

The Physics and Timing of the Infield Bounce Throw

by Andrew Dominijanni

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Maybe bounced infield throws aren't as ineffective as we've thought. (via James G)

*Editor's Note: This initially was a presentation at the 2017 **Saberseminar**.*

Back in early April, when the 2017 season was only four days old, I was listening to **episode 1041** of Effectively Wild, as hosts Ben Lindbergh and Jeff Sullivan answered a listener e-mail question centered on a claim **Paul O'Neill** made on the Yankees broadcast. The claim, which O'Neill backed up with an anecdote about **Dave Concepcion**, was that the ball can speed up when bounced off the turf, and that tactic can be employed to get the ball to first base faster on throws across the infield.

Perhaps other players have their opinions on this topic; maybe it is even well known within the game that fielders skip the ball on purpose. The e-mailer, at least, suspected the influence of friction made this claim implausible. Ben then also read a response he solicited from Dr. Alan Nathan, noted baseball-loving physicist. Dr. Nathan noted that a ball impacting the ground with heavy topspin may actually speed up, but that this scenario is unlikely on a throw.

Ben and Jeff went on to discuss possible perceptual illusions explaining the “effect,” but on the whole, I was not satisfied that the question was put to bed. In particular, I felt the ballplayers might be onto something, and even if the ball does not actually speed up when it skips off the ground, it potentially could reach first base sooner if bounced off the ground than thrown in the air. I emailed Ben and Jeff, with a (now cleaned-up) sketch and a rambling explanation. This is that original sketch:

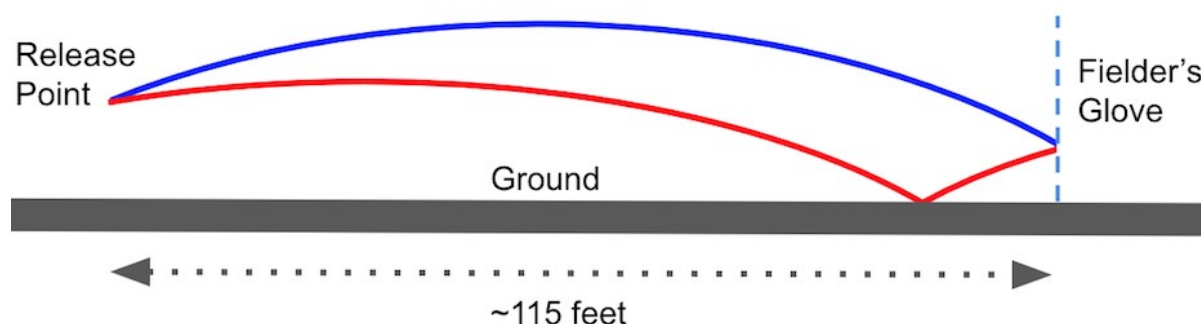


Figure 1. Cleaned-up sketch of initial bounce throw intuition

The logic is simple. From any given position on the diamond, the fielder must throw to first. He can do so either by getting the ball to first base on the fly or by skipping the ball before it reaches first. For the purposes of this thought experiment, I will assume the fielder can “choose” between the two options, and furthermore, that he releases the ball at the same speed in either case. We’ll revisit these assumptions later.

As the sketch tries to illustrate, it seems possible the air throw option would have to travel a longer path than the bounce throw, which can be released at a lower, more direct angle. As long as the ball does not lose too much speed on the bounce, a shorter path likely would mean a shorter time for the ball to reach first, which is the ultimate goal of the fielder. He wants to pick up the ball and get it to first as fast as possible.

The hypothesis, restated, is that under some conditions, the fastest way to get the ball to first is to bounce it. As usual, it all comes down to the details. In this case, the details are the physics of the ball in flight, its interaction with the ground, and the assumptions required to test the hypothesis. Fortunately, I felt I had the necessary background in physics to continue the inquiry.

