on the mound to dry out their hands and try to increase grip. While both of those are legal under a set of circumstances, there has long been speculation that pitchers use substances to improve spin, and those close to the game reaffirm that notion (Sarris, 2020). The benefits to the use of substances are clear. A pitching development lab had pitchers throw a series of pitches with no grip, a series of pitches with pine tar, and a series of pitches with Pelican Grip (Sarris, 2020). The range of velocities were between 82.3 and 82.6 mph under all three conditions, but the spin rate jumped from 2193 rpm with no grip, to 2431 rpm with pine tar, and 2520 rpm with Pelican Grip. Even without a perfect spin axis, the vertical break changed by nearly three inches due to the increase in spin. Whether substances remain illegal or not, it is clear that they have a substantial impact on friction and therefore spin.

While friction is important in determining shear force, it is irrelevant if the pitcher does not have the strength to generate force in the first place. Regarding linear velocity, it has been demonstrated that finger forces during high speed pitching can reach up to around 88% of maximal finger strength (Kinoshita et al., 2017). With professional pitchers, this amounts to somewhere between 90 N and 100 N on both the pointer and middle fingers, or just under 200 N between the two (Kinoshita et al., 2017; Matsuo et al., 2018). This suggests that in order to throw a ball with control and the proper velocity and spin, it requires the ability to generate 200 N of force with the pointer and middle fingers. As previously mentioned, there is no clear description of the magnitude of shear force on a baseball, which means 200 N may be an underestimation of the force required to pitch a fastball at high velocities. However, if maximal finger strength is proportionate to linear velocity, it stands to reason that increasing maximal finger force ability would increase velocity and could translate to additional shear force. It is also worth noting that an examination of college baseball pitchers demonstrated that pinch strength of the index and pointer fingers significantly correlates with spin generated on curveballs (Woods et al., 2015).

Finger Position

Research on forces has suggested that finger placement may play a significant role in kinematic patterns of the hand, and therefore spin (Takahashi et al., 2001). Further, finger position has been shown to be one of the primary determining factors of spin axis (Jinji et al., 2011). It has been established that there are two phases required to throw the ball (Hore & Watts, 2011; Matsuo et al., 2018). The first extension of the fingers releases the ball from the pitchers grip so that it can begin to move. The second extension occurs as the ball begins to roll up and off the fingers. The ball rolling phase is where both the resultant and shear forces peak to generate velocity and spin.

When throwing a four-seam fastball, the fingers are placed in a V pattern along the backside of the ball (Figure 13). The width between the fingers can vary, and there does not seem to be any consensus on which is more effective. In fact, it has been suggested that different grips are more effective on a case by case basis (Driveline Baseball, 2020a). The little testing that has been done on finger placement width has shown that a regular fastball grip and the close finger grip have similar results, with the regular grip having slightly more spin and velocity (Driveline Baseball, 2017b). On the other hand, using three fingers or gripping the ball with a wide, or split grip, results in significantly lower spin and velocity.

Although initial testing shows a close grip to be marginally slower and lower spin overall, the spin factor remains about the same (increases by a negligible margin). While it may not be an explicit improvement in performance, the close finger grip will be unusual for most pitchers. If given the time to acclimate to the new grip, the results may demonstrate a significant change. When the pointer and middle fingers are brought closer together at the center of the ball, the ball rolling phase would see a small increase in time as the fingers would remain in contact with the ball longer. This could allow for an increased window of shear force application, and as such, would result in greater spin rates. In practice, this may be challenging for most pitchers as placing the fingers together may significantly reduce control of the pitch.

Central to this discussion is the difference between four-seam and two-seam fastballs. Two-seam and four-seam fastballs are held with similar finger positions (Driveline Baseball, 2020a,b). While each pitcher will have their own personal preferences, the general grip places the ball between the pointer and index fingers on top of the ball with the thumb on the opposite side. The ring finger supports the ball, and the pinky finger is not in contact with the ball. The primary difference between the four and two-seam fastballs is the depth of grip. The two-seam fastball sits deeper in the hand than the four-seam fastball. When the four-seam fastball is thrown, the pitcher is instructed to "yank" downwards (Driveline Baseball, 2020a).

