How baseball spin influences the performance of a pitcher

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Abstract In the present review, we include a series of recent experiments in order to update and summarize the characteristics of ball spin in baseball pitching. The motion of a ball thrown by a pitcher is influenced by three forces: gravity, the drag force due to air resistance, and the lift force which deflects a ball vertically or laterally due to the Magnus effect (Magnus force). The forces acting on a baseball are influenced by the ball’s translational speed and spin rate as well as the orientation of the spin axis. The lift force acting on the ball becomes greater with increases in the “spin parameter” (proportion of the spin rate and the movement speed) when the spin axis of the ball is orthogonal to the direction of movement. On the other hand, when the spin axis is located in line with the direction of the movement (so-called “gyro ball”), the drag force becomes smaller and the lift force decreases to nearly zero regardless of the spin parameter. The orientation of the spin axis also affects the direction of the lift force on the ball; that is, the lift force acts perpendicular to the cross product of the spin axis and the direction of motion. There are great variations in the spin of fastballs; both spin rate and orientation of the spin axis vary widely across individual pitchers. When the spin rate is extremely low, such as with a knuckle ball, the amount and direction of lift force changes irregularly during flight. This is caused by seams on the ball surface, which cause an unpredictable “fluttering” trajectory. The reason for the success of pitchers that can produce abnormal or unique ball spins is discussed.

Keywords: lift force, drag force, wind tunnel experiment, video analysis

Introduction

In the faceoff between a pitcher and a batter, two skilled athletes have diametrically opposed goals. The goal of the batter is to make a clean hit, while that of the pitcher is to get the batter out. Although the pitcher must throw the ball in an area where the batter has the potential to make contact, pitchers have many ways of thwarting the batter’s ultimate goal. Good pitchers can throw many kinds of pitches, including fastballs and various kinds of breaking balls, such as curveballs and forkballs. Each type of pitch has a unique flight trajectory. For example, a curveball has a larger amount of vertical drop as compared with a fastball². Even the trajectories of pitches of similar speed and expressed with the same word can be different between pitchers, and these subtle differences can have a major influence on the pitcher’s overall performance. Thus, a particular individual’s fastballs are typically distinguishable from those of other pitchers due to slight differences in lateral trajectory and/or the appearance of an upward “hop”.

Flight trajectory of an object is affected by the particular forces acting on it. For a pitched ball, the three main forces are gravity, drag force and lift force². Since the gravitational force is constant, differences in a ball’s flight trajectory are due to alterations in the drag force and lift force. In the case of an airplane, the shape and orientation of the airfoils have a significant influence on the drag force and lift force. Although a baseball has no such structures, the drag force and lift force nevertheless affect a baseball’s flight trajectory. In this review, we first describe previous research on the determinants of the drag and lift forces acting on a pitched ball, and subsequently summarize recent studies that elucidate how these forces are affected by ball spin.

Drag force

The drag force acts on a ball in the direction opposite to translational movement, and thereby decreases ball velocity. In general, drag force is expressed by the following equation:

\[ F_D = \frac{1}{2} \rho v^2 A C_D \]

where \( F_D \) is the drag force on a ball (N), \( \rho \) is air density (kg/m³), \( v \) is the translational velocity of the ball (m/s), \( A \) is the ball’s cross-sectional area, and \( C_D \) is the drag coefficient². \( C_D \) is an independent variable whose value de-
pends upon the shape, orientation, spin and other aspects of a flying object. Clarifying these factors would lead to a greater understanding of the drag force acting on a ball.

To analyze the drag force acting on a baseball, the most commonly conducted experiments involve wind tunnels in which the tension on a wire suspending a spinning ball is measured. This experimental setting allows the control of the ball spin rate and ball speed (speed of the air current). However, the direction of the spin axis is limited to horizontal, and is perpendicular to the airflow. Wind tunnel experiments have been utilized to analyze the aerodynamics of not only baseballs, but also balls used in many sports.

