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Trajectory of a pitched baseball

– How and why does the forkball break downward? –

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ABSTRACT

The purpose of this study was to investigate the three-dimensional trajectory of fastball (FB), curveball (CB), slider (SL) and forkball (FK) baseball pitches thrown by a professional player. Flight was recorded with two synchronized video cameras (60 Hz) and analyzed using DLT procedures. A second order polynomial function using the least square method was used to derive time-displacement data of ball trajectory for each pitch. Estimated vertical acceleration during the flight was -4.5 (FB), -12.9 (CB), -7.4 (SL), and -9.6 m/s^2 (FK), respectively. The mean ratio of final / initial velocity of the horizontal velocity of the pitch was 0.877 (FB), 0.864 (CB), 0.882 (SL), and 0.850 (FK). These results suggest that horizontal deceleration rather than vertical drop in the latter part of the flight is the unique characteristic of the forkball.

INTRODUCTION

Curveball is recommended as the best means of supplementing the pitcher's ability, though fastball is the most important pitch in any pitcher's arsenal (10). In the early 1870's an argument, "Are baseball's curveballs optical illusions, or real curves?" stormed the world of baseball (9). Even after the reason of the curvature of the baseball was interpreted physically (7), the long debate and experiments have continued (5, 12, 2, 9). Allman (3) expressed the recent view succinctly by noting it looks like everybody agrees that the curveball does curve but nobody can agree on where it curves.

Many other types of pitches such as the slider, change-up, forkball, knuckleball are also thrown in baseball. Recently, the forkball and knuckleball have become more important pitches. Characteristics of these types of pitches are generally thought to be erratic motion with a sudden drop during flight (10).

Selin (11) filmed several types of pitches by varsity pitchers using two high-speed cameras, and obtained both the rotation of the ball and the deviation of the trajectory due to aerodynamic force. According to his data, a knuckleball with very slow spin (2.9 - 9.2 rounds/s) flew inconsistently but did not show any remarkable breakdown.

Watts and Sawyer (13) investigated the reason for the erratic motion of the knuckleball. They measured the aerodynamic lift with various orientations of the ball in a wind tunnel, and suggested that the non-symmetrical location of the stitches was the cause of the irregular lateral movement of the ball as the ball spun very slowly.

Allman (4) suggested that the knuckleball's movement may be due to drag force. The concept of critical speed and its effect on drag is well known. Beyond this critical speed the drag coefficient dropped (8). If the ball is thrown with a velocity slightly beyond the critical speed, the ball might decelerate suddenly when the ball speed falls across the critical speed. However, Watts did not think that the drag crisis was involved in the knuckleball's movement, because he could not find any signs of an obvious drop in drag up to 80 miles/hour (35.8m/s) in his wind tunnel experiment (4).

There have been very few experimental research projects dealing with the trajectory of various types of baseball pitches since Selin's early study. Therefore we have very little knowledge about the exact trajectory of the forkball and

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other types of pitches. The purpose of this study was to obtain a trajectory of each type of baseball pitch. The characteristics of the flight of the forkball would specifically be compared with the other pitches.

METHODS

Data Collection

The subject was a left-handed baseball pitcher, 29 years old, 1.75m tall and had a mass of 74 kg. He had an eight year career in Japanese Major League Baseball with 61 wins and 70 losses. He throws four types of pitches in a game, namely fastball (FB), curveball (CB), slider (SL), and forkball (FK). His pitching style was classified as "three-quarter" arm by the coach.

The experiment was conducted on a baseball field with still air. The temperature was approximately 10.0°C and the atmospheric pressure was 1005 hPa. The subject was asked to throw eight of each of the four types of pitch; FB, CB, SL, and FK. The flight of the ball released from the pitcher's hand to catcher's mitt was recorded using two fully synchronized video cameras set at 60 fields/s and 1/10000s exposure time. Figure 1 outlines the experimental set-up.

One camera was positioned close to first base so that the optical axis of the camera lens was almost perpendicular to the pitching direction. Another camera was positioned behind of the pitcher such that the angle between the optical axes of two cameras was approximately 80 degrees. As a pitching warm-up and to enable familiarization with the experimental set-up, the pitcher was allowed as many practice pitches as he wanted prior to the video recording.