Figure 13. Basic four-seam fastball grip (left). Basic two-seam fastball grip (right). Notice the ball sits further back in the hand with the two-seam fastball. From Driveline Baseball (2020a,b).

A recent study demonstrated that spin may be determined by how far the fingers reach over the top of the ball prior to the ball rolling phase (Kanosue et al., 2014). By reaching the fingers further over top of the ball, the ball rolling phase is extended and the “yanking” motion has more time to generate spin. A two-seam fastball is cued by telling the pitcher to come over the top of the ball to generate sidespin (Driveline Baseball, 2020b). For a right-handed pitcher, this means coming across the ball to the left in an effort to generate both backspin and sidespin. Four-seam fastballs have a higher average spin and a higher velocity than the two-seam fastball across major league baseball, however, that could be due to a number of factors including variation between pitchers and intent when throwing (Petriello, 2016). The four-seam fastball is thrown to generate maximum velocity, while the two-seam is thrown to generate movement. If a four-seam fastball was thrown with a deeper grip, like the two-seam fastball is, would more spin be generated? It is also not clear as to the potential variations that could arise when a pitcher pitches the ball with an orientation that is neither four-seam or two-seam without changing the grip or movement pattern. However, as previously noted, four-seam fastballs have greater lift coefficients than two-seam fastballs which suggests throwing a four-seam fastball with two-seam orientation may reduce the Magnus force acting on the ball (Alaways & Hubbard, 2001). Nevertheless, it is still possible that these slight differences would lead to changes in spin and increase the likelihood for the batter to be deceived.

Gripping the ball deeper in the hand, or choking up on the ball, could have a similar effect to placing the fingers on the middle of the ball. By choking up on the ball, the ball would sit further away from the fingertips and more time would be spent in the ball rolling phase. This could increase the time for shear force application, and in that case, spin would increase. Additionally, one of the biggest determinants of friction is contact area (Lewis et al., 2014; Pasumarty et al., 2011). By increasing the surface area of the hand in contact with the ball, the force of friction should increase. A significant challenge to choking up on the ball would be maintaining control. The sequence in which the fingers flex and extend is critical to accuracy (Hore & Watts, 2011). With an altered ball rolling pattern, pitchers would be required to learn the timing of a new finger kinematic sequence. Velocity may be impacted in a similar fashion as force generation patterns would change as a function of different finger movement patterns. Additionally, research has demonstrated that a majority of spin is generated from the fingertips in the last few milliseconds leading up to ball release (Kinoshita et al., 2017; Matsuo et al., 2018). If this is the case, increasing the amount of time with the ball in hand may not make a significant difference on the spin of the baseball.

Nevertheless, increased contact surface area between the hands and the ball may still increase the force of friction.

Upper Extremity Position

This section will specifically cover the rest of the upper extremity, and associated trunk position, during the pitch. This does not include the finger position as discussed in the previous section. Apart from finger position, palm position has also been shown to be the primary determining factors of spin axis (Jinji et al., 2011). It is hypothesized that to maximize the upward lift force on a fastball, the index and middle fingers need to be vertically oriented along the surface of the ball for the duration of the ball release phase. This allows the pitcher to generate the maximum true backspin on their pitch. To achieve this perfect alignment with the fingers, the palm and the forearm must also be vertical which includes a neutral wrist at release. This position can be achieved at various elbow and shoulder joint angle positions. For example, the pitcher could have a vertical forearm and finger position with a high degree of elbow flexion at ball release, or the pitcher could have a low degree of elbow flexion at ball release while releasing the ball from an overhead position (Figure 14).