The Ball in Flight

In aiming to build an infield throw simulation including a bounce off the ground, the first step is to construct a model of the ball in the air. This topic has been covered in plenty of detail, even recently in Dr. Nathan's article about home run trajectories and the accompanying technical write-up. The same model can be found in Rod Cross' text.

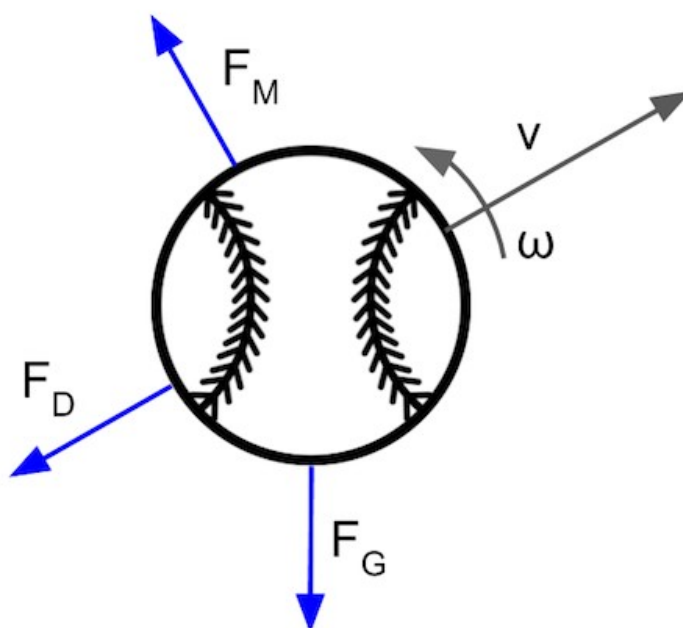


Figure 2. Forces on a spinning baseball including drag (F_D), Magnus force (F_M), and gravity (F_G).

Assuming we are observing a ball in flight side-on, as shown in Figure 2, where the ball is spinning about an axis normal to the view plane, i.e. pure topspin or backspin, there are three forces acting on the ball. First is the constant force of gravity acting always toward the ground with a magnitude proportional to the mass of the ball.

Next is the drag force acting in a direction opposite to the velocity of the ball, with magnitude proportional to the cross-sectional area of the ball, the air density, the squared speed of the ball, and the drag coefficient. In principle, the drag coefficient can be a function of the speed and spin of the ball, although it has been shown that for the range of speed and spin typically encountered in baseball, a fixed drag coefficient of 0.35 is reasonably accurate.

More from The Hardball Times



Do The Splits

by Evan Boyd

There are a lot of reasons these players were signed, but their presence should improve a few specific splits for their new teams.

While the drag force simply serves to slow the ball down, the Magnus or “lift” force acts to deflect the ball perpendicular to its direction flight and to the axis of spin. This force is responsible for the extra carry of a ball hit with backspin or the downward action of a classic 12-to-6 curveball. Here, the Magnus force is again proportional to the cross sectional area of the ball, the squared speed of the ball and the lift coefficient.

The lift coefficient has been shown to be a function of the “spin ratio” of the ball, defined as the angular velocity divided by the linear velocity. With these three relations, summarized below with air density ρ and ball cross-sectional area A , we are able to determine all the forces acting on the ball during its flight as a function of the speed, direction, and spin rate of the ball at any given time.

$$F_G = -mg\hat{y}$$

$$F_D = -\frac{1}{2}\rho AC_D v^2 \hat{v}$$

$$F_M = -\frac{1}{2}\rho AC_L v^2 (\hat{\omega} \times \hat{v})$$

To calculate the trajectory of a thrown ball, we need to establish initial conditions of position and velocity at release and then numerically integrate Newton’s third law

twice to obtain the position of the ball over time. The exact details are not critical, but I used a fourth-order Runge-Kutta method to perform this integration. For all calculations, simulations, and visualizations, I have used the Python language, and especially the excellent **Scipy and Numpy** libraries. If the same assumptions on the spin axis, drag coefficient, and lift coefficient hold, this method can be used to simulate any baseball trajectory, be it a pitched ball or a batted ball.