The right-handed orthogonal reference frame was defined by axes X, Y, and Z with the origin at the center of the front edge of the pitching rubber. The Z axis was defined as vertical, the X axis was defined as horizontal and pointing toward home plate, and the Y axis was then defined as the cross product of the Z and X axes.

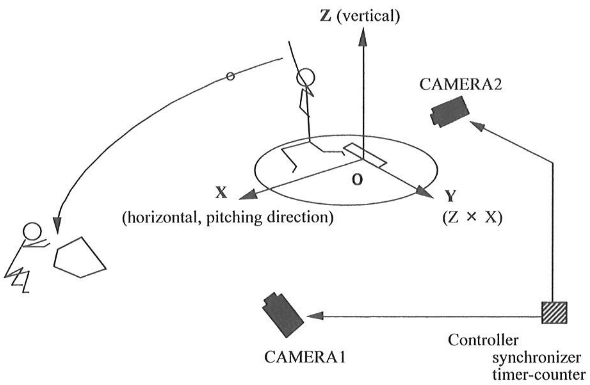

Figure 1: Experimental setup

Two vertical poles containing two markers with heights of 0.250m and 2.850m were used to permit calibration of the field of ball flight. At 13 places within the field of X = 0.000m ~ +18.440m, Y = -1.00m ~ +1.00m, the poles were set vertically and video-taped with the same camera set-up as the pitching experiment. Differences in the height of the poles due to the inclination and unevenness of the ground were corrected using the surface height of water filled in a tube attached to the poles. Home plate was 0.284m lower than the origin point.

Data Analysis

The video image was super-imposed on a personal computer (Sharp Co. Inc., X-68000) and the center of the ball was digitized every other field (30 Hz). The frame immediately after ball release was assigned the time t = 0.017 s. The three-dimensional coordinates of the ball were obtained with Direct Linear Transformation (DLT) procedures (1) using the coordinates of the 26 markers as the control points. Average root mean square errors for the calculated positions of the markers on the calibration poles were 0.024m, 0.013m, and 0.007 m, for X, Y and Z directions, respectively.

Figures 2 (A) and (B) show the trajectory of the ball for a CB pitch in the X-Y and X-Z planes, respectively. Figures 2 (C), (D), and (E) represent time-coordinate relationships for X, Y, and Z, respectively. A regression equation was determined for each graph using second order polynomial functions. As for time - X, Y, and Z relationships (graphs C-E), the flight was divided into two parts and furthermore the regression equation was established for the first and latter half, respectively.

Initial and final velocity was determined as a first derivative of (C) time-X relationship, when t = 0.000 s and x = 18.440 m, respectively. Average acceleration in each direction during the flight was estimated from the coefficient of the second order term of the regression equation of time-displacement relationships (graphs C-E) multiplied by two. Average force (F) in the X direction was calculated from ball mass times average acceleration, and average drag coefficient during the flight (CD) was estimated with the equa-

