Optimizing the Swing

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When I first started writing this article a few weeks ago, the focus was very simple. It was motivated when someone posted a link to a 2004 WSJ article, "Why Hitting Curveballs Scores More Runs; How Pedro Proves Rule" in which it was claimed that an optimally hit curveball can be hit farther than an optimally hit fastball. The article was based on an interview with Professor Mont Hubbard of U.C./Davis, who had earlier published an article in American Journal of Physics, "How to hit home runs: Optimum baseball bat swing parameters for maximum range trajectories", that directly addressed this topic. Some discussion ensued on Twitter, concluding with a question posed to me: Is the claim ``fact, theory, or nonsense"?

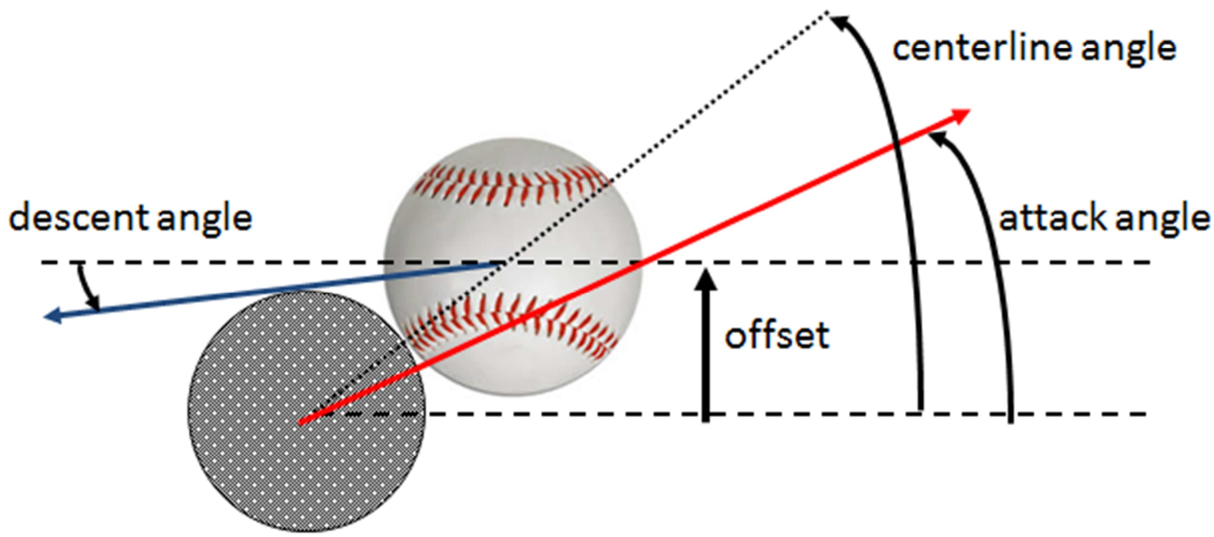
The essential idea behind the claim is quite easy to state. On the one hand, a faster pitch can be hit harder and can therefore travel farther than a slower pitch. That would seem to give the edge to a fastball over a curveball. On the other hand, a curveball can be hit with greater backspin than a fastball. Greater backspin means more lift, which leads to a longer distance on a fly ball.

Hubbard goes through a very nice explanation in the WSJ article for why a curveball can be hit with greater backspin than a fastball. It is the ultimate in simplicity and worth repeating here. If the ball approaches the batter with topspin, then reverses direction, the topspin becomes backspin. That is, a curveball with topspin is already spinning in the right direction for the batted ball to have backspin. But a fastball with backspin has to reverse its spin direction for the batted ball to have backspin. So, for two pitches otherwise identical pitches, the one with topspin will be hit with more backspin than one with backspin. That in a nutshell is the qualitative argument.

So we have two competing effects. On the one hand, we have the higher exit speed on the fastball. On the other hand, we have the higher rate of backspin on the curveball. The ultimate question is, which one `"wins"? Based on a detailed calculation by Hubbard et al. (hereafter denoted by SHS, the first letter of the names of the three authors), the curveball wins. To state the result more precisely, SHS determined that an optimally hit curveball can be hit farther than an optimally hit fastball. The claim is based on real science and is definitely not nonsense. And it definitely is theory, in the sense that it is based on a calculation. Is it fact? I will address that shortly.