The Ball-Ground Collision

To compare a thrown ball that reaches first base in the air to one that bounces, we need to have a model that can account for the ball hitting the ground. In the simulation, I will simply enforce a rule that when the vertical position of the ball reaches zero, the vertical velocity component of the next time step is reversed in direction and reduced in magnitude, and the horizontal velocity component is reduced in magnitude.

Because we are considering situations in which the ball is impacting the ground obliquely, I use the model of Cross, in which the surface of the ball is assumed to slide against the ground during the collision, and the resulting velocity is a function of the incident velocity, the coefficient of friction between ball and dirt μ , and a vertical coefficient of restitution (COR) γ . Illustrated in Figure 3, the velocity and spin of the ball before and after bounce are modeled by the three simple equations below.

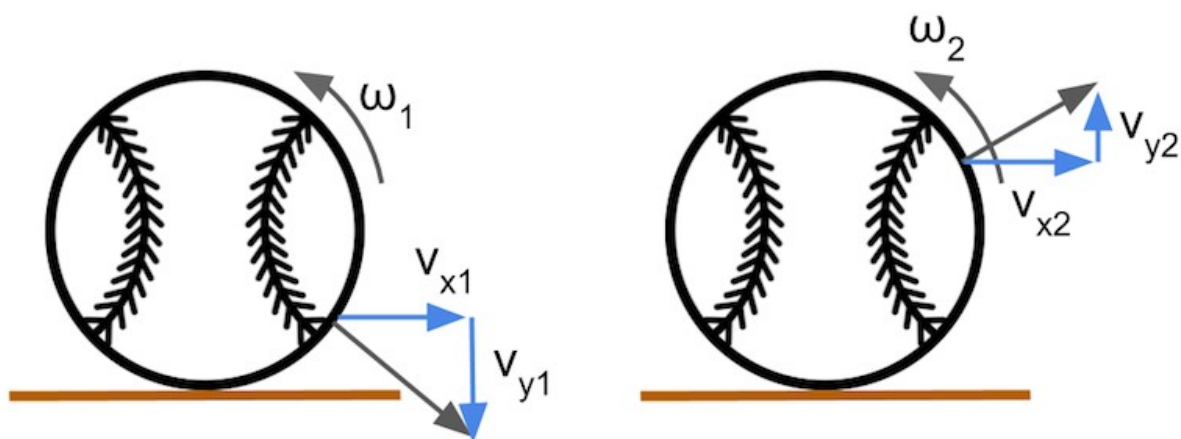


Figure 3. Velocity and spin before bounce (left) and after bounce (right)

$$v_{x2} = v_{x1} + \mu (1 + e_y) v_{y1}$$

$$v_{y2} = -e_y v_{y1}$$

$$\omega_2 = \omega_1 + \frac{\mu(1+e_y)v_{y1}}{0.4R}$$

The coefficient of restitution and coefficient of friction are, in general, not well characterized together. Separate measurements of each are sometimes performed, as well as metrics that conflate the two, such as “surface pace.” For this study, I will use values of 0.55 and 0.4 for vertical coefficient of restitution and dynamic friction, respectively, the values of which are found in Cross’ text and also in reasonable agreement with Brosnan and Goodall’s data.

With these values and the equations above, because the incident vertical velocity component, v_{y1} , is negative, clearly the collision ground serves to slow the ball down, as well as reduce its spin. Therefore, the ball will take longer to travel a given amount of horizontal distance after it bounces than it would have if it stayed in the air. The only way for the bounced throw to reach first base faster than the air throw is if it can traverse a significantly shorter path.