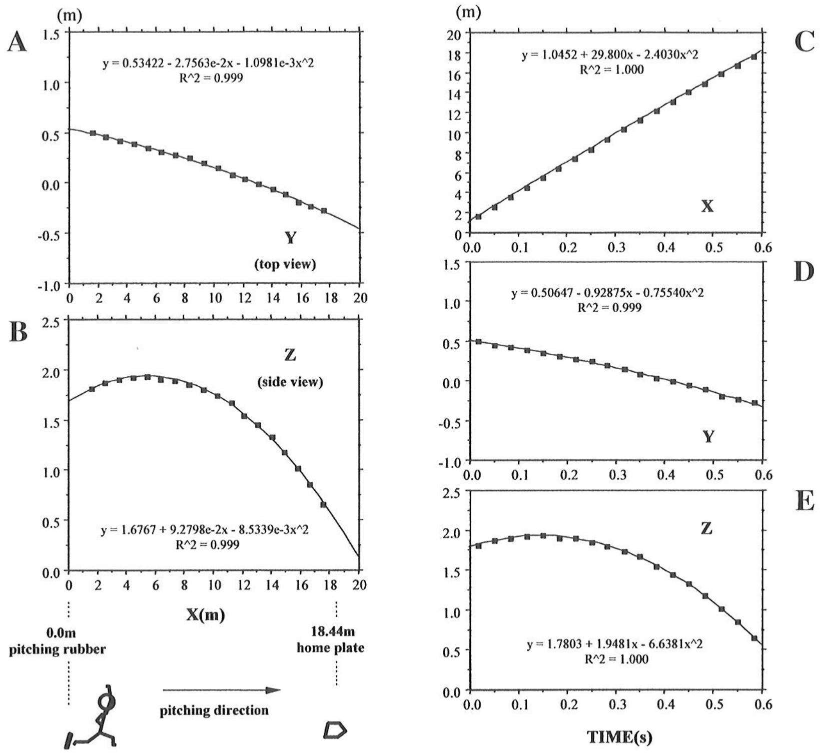

Figure 2: An example of trajectory and time-displacement relationship of a curveball pitch.

tion below (8).

$$F = 1/2 \cdot \rho \cdot v^2 \cdot A$$

- ρ : density of the air at the ambient pressure and temperature
- v : average ball velocity in X direction during flight phase
- A : cross sectional area of the ball

Effects on the flight of the ball due to aerodynamic force was estimated and expressed as a deflection of the trajectory with respect to the arrival point both with and without aerodynamic force.

An analysis of variance (ANOVA) was used to examine the statistical significance among the variables for the four types of pitch. The Fisher's PLSD post hoc analysis provided a measure of the significance between each possible pair of pitches. A probability of $p<0.05$ was required for significance.

RESULTS

Figure 3 shows an example of the X-Y (top) and X-Z (side) relationship for one trial of each type of pitch. Table 1 shows the mean and standard deviation values for several parameters, such as release angles, initial and final velocity, speed reduction rate (final / initial velocity), flight time, average acceleration in three directions, drag coefficient (CD), and deviation of the trajectory due to aerodynamic force.

Average initial velocity of the FB was 37.00 m/s (S.D.: 1.16 m/s), which was the fastest of all pitches. There was no statistical difference between the initial speed for the FB and SL pitches. However, the FK was slower than the FB and SL, and faster than CB. Speed reduction ratio from initial to final ball speed was largest in the FK pitch. Drag coefficient was also largest for FK pitches, and smallest for FB and SL pitches.

Vertical acceleration for CB pitches was largest among all types of pitches and exceeded gravitational acceleration (free fall : $g=-9.8m/s^2$). There was no pitch with positive vertical acceleration, which shows that even the FB pitch