Rather than try to explain all that 140 characters at a time, I thought it might be a good topic for The Hardball Times, so I proposed it to Paul Swyden and he agreed. I promised Paul to deliver a completed article in a few days. Well, here we are a few weeks later and I'm finally writing this up. Why has it taken so long? Well, as often happens with me, I get sidetracked. In the process of going back and re-reading the SHS article, I decided to redo all of their calculations using the most up-to-date physics models for the ball-bat collision and for the flight of a baseball. What started out as a simple article has turned into a real research project, with an emphasis not only on the fastball/curveball issue but more generally on optimizing the batter's swing. So, with that lengthy introduction, here we go.

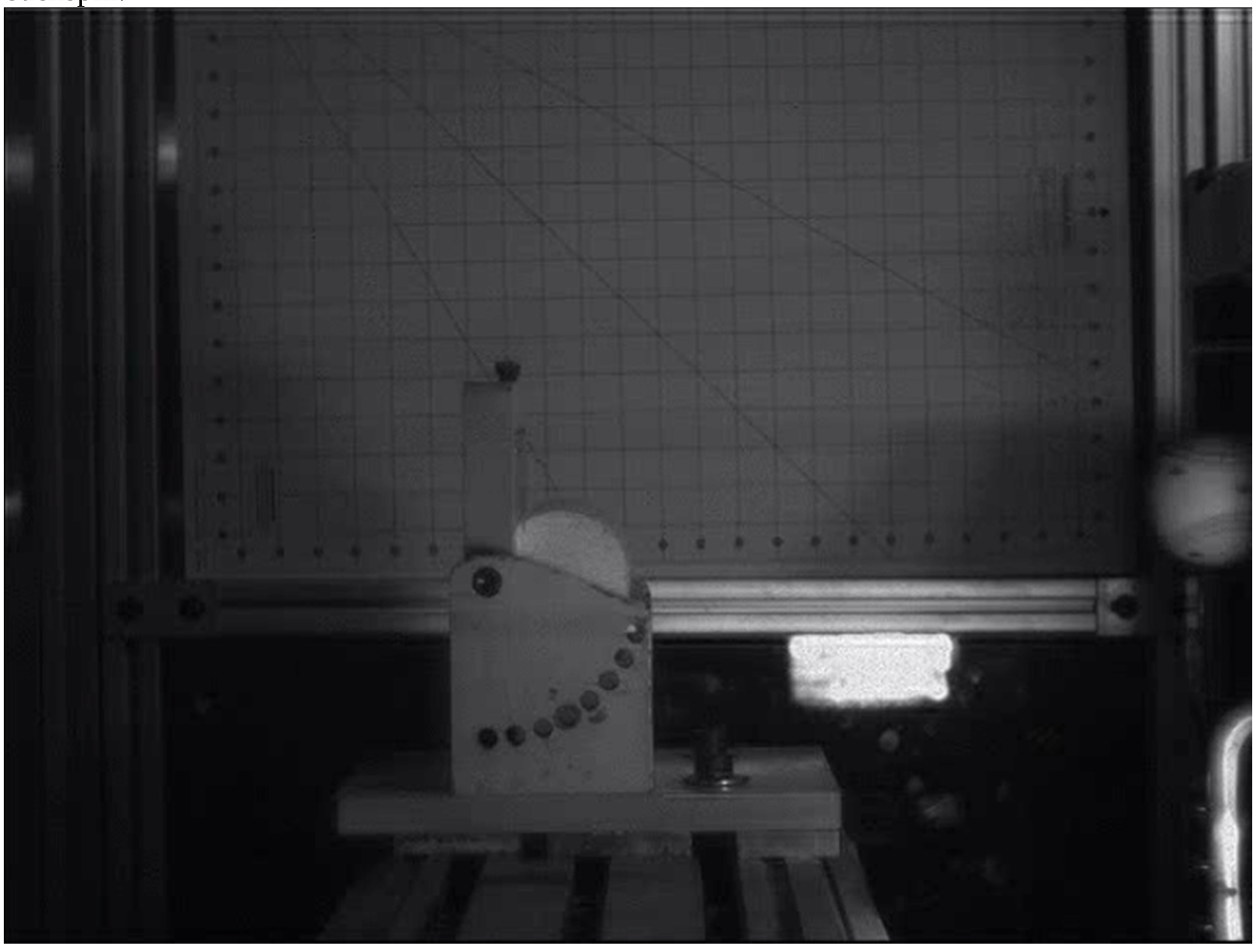
To set the stage for the analysis to follow, let me first show you a simplified diagram of the geometry of the ball-bat collision. This is a side view at the moment of initial contact. The ball moves downward from right to left along the blue arrow at the "descent angle" relative to the horizontal. The bat moves upward from left to right along the red arrow at the "attack angle".