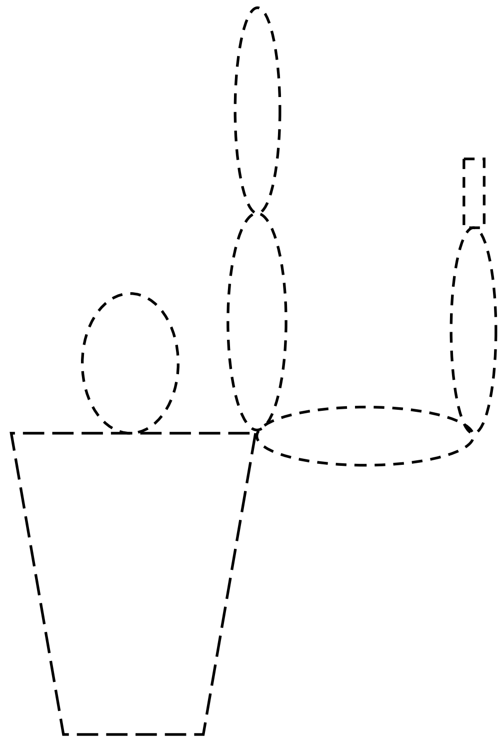

Figure 14. Two possible arm positions to achieve a vertical wrist and forearm

However, it is evident when analyzing pitching movement that this hypothetical situation does not take into account trunk motion. When including the possibility of trunk movement, it becomes clear that the pitcher has infinite possibilities to release the ball in this ‘optimal’ position (Figure 15). By laterally flexing the trunk to various degrees, the pitcher can achieve a vertical forearm and finger position without a substantial change to their existing throwing pattern. Achieving the vertical forearm and finger throwing position at release should allow the pitcher to generate the maximum amount of true backspin, and therefore results in the most upward lift possible.

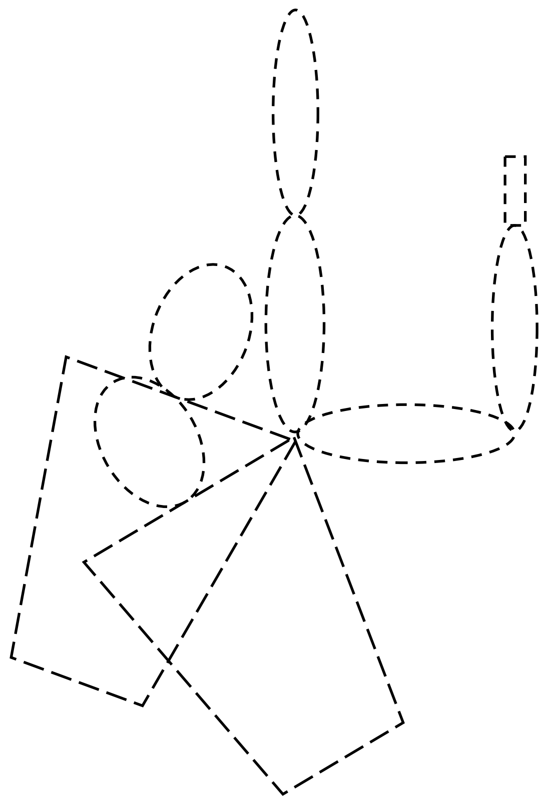

Figure 15. A vertical wrist and forearm position taking into account trunk flexion in either direction.

However, in practice this is not the case. The hand or finger position is not necessarily vertical. In practice, the vertical forearm and finger pattern is almost never achieved. Barrentine and his colleagues examined wrist kinematics in a group of male collegiate pitchers and found that there was an average ulnar deviation of 19 ± 15 degrees and the forearm was also pronated 24 ± 17 degrees (Barrentine et al., 1998). This confirmed the ulnar deviation found by previous studies at ball release (Sakurai et al., 1993). Conversely, breaking balls, like the curveball, with the highest spin rates, have been shown to be thrown with the greatest forearm supination (Solomito et al., 2018). This suggests that while supination may be a viable option for increasing spin, it likely does so at the cost of velocity.

Research examining the optimal wrist position for maximal force production reported what wrist flexion and ulnar deviation values were required to produce maximal finger forces (Li, 2002). When the wrist is positioned at 20 degrees of extension and 5 degrees of ulnar deviation, the fingers are capable of producing peak force. This suggests that a neutral wrist position, while it may be optimal for production of true spin, would result in decreased force production from the fingers. However, it is important to note that the vertical and neutral wrist position could still be achieved with wrist extension. The decrease in finger force production as a function of changing wrist position was not proportional for all fingers, and by eliminating the ulnar deviation, force production remains near peak values (Li, 2002). In fact, the neutral wrist position is more conducive to maximal force production than the roughly 19 degrees of ulnar deviation found in the average pitcher (Barrentine et al., 1998; Sakurai et al., 1993). This suggests a neutral wrist position could be viable as far as force production requirements go.