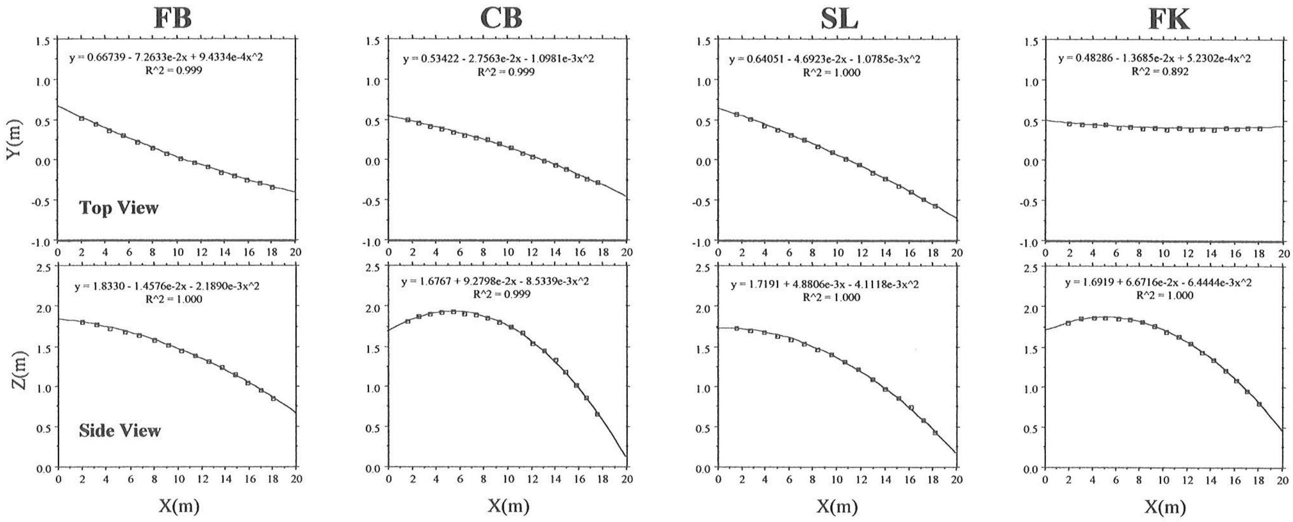

Figure 3: Examples of trajectory of four pitches.

Table 1: Comparisons of several variables among four types of baseball pitches.

pitch		release angle (X–Z) (deg)	release angle (X–Y) (deg)	velocity initial (m/s)	velocity final (m/s)	velocity rate (f/i)	time (s)	acceleration X (m/s²)	acceleration Y (m/s²)	acceleration Z (m/s²)	acceleration Z (first) (m/s²)	acceleration Z (latter) (m/s²)	CD	deviation ΔY (m)	deviation ΔZ (m)
Fastball (FB)	M	–1.48	–3.75	37.00	32.44	0.877	0.519	–8.12	2.53	–4.45	–4.74	–4.88	0.387	0.245	0.512
	SD	0.40	0.96	1.16	1.10	0.016	0.016	1.33	0.35	0.52	1.29	2.71	0.050	0.023	0.070
Curveball (CB)	M	4.05	–1.81	29.99	25.91	0.864	0.635	–5.88	–1.38	–12.92	–11.47	–12.48	0.429	–0.300	–0.746
	SD	1.17	0.65	0.62	0.90	0.016	0.021	0.58	0.32	0.31	4.48	1.58	0.047	0.051	0.057
Slider (SL)	M	0.18	–3.01	36.13	31.86	0.882	0.532	–7.68	–0.90	–7.44	–7.07	–7.88	0.380	–0.168	0.188
	SD	1.15	0.59	0.60	0.91	0.023	0.021	0.75	0.89	1.09	1.25	1.06	0.037	0.118	0.135
Forkball (FK)	M	1.98	–1.89	32.71	27.80	0.850	0.585	–7.30	0.68	–9.58	–10.29	–7.97	0.453	0.082	–0.135
	SD	1.38	0.92	1.68	1.95	0.030	0.024	0.63	1.23	1.16	1.48	2.17	0.056	0.195	0.178
statistical significance FB vs CB		*	*	*	*		*	*	*	*	*	*		*	*
FB vs SL		*							*	*		*		*	*
FB vs FK		*	*	*	*	*	*		*	*	*	*	*	*	*
CB vs SL		*	*	*	*		*	*		*	*	*		*	*
CB vs FK		*		*	*		*	*	*	*		*		*	*
SL vs FK		*	*	*	*	*	*		*	*	*		*	*	*

NOTE. Values are mean (M) and standard deviation (SD).
* shows statistic significance between two pitches ($p<0.05$)

did not rise. Vertical acceleration for the FK was similar to gravitational acceleration. Average vertical acceleration for all pitches was obtained separately for the first and latter half of the ball flight. There was no tendency for an increase in the vertical acceleration in the latter half of the flight for any pitches.

Deflection in trajectory due to aerodynamic force was obtained and indicated as displacements (ΔY and Δ Z) at