To determine the paths of both the bounced throw and the air throw, we will need to return to the throw simulations. To study this question, I will simulate throws from 21 discrete distances from 60 feet to 130 feet from first base. As previously mentioned, I will assume the release speed of the ball is the same for the bounced throw or air throw from a particular distance. For each distance, I will simulate 21 different release speeds from 60 mph to 100 mph. Altogether, this means that I have 441 combinations of distance and release speed, each of which will have a simulated bounce throw and air throw.

To run these 882 unique simulations, we are only left to supply a few final initial conditions. I will assume the ball is released 5.75 feet from the ground, and the initial spin rate is determined by the release speed, extrapolating from the least-squares linear regression on 2017 pitcher fastballs as of late July, sourced from **Baseball Savant**.

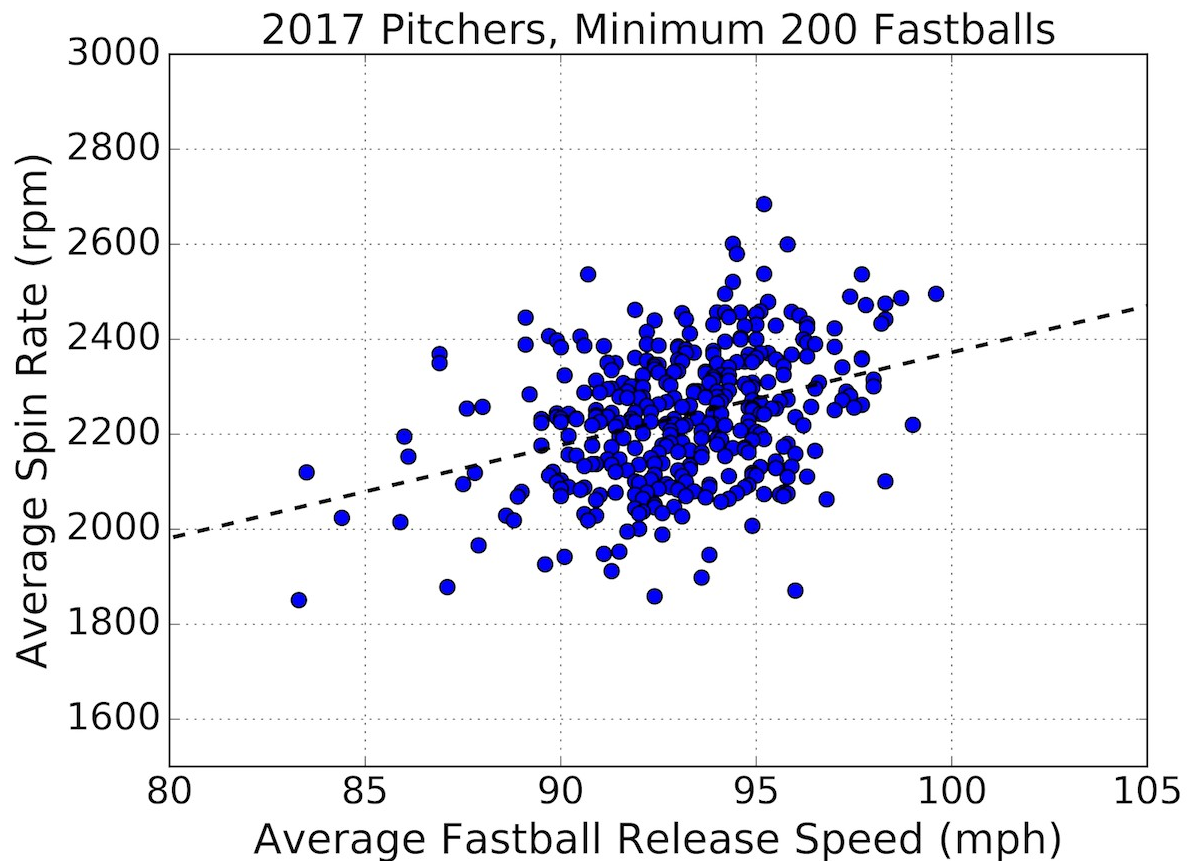


Figure 4. Modeling spin as a function of release speed.