Apart from finger and forearm positions being different from what would be considered optimal, the arm and trunk positions also vary considerably. Arm slots have also been shown to vary dramatically between pitchers. There are 3 groups that can categorize professional baseball pitchers (Escamilla et al., 2018). Overhand pitchers throw with their arm near vertical. Sidearm pitches throw with their arm near horizontal. 3-quarter pitchers throw with their arm somewhere in between overhand and sidearm pitchers. Amongst all three groups, elbow flexion remains consistent at around 25 degrees. Overhand pitchers exhibit shoulder abduction of around 94 degrees, while 3-quarter pitchers only abduct about

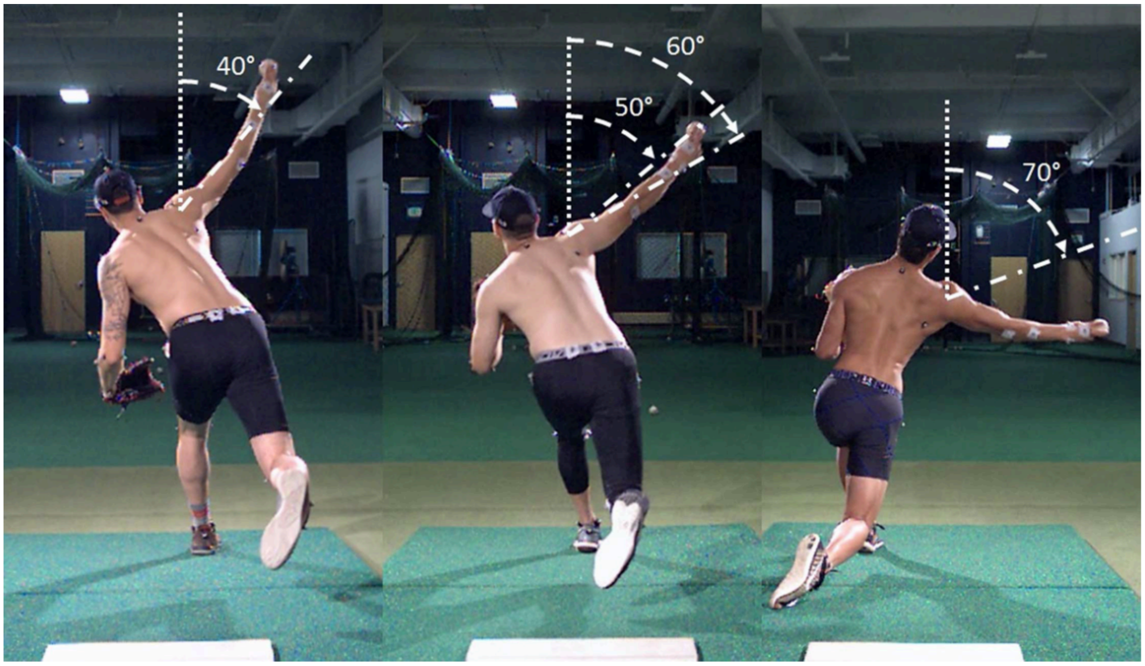

Figure 16. Different arm slots of elite pitchers; overhand, 3-quarter, sidearm (from left to right). From Escamilla et al. (2018)

88 degrees, and sidearm pitchers only about 81 degrees. The largest variation, however, comes from contralateral tilt of the trunk. Overhand pitchers have a contralateral trunk tilt of 32 degrees, 3-quarter pitchers tilt an average of 21 degrees, while sidearm pitchers exhibit almost no trunk tilt at 2 degrees (Figure 16).

If there is such a large variation in arm slots and the throwing motion, why do pitchers not throw with their fingers and forearm in the ideal vertical position for generating maximum true backspin and lift force? One reason could be due to the ability to replicate the pitching motion. Effective pitchers rely on a similar pitching motion and release point across their pitches to deceive hitters in regard to what pitch they are throwing (Whiteside et al., 2016). That means that a pitcher would have to throw all of his pitches in the same way and while this vertical position may be optimal for throwing a fastball, it may not be the most efficient way to throw another pitch like a curveball or slider. That begs the question of how effective a fastball could be thrown from this position, even if all other pitches were thrown from a different arm slot. Would it be possible for the fastball to be so effective, that a batter still would struggle to hit it, even if they knew the fastball was coming?