For a baseball, when the spin axis of the ball is orthogonal to the direction of motion, \(C_D\) increases with an increase in the “spin parameter” \(Sp\). Spin parameter \(Sp\) is expressed by the following equation:

\[
C_D \propto Sp = r \omega / v
\]

wherein \(r\) is the radius of the ball (0.036 [m]), \(\omega\) is the angular velocity [radian/s] of ball spin, and \(v\) is the free-stream velocity (= ball speed) [m/s]. The faster the ball spin, the bigger the \(C_D\), that is, the bigger the drag force. When the spin axis is located in line with the direction of movement (the so-called “gyro ball”), the \(C_D\) receives almost no influence from the spin parameter and tends to be smaller than the \(C_D\) at the spin axis orthogonal to the direction of motion. In this manner a “gyro ball” has a smaller drag force than a fastball with an identical ball speed and spin rate; and it thus reaches home plate with a faster ball speed.

**Lift force**

Lift force acts on a ball in a direction perpendicular to the line of ball motion and deflects the ball vertically and laterally. (Some researches have defined the lift force as the force acting on the ball in a vertical direction, and the “side or lateral force” as a force acting on the ball in a lateral direction. In this review, however, any force acting on the ball perpendicular to the line of ball motion, either vertical, lateral or a combination of both, is termed a “lift force”.)

Magnus (10,11) noted that the spin of a flying object in fluid (including air) creates a force that pushes the object sideways. This phenomenon is commonly called the “Magnus effect”, and two different mechanisms have been invoked to explain this effect. One mechanism is based on conservation of momentum and the other based on Bernoulli’s principle (12). As pictured in Fig. 1, when the ball moves leftward while spinning clockwise, the air under the ball decelerates as it is dragged by the spinning ball’s surface. On the other hand, the air above the ball accelerates. As a result, a pressure gradient is created with lower pressure above the ball due to the faster air speed at that location. This produces an upward force. If Fig. 1 is viewed from an alternative perspective, such that the axis of spin points directly at the viewer, then the view is from the top, and the upward (lift force) force acts on the ball so that it moves toward the right.

In general, the magnitude of the lift force \(F_L\) on the flying object is expressed by the following equation:

\[
F_L = 1/2 \rho v^2 A C_L
\]

wherein \(\rho\) is the air density, \(v\) is the velocity of object (m/s), \(A\) is the cross-sectional area of the ball, and \(C_L\) is the lift coefficient. As with \(C_D\), \(C_L\) depends on several factors such as shape, orientation, and spin of the flying object; so it is obtained only experimentally, by monitoring the object’s flight under various conditions.

A series of wind tunnel experiments (8,13-15) and high-speed motion analyses (2,16,17) indicate that the effect of \(C_L\) on a baseball with back spin, axis of which is perpendicular to the movement direction, has a linear relationship with a spin parameter greater than 0.1. Under conditions when other factors are equal, the faster the spin rate, the greater the \(C_L\) and lift force.

The above results are true only when the ball is spinning with its axis perpendicular to the movement direction. Jinji and Sakurai (18) made a detailed video analysis and calculated the spin rate and spin axis of fastballs and curveballs thrown by ordinary collegiate pitchers. They demonstrated that the \(C_L\) for the balls thrown by actual pitchers was not correlated with the Spin parameter, but was closely correlated with the product of the spin rate and the sine of the angle between the spin axis and the movement direction. Mizota et al. (19) also demonstrated, utilizing a wind tunnel, that no lift force acts on a ball having a spin axis in line with the direction of forward movement. A pitch with these characteristics is sometimes termed a “gyro ball.” Thus, the lift force on a spinning baseball is influenced not only by its spin rate, but also by the angle between the spin axis and movement direction.

Additionally, the orientation of the seams on a baseball may influence the lift force acting on the ball. An official baseball is covered with 2 pieces of hide that are stitched together with strings. The seam is approximately 1 mm
high and approximately 8 mm wide, so it is likely that differences in seam orientation relative to flight direction would have an effect on movement of the air stream. This effect is reflected in popular baseball terminology, which differentiates between “four-seam” and “two-seam” fastballs. Technically, this terminology refers to the number of seams per rotation that pass a point in the plane perpendicular to the axis of rotation (Fig. 2). In general, since they are much more commonly thrown, the term “fastball” generally refers to a four-seam fastball. All the studies cited above examined four-seam fastballs. Data from a study by Sikorsky and Lightfoot\cite{Sikorsky2013} show that a difference in seam orientation has a large effect on the lift coefficient, and hence the lift force and lateral deviation for spin parameters less than 0.2. Alaways and Hubbard\cite{Alaways2016} examined the difference in \( C_l \) between four-seam and two-seam fastballs. The lift force on fastballs launched by a pitching machine was bigger for four-seam spin than two-seam spin, although their spin parameters showed the same values. On the other hand, Mizota et al.\textsuperscript{12}, using a wind tunnel, found that the \( C_l \) of two-seam backspin was unchanged when the spin parameter was between 0.2 and 0.3. These results do not coincide with those of Alaways and Hubbard\cite{Alaways2016}. High-speed motion analysis by Takami et al.\textsuperscript{19} showed that differences in the orientation of the seams did not directly affect the aerodynamic characteristics of the ball. There is still controversy regarding the effect of seam orientation on a ball’s flight trajectory, and it is likely that other factors, as yet unappreciated, are involved.