The last initial condition to supply is the release angle. My methodology to establish this is to set target vertical positions or “catch height” for the throw when it reaches the horizontal target distance. These are somewhat arbitrary, but for the bounced throw I assume a catch height of six inches and for the air throw, two feet. Once these are chosen, I use a search algorithm to determine the initial release angle that is required for each throw type to hit its target. The following chart illustrates, for a particular distance/speed combination, the target height for bounce and air throws as the vertical position when the trajectory intersects the first baseman target (black vertical line).

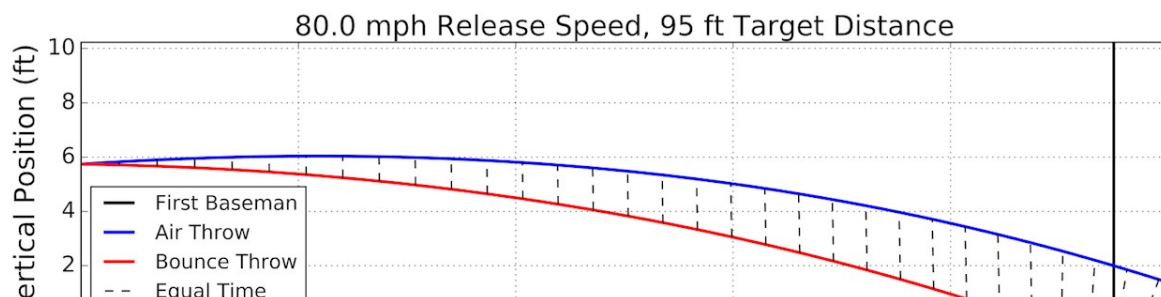




Figure 5. Trajectory and target height illustration.

The Results

After determining the initial release angle required to reach the target catch height, the time elapsed from release to “catch” is calculated for both cases. Below is a slice of this data, here comparing the bounce and air throw times from a distance of 95 feet, across the range of release speeds.

As expected, the ball reaches first base more quickly with faster release speeds. For each release speed case here, the air throw is slightly faster than the bounce throw, although the difference between them is typically less than the time difference between adjacent release speeds.