Also shown on the diagram are the "centerline angle" and the "offset". The centerline is the dotted line connecting the center of the bat to the center of the ball, and the centerline angle is the angle the centerline makes with the horizontal. The offset is the vertical distance between the centers of the ball and bat. Those two things are related. For those of you who like a little math, the sine of the centerline angle is the ratio of offset to the sum of ball and bat radii (about 2.7 inches).

Armed with this diagram, let's talk about the forces that the bat exerts on the ball that cause it to change both its direction and its spin. First is the "normal" force, which acts directly along the centerline, pointing up and to the right in the diagram. It is the primary force that changes the direction of the ball. Second is the frictional force, which occurs whenever there is relative motion between the ball and bat along their mutual surfaces (i.e., perpendicular to the centerline). Friction contributes both to a change in direction and to a change in the spin rate.

As an example of these forces in action, take a look at the gif below, which comes from an experiment I did a few years ago. A baseball is fired without spin from a cannon at 120 mph, impacts a fixed cylinder made of ash, then bounces, all the while viewed by a high-speed video camera at 2000 frames/second. This collision is very much like the one in the above diagram, with the ball direction horizontal and zero bat velocity. The ball strikes above the center of the cylinder, then bounces off the cylinder up and to the right with a considerable amount of backspin.



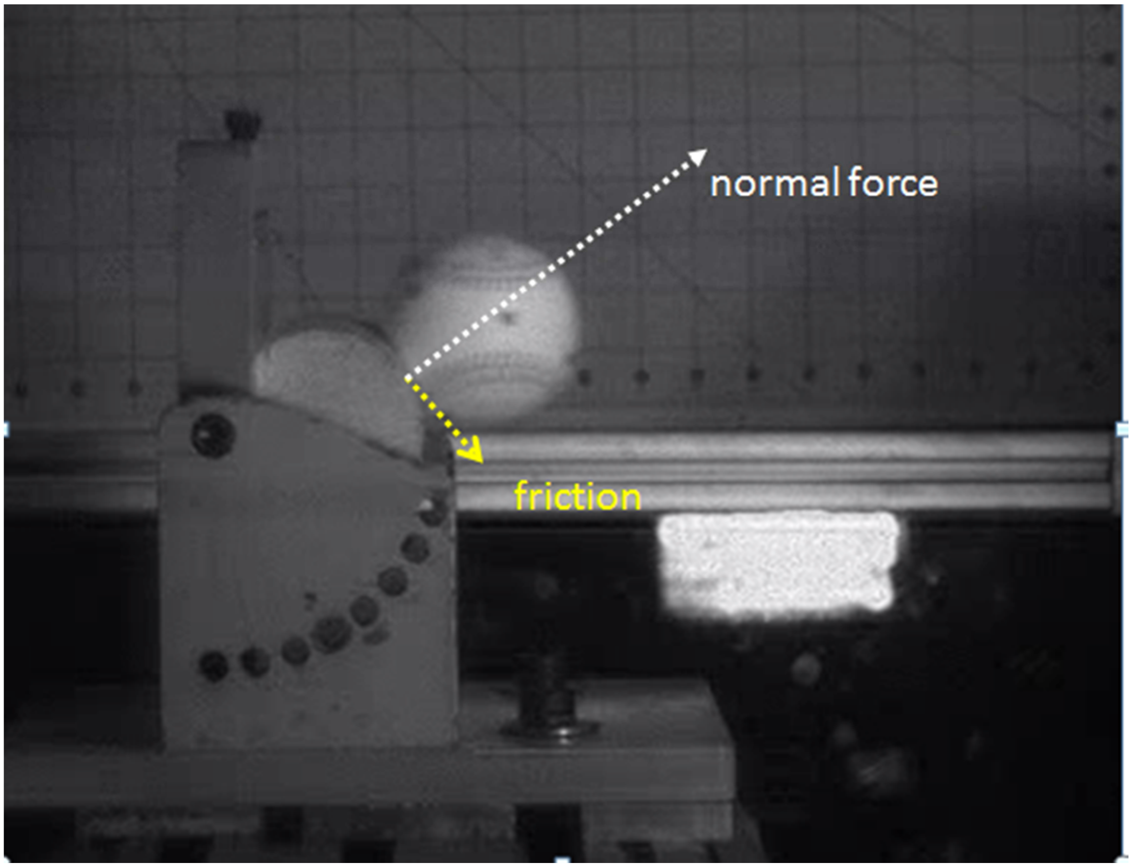
A still image captured from the video is shown in the next picture, with the ball in contact with the cylinder. The dotted white arrow shows the direction of the normal force, which is along the centerline. A component of the initial velocity is along the surface of the bat, perpendicular to the centerline and pointing up and to the left. During the collision, the ball slides in that direction, resulting in a frictional force acting in the opposite direction, as indicated by dotted yellow arrow. The friction contributes to the change of direction of the ball and causes the ball to rotate counterclockwise (i.e., with backspin). If the ball had impacted below the center of the cylinder, the friction would have been in the opposite direction, so that the ball would have bounced down and to the right with a clockwise spin (i.e., with topspin).