Direction of the lift force

As already described, the lift force deflects a ball vertically or laterally, and orientation of the spin axis is the main factor determining the direction of the lift force. Bahill and Baldwin\cite{Bahill2000} have demonstrated that the direction of deflection of the ball is perpendicular to the cross product of the spin axis and the direction of motion. Thus, when the spin axis of the ball is orthogonal to the direction of motion, the direction of the spin-induced deflection of the ball can be determined using the right-hand rule (Fig. 3). As shown in Fig. 3A, if the fingers point in the direction of rotation, the thumb points in the direction of the spin axis (the angular right-hand rule). If the thumb points in the direction of the spin axis and the index finger points in the movement direction, then the middle finger will point in the direction of the spin-induced deflection (the coordinate right-hand rule) (Fig. 3)\textsuperscript{20}. For example, in the case where the azimuth angle is 0° and the elevation angle is -45° (45° downward, Fig. 4), the lift force will act on the ball in an upward and rightward direction as viewed from the pitcher. In the case where the elevation angle is -90°, no upward lift force acts on the ball, but it increases the rightward deflection. Thus, in order to have optimal control over the ball flight trajectory, the ability to control not only the ball’s spin rate but also the direction of its spin axis is required.

Spin on fastballs thrown by actual pitchers

Until recently, little was known about the spin of balls actually thrown by baseball pitchers. Jinji and Sakurai\cite{Jinji2015} showed that the spin axes of fastballs thrown by collegiate pitchers were tilted vertically and horizontally. In their terminology, the orientation of the spin axis was defined by azimuth \( \theta \) and elevation \( \varphi \) (Fig. 4). In their study the mean initial ball speed was 34.5 ± 0.2 m/s and the mean ball spin rate was 31.2 ± 1.5 rps. The mean angles of \( \theta \) and \( \varphi \) were 31 ± 13°, and -26 ± 11°, respectively, for right-handed pitchers. Given these values, the lift acts on the fastball upward and rightward; the ball would move

![Fig. 2](http://example.com/fig2.png) Difference in the direction of seams between 4-seam spin and 2-seam spin.

![Fig. 3](http://example.com/fig3.png) A) Angular velocity - right hand rule. B) Coordinate system right hand rules. (cf. Bahill and Baldwin\cite{Bahill2000})

![Fig. 4](http://example.com/fig4.png) Definition of the direction of ball spin axis with azimuth \( \theta \) and elevation \( \varphi \). (Cited in Nagami et al.\textsuperscript{21})
0.37 ± 0.12m upward and 0.20 ± 0.12m rightward as compared to a trajectory with free fall. The authors also noted a significant, important correlation: the higher the ball speed, the greater the spin rate.

We recently examined the direction of the spin axes of fastballs thrown by 11 elite professional and 11 elite collegiate pitchers. There was no significant difference in the spin rate or direction of the spin axis between the professional and collegiate pitchers. Also, there was a positive correlation between the initial ball speed and the spin rate (Fig. 5A), which agrees with the results of Jinji et al. It should be noted that spin rate was more variable across subjects as compared with ball speed (Fig. 5B).

The spin parameter (the ratio of the spin rate to the ball speed) of the fastball thrown by one of the collegiate pitchers (Sub. C in Fig. 5) was greater than those of any other subjects. In addition, the direction of the spin axis was closer to true back spin (a spin axis that is completely horizontal and perpendicular to the direction of motion) than that of any of the other subjects (Figs. 6, 7). So his fastballs would have a larger upward lift force than fastballs of similar speed thrown by the other pitchers. This particular pitcher led his collegiate league in strikeouts per 9 innings, and batters facing him described his fastball as having good hop.