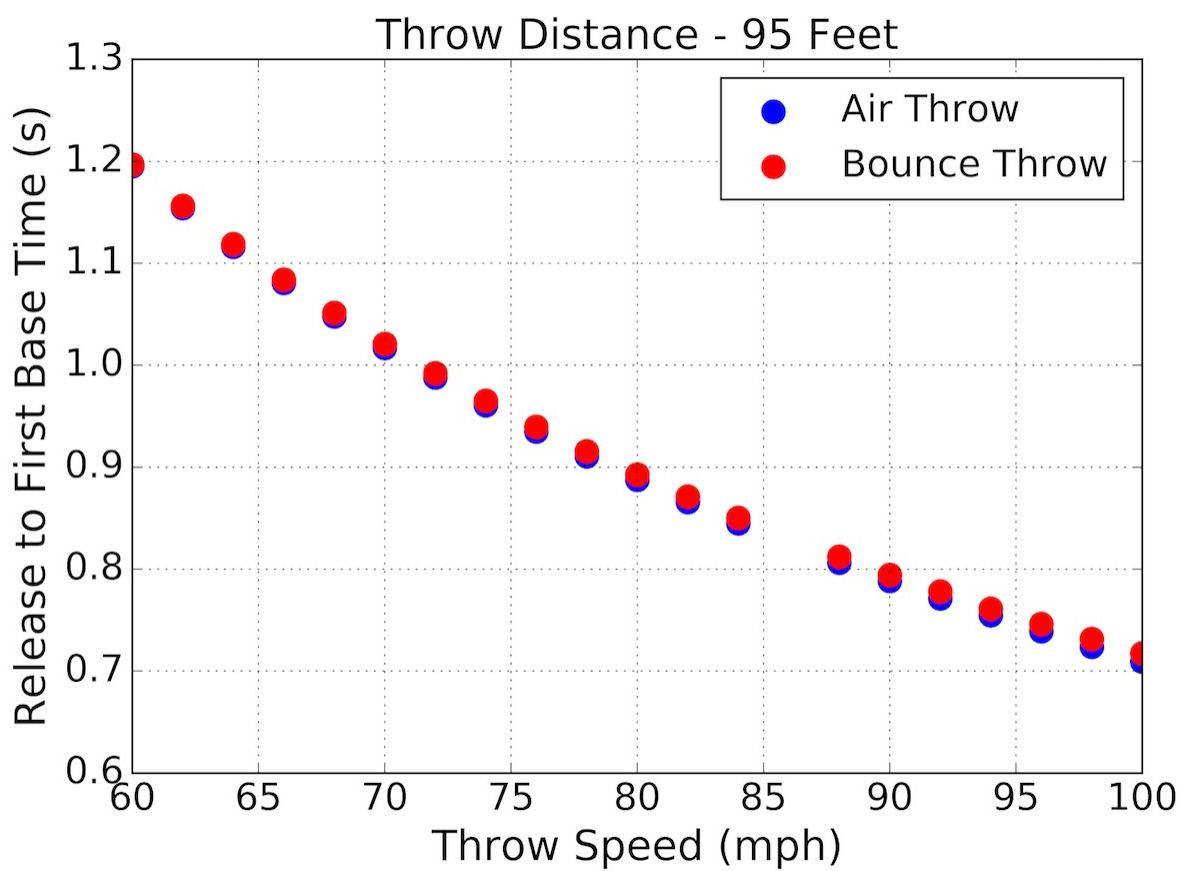


Figure 6. Throw time as a function of speed for 95 foot throw distance.

Including all the other simulated distances, the results occupy a three-dimensional plot. To more clearly compare, I plot the difference in time elapsed between bounce throw and air throw, when the difference is positive (blue markers) the air throw is faster, and when the difference is negative (red markers), the bounce throw is faster.