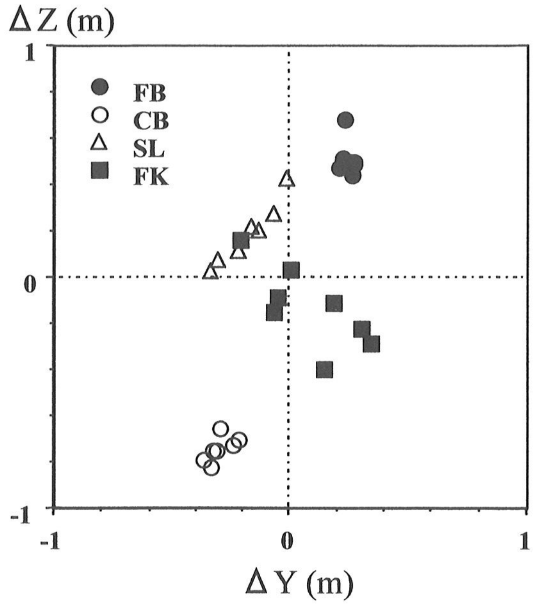

Figure 4: Deflections of the trajectory due to the aerodynamic force.

the home plate (X = 18.44m). The individual deflections are shown in Figure 4. The effect of the aerodynamic force was large and consistent in the FB and CB, but in opposite directions for these two pitches. For the FB pitch, the ball received a force in upward and Y-positive directions. In general, the SL pitch deviated slightly in an upward and Y-negative direction. The magnitude of the deviation in vertical and horizontal directions was inversely related to each other. The aerodynamic effect was most inconsistent for the FK. Average deviation in the Z direction due to aerodynamic force for FK (0.135m) was far smaller when compared to the CB (0.746m) pitch.

DISCUSSION

Flight of the ball is affected by aerodynamic force as well as gravity. Selin (11) tried to analyze the ball velocity changes of several types of pitches of university level subjects by plotting a time-displacement graph. The initial velocity of the pitched baseball was generally larger in this study compared to results from Selin (11) due to the level of the players tested. He reported that there was no change in the velocity of the ball during the flight for all types of pitches. Contrary to his results, decreases in the horizontal velocity from 11.8% to 15.0% were observed across four types.

Selin (11) also reported the deviation of the trajectory due to the aerodynamic force. The deviation in FB obtained in this study was very consistent with Selin's findings. Directional movement for the CB was similar but the deviation was larger, especially in the vertical direction. Contrary to Selin's findings on SL, the ball was deflected upward in the SL pitches of this study. Jordan (10) noted that at the moment of SL release the ball slipped out of the pitcher's hand with an off-center, right to left (for right-handed pitcher), and downward spin. The results suggest the subject in this study throws SL with a different manner.

Within the accuracy of the measurements, the erratic motion of the ball in a lateral direction was not found for any FK pitch. The average acceleration value during the flight for the FK pitches was very similar to gravity, which was smaller when compared to the CB. This shows that the ball does not drop more steeply in the FK pitch than the CB pitch. Moreover, the acceleration in the latter half of the flight was not larger in any pitches including FK, when compared to the first half of the flight.

Therefore an FK breaking straight down should be considered an optical illusion of the batter. The remarkable characteristic of the FK pitch was that the horizontal deceleration was larger than for any other type of pitch.

For a good result in batting, both spatial and timing control of the bat swing is essential. Batters estimate the time the ball will take to reach the plate and start their swing. However the FK is decelerated markedly compared to other pitches. The delay of the arrival to home plate could cause the batter to inadvertently believe that the ball dropped suddenly. The FK is therefore not a breaking ball but a braking ball.

As for other high velocity projectiles, the existence of the so-called critical speed and its effort on drag is well known (8). The initial speed of FK was smaller than the FB and SL, but larger than the CB. If the critical speed value is very similar to FK pitch speed and the critical speed is not affected by the spin of the ball, the average CD values during flight for the FK pitches should be higher compared to CB, and smaller compared to FB and SL pitches. However, the CD value of the FK was largest among the four types of pitches in this study.

At this stage the reason for the large deceleration of the FK is unknown. There have been very few studies on the aerodynamic force on the actual balls used in sports activities under various conditions. There is a possibility that the magnitude of the drag depends on the spin as well as the roughness of the ball. Aerodynamic measurements of the actual ball in a wind tunnel would be necessary for a better understanding of the ball flight.

CONCLUSION

The characteristic of the forkball was horizontal deceleration rather than a vertical break with larger vertical acceleration. The reason of the large speed reduction of FK pitch in flight was not obvious, but might be related to the low spin rate of the ball.

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