Another challenge to this pitching motion would be related to the ability to maximize force production. If this ideal position was used, would the pitcher still be able to generate enough force to throw the ball hard and generate the spin required to maximize the true backspin? Based on the significant variation in arm slots across professional pitchers, it seems reasonable that a pitch thrown with increased lateral trunk flexion could maintain similar force production. An overhand pitcher could theoretically increase their trunk flexion by a few degrees, allowing the forearm to come vertical, without a noticeable loss in force production. That would allow for similar pitch velocities and spin rates, while simultaneously converting the spin to true backspin, increasing lift.

If it is determined that the optimal vertical orientation of the fingers and forearm is not possible, it is worth noting that true backspin may still be achievable through other means. If the wrist shows deviation and the arm slot is to the right of the body, then the finger action could alter to produce true backspin. Instead of having the fingers vertically on the baseball and flexing straight down, the fingers could rotate down and to the right to generate true backspin on the ball relative to the pitch's direction of motion. However, this would require the fingers to move at an angle across the ball, perpendicular towards the ground, and that would potentially reduce the total spin on the baseball. When pitchers are taught to throw a four-seam fastball, they are often cued to "yank" the ball down (Driveline Baseball, 2020a). Coming across the baseball at an angle would change the prompt and possibly reduce the ability to generate spin from pulling straight down on it.

While vertical wrist and forearm positioning may be optimal for generating maximum spin and lift force, it is not a position that is often achieved in game scenarios. Based on experimental values of ulnar deviation and arm slot position, it is evident that baseball pitchers mostly deviate from this 'optimal' position. This could be due to a number of factors including the ability to produce force and the lack of a consistent pitching motion across all pitch types in a pitcher's repertoire. However, the natural variation between pitchers suggests that it may be possible to pitch effectively with a vertical forearm and wrist through increased lateral trunk flexion. Should this position be achieved without a substantial loss in force production, the pitcher would generate increased lift force and be more effective in achieving their goal of missing the batter's bat with a 'rising' fastball.

Conclusion

After a thorough investigation of baseball pitching, it is clear that there are a number of factors affecting the movement of a fastball. Fastballs are the most common pitch in Major League Baseball today and as such, carry significant importance to the game. Gravitational force, drag force, and Magnus force are the three forces behind the movement of a pitched baseball. While gravity and drag remain relatively constant across the game of baseball, Magnus force is modifiable. The direction and magnitude of the Magnus force is determined by spin and the spin axis. The rate of spin affects the magnitude of the movement while the spin axis alters the direction of the movement. Spin is improved by increasing the amount of friction between a pitcher's hand and the ball, while the spin axis can be changed through altered kinematics of the pitching motion. The greatest upward force on a fastball occurs when the spin is maximized, and the spin axis is perpendicular to the ground.

Based on the literature reviewed in this work, there are areas that could be explored in future research. Spin increases as shear force increases and finger strength appears to have a notable impact on force production. Therefore, increasing finger strength could significantly increase spin rate. Substances, surface roughness of the finger pad, and finger placement on the ball may all increase the spin rate through greater frictional force. Manipulation of finger placement to maximize friction warrants further investigation. Studies comparing positioning of fingers on different areas of the ball, such as on the seam, behind the seam, on smooth surfaces and possible changes throughout a game due to finger characteristics should be comprehensively investigated. Further, the ability of different finger positions – a grip with the index and middle fingers closer together or with the ball sitting deeper in the hand at release – to generate increased friction, and ultimately spin rate, during the final finger action before ball release should be explored. Additionally, future research should look at rosin placement on the fingers and which locations yield the greatest spin rates. Finally, arm slot and trunk lean, as it ultimately relates to the angle at which the ball is released, plays a significant role in altering spin axis. Future research should examine different trunk and arm positions to achieve the 'optimal' vertical forearm and wrist position.

It is reasonable to assume that many coaches and players investigate many different variations in pitching technique throughout the course of their careers. Unfortunately, not all of these investigations, although extremely valuable, are shared among the baseball community as a whole. Designing well-controlled research studies to investigate these pitching variations could be helpful in producing results to be shared more generally and further the body of knowledge on the subject.

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Vita

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