We also examined baseball batters’ accuracy in hitting fastballs with different backspin rates (30, 40, 50 rps) at a constant ball velocity (36 m/s) and with a constant orientation of the spin axis (straight back spin). We found that ball spin rate was positively correlated with increases in the distance from the optimal contact point of the swung bat (sweet spot) to the actual point of contact \( r = 0.38, p < 0.001 \). One explanation for this result is based on the positive correlation between launched velocity and ball spin rate that exists for real pitchers (Fig. 5A). This correlation may allow batters to estimate spin rate from their judgment of a launched ball’s velocity. Since the typical spin rate is around 30 rps for the 36 m/s fastball that was used in our study, this is likely the spin rate that the batters assumed was occurring for the pitches. However, this expectation would cause a misestimate of the trajectory of this experiment’s 36 m/s fastballs that had backspin rates other than 30 rps. This result and performance of the collegiate pitcher described above (Sub. C in Fig. 5) suggest that throwing pitches with abnormal ball spin rates and/or unique spin axes make pitches more difficult to hit.

Spin on a breaking ball

There have also been relatively few studies on the spin of breaking balls. Selin filmed flight trajectories of various kinds of pitches and reported that each pitch showed vertical and horizontal deviations. Jinji et al. also analyzed the spin and flight trajectories of curveballs thrown by collegiate pitchers. Curveballs rotated in a top-spin direction, and the balls moved 0.29 ± 0.09 m downward and 0.20 ± 0.10 m leftward compared to a trajectory with free fall. These ball movements were the opposite of the movements of fastballs. Therefore, this feature of the curveball would make it an effective option for retiring a batter.

Recently, we had the chance to analyze the spin on eight different types of pitches thrown by an elite professional pitcher. Each type of pitch had a unique combination of speed, spin rate, and orientation of the spin axis. His “slider” had an orientation of the spin axis that was almost identical to the direction of movement. These same characteristics describe the so-called “gyro ball”. This pitch would have a minimal lift force, and the ball would just drop with the gravitational force. His “cut fastball” showed a spin rate and orientation of the spin axis just between those of the four-seam fastball and the slider. Thus the flight trajectory of the cut fastball was intermediate between those of the four-seam fastball and the slider. These examples indicate that practicing pitchers really do throw pitches with a wide variety of flight trajectories by manipulating ball spin rate and orientation of the spin axis.

Recently, advances in the techniques employed in the

![Fig. 5](image) A) Relationship between initial ball speed and ball spin rate. B) Variability of initial ball speed and ball spin rate. (Cited in Nagami et al.21)
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wind tunnel domain have enabled investigators to calculate the force on a ball with a spin axis which is not perpendicular to the direction of movement. The calculations indicate that even if the elevation angle of the spin axis is 0°, the lateral component of the lift force created depends on the degree of the azimuth angle. Indeed, Nathan reported a similar phenomenon through visual observation of the video image captured by a baseball game broadcast. The above results suggest that a baseball is subject to forces from causes other than the Magnus effect. Future investigations will hopefully clarify the details and mechanisms of these phenomena.

**Pitches with a lower spin rate**

The pitches termed “forkball”, “change-up”, and “knuckle ball”, generally have spin rates that are lower than the pitches previously described. They would thus have a lower lift force, and the pitched balls would follow the trajectory close to that of a ball in free-fall. However, a knuckle ball, which is thrown with almost no spin, seems not to be flying solely in a state of free-fall, but in addition is characterized by a “fluttering movement”. Watts et al. and Mizota and Kawamura elucidated the irregular movement of these pitches by determining the variable lift forces created by changes in airflow that result from different seam orientations relative to the direction of ball movement. In addition, the investigators also noted that slight changes of seam orientation throughout the flight of a ball with lower spin rates resulted in changes in the magnitude and direction of the lift force. This could also
lead to a fluttering movement of the ball. These characteristics of pitches with lower spin rates cannot be found in pitches with high spin rates, and thus, lowering the ball spin rate is another effective strategy that allows the pitcher to deliver balls with yet another set of flight trajectories.

Conclusion

In this review, the forces that impinge on a thrown baseball and the factors that determine its flight trajectory were summarized. Dexterous manipulation of ball spin rates and ball spin axis, which determine the direction and magnitude of the drag force and lift force, are critical elements that allow pitchers to achieve a superior level of performance.

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References