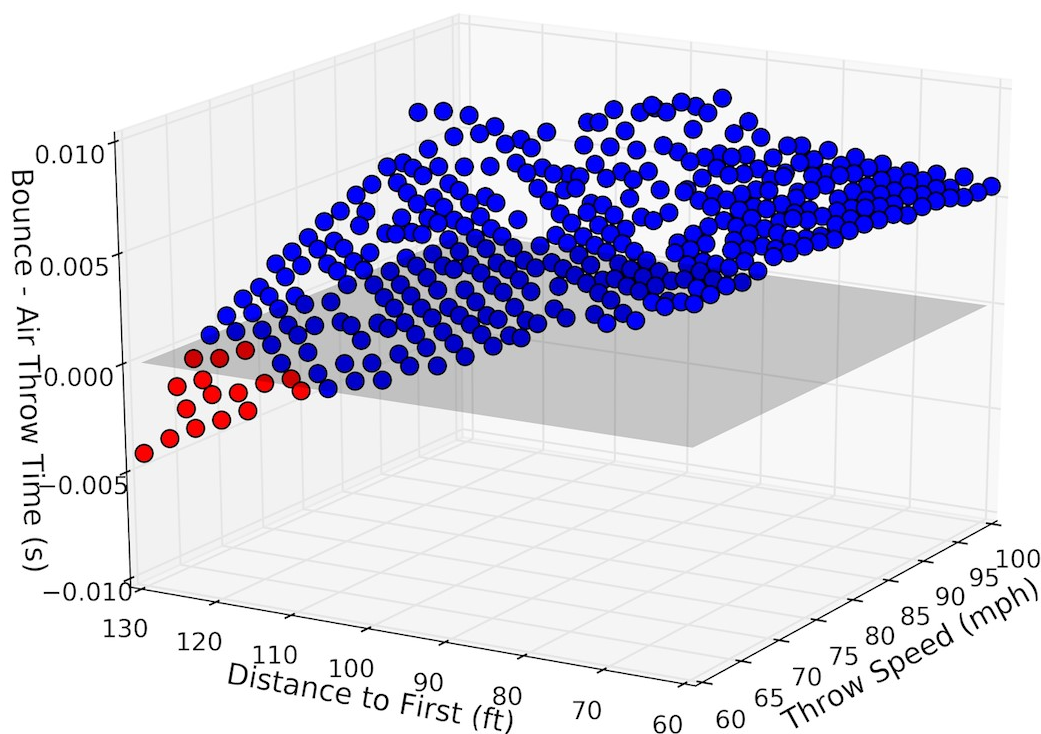


Figure 7. Air throw to bounce throw time difference, all distances and speeds.

The data in Figure 7 show that, for the present assumptions, a bounce throw is faster only for throws from very long distances, 110 feet or more, at very slow speeds, less than 66 mph. This result is, of course, sensitive to the choice of model parameters. If the physics of the bounce are modeled with lower energy loss, the bounce throw becomes favorable over a wider range of throw distances and speeds. Because the bounce throw and air throw use the same aerodynamic parameters, the comparison between them is not particularly sensitive to inaccuracies in the assumed values. Lastly, an important point arrives in revisiting the catch height assumption.

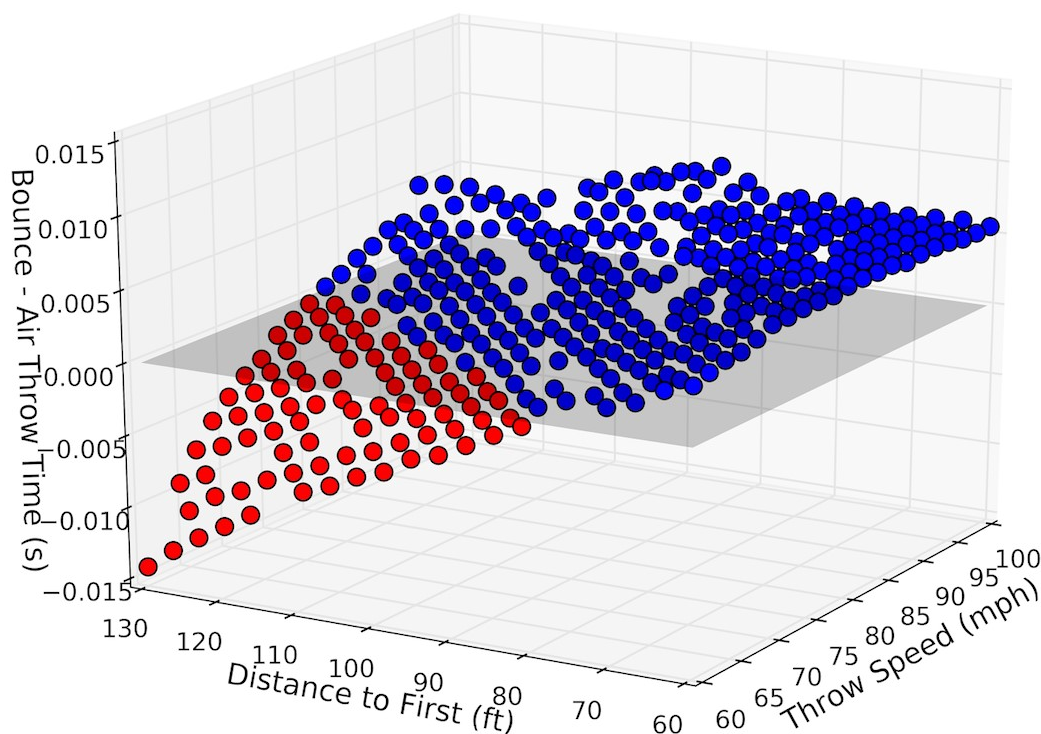


Figure 8. Air throw to bounce throw time difference, higher air throw target height.

Figure 8 shows the same comparison as Figure 7, but for a four-foot target height for the air throw, compared to a two-foot target height previously. The bounce throw target height is the same six inches, and this time it is faster over a larger range of distances and speeds. If the bounce throw target height also was increased, the air throw would become more favorable again. Indeed, if the bounce throw target height is increased enough, it will not be faster than the air throw for any conditions on this speed-distance domain.

The conclusion that falls out of these observations is that infielders should optimally aim to have the ball caught by the first baseman as close to the ground as possible, whether it is bounced or not. To the thrower this means trying to release the ball at as low an angle as possible so that the ball reaches the first baseman's glove just above the ground or bounces just before the glove.

Wrinkles in Timing

The time differences modeled here between a bounced throw and an air throw at the same release speed are on the order of 5-10 milliseconds. For reference, cameras

used for some recent broadcast replays have frame rates up to 2,000 frames per second, and commonly 360 or 960 fps. A frame rate of 1,000 fps represents one millisecond per frame, while 2.8 milliseconds separate each frame at 360 fps. For slow-motion replays, then, a time delta of 5-10 ms would certainly be detectable and could be the difference between a safe call being upheld or reversed upon review.

For additional context, consider that the total throw time is on the order of one second, while a typical home-to-first time for a runner is about four seconds. The bounce throw-to-air throw time differences are less than one percent of each of these actions. Clearly we are probing the margins of importance, but baseball, it is said, is a game of inches.

A key assumption of this analysis is that, in “choosing” between a bounce throw and an air throw, the infielder releases the ball at the same speed in either case. While this assumption makes the analysis easier, it also may not be true.

Especially in scenarios in which a fielder does not have time to make a normal throwing motion, holding onto the ball for an extra split second may allow the fielder to accelerate the ball more, resulting in a lower and faster release. As has been shown, a faster release has a much larger impact on reducing throw time than an ideally executed bounce throw. This could turn out to be a major effect in favor of the bounce throw, but without data from an empirical study or additional input from players, it is difficult to quantify.

Validation

My literature search did not reveal extensive characterization of the baseball-ground collision, but the model described here would seem well suited for application to modern tracking data. Though not available to the public, or to this inquiring researcher as of the time of this writing, detailed velocity and spin data likely exist for every throw on the field via the Statcast system.

If infield throws that bounce are fully captured, it should be possible to tabulate the velocity and spin of the ball immediately before and immediately after the bounce. For each bounce, the effective coefficient of restitution and coefficient of friction can be calculated. With enough bounced throws on a particular infield, average values of

both could be obtained. Further, the variation of bounce parameters from field to field could be studied, including grass and turf.

Because in-game bounce throws are not very frequent, the ideal scenario to study the bounce model parameters would be in a controlled experiment with appropriate tracking equipment on an empty field, where baseballs can be repeatedly fired at the ground over a range of velocities and spins. While such a study is not difficult in concept, its value is not immediately clear.

As demonstrated, the time to be shaved from infield throws by employing optimal trajectories is likely quite small, and the number of bang-bang plays per game is also small. Even if fielders were able to perfectly execute the optimal throw from any particular position, there may only be a handful of extra outs per team per season to be gained. The marginal value of a model with accurately measured bounce parameters vs. with estimated nominal values would be smaller still. Consider, however, that the same model and analysis could be applied to attempted outfield assists, and at least a baseline validation seems worthwhile.

As usual, getting into the weeds to answer a simple question has spawned even more questions. I would be interested in hearing from players and physicists on this topic, as I'm sure there are other angles I have not considered. While the debate may not be settled, I've at least shown that even though the shortest path between two points in space is a straight line, the quickest path between two points on a diamond may include a bounce off the ground.

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