In general, there are two independent parameters under the batter's control that characterize the swing and that I will seek to optimize in the calculations. First is the offset, which is a measure of the batter's aim and determines the centerline angle. The second is the attack angle. The interplay among the attack angle, the descent angle, and the centerline play important roles in the fate of the batted ball, as we will see in the following simple example.

Suppose a ball is hit off a tee, so that there is zero pitch speed and spin. Suppose further that the offset and attack angle are adjusted by the batter so that the attack angle of the bat is right along the centerline. Under such conditions, there is no sliding and therefore no friction, and the ball will exit along the centerline with zero spin. If the attack angle falls below the centerline, the friction will be down and to the right on the diagram, so that the ball will exit the bat with backspin and in a direction below the centerline. Similarly, if the attack angle falls above the centerline, the ball will exit with topspin and above the centerline.

These observations are all qualitative. To find quantitative results requires a detailed model for the ball-bat collision. The model used by SHS was largely untested experimentally at the time of his publication. Since then newer experiments have been done leading to an improved understanding of the ball-bat collision and a better model, particularly as relates to the spin of a batted ball. Similarly the aerodynamic model used herein is also improved based on experiments that were done subsequent to the SHS work.

Before going to the calculations, I want to emphasize that I have made several simplifying assumptions in my model for the swing. SHS made the same assumptions. I have assumed that the bat is perfectly horizontal and perpendicular to the line connecting home plate to second base at the time of collision. In PITCHf/x language, the pitch is moving along the y axis and the bat is oriented parallel to the x axis, so that the batted ball goes to straightaway CF. Clearly, this assumption ignores the timing issue, so that the batter is neither out in front nor behind on the pitch. It would be straightforward to relax these assumptions in future studies.



Now let's move on to the calculations. A generic wood bat typical of that used in MLB was used along with four different pitch types, as shown in Table 1. Two different pitches were studied, a fastball with 2000 rpm backspin and curveball with 2000 rpm topspin. The speed and descent angle were based on typical MLB pitches from the PITCHf/x database.   Also investigated was the situation where a ball was hit off a tee. A fixed bat speed of 70 mph was assumed in all cases.   Contact was assumed to occur at the front edge of home plate and three feet off the ground.

Table 1 Properties of pitches used in investigation.

Pitch type	**Speed at home plate (mph)**	**Descent angle (deg)**	**Spin rate (rpm)**
Fastball	85.8	6	2000 backspin
Curveball	70.7	10	2000 topspin

The first question I asked was the one asked by SHS in their investigation: What are the swing parameters that give the maximum batted ball distance? The results of the optimization process are shown in the contour plots and summarized in Table 2. The plot shows contours of equal distance in the space of attack angle and offset, for fastball and curveball separately. These results may surprise you; they certainly surprised me and forced me to think carefully about why they turned out the way they did. I will now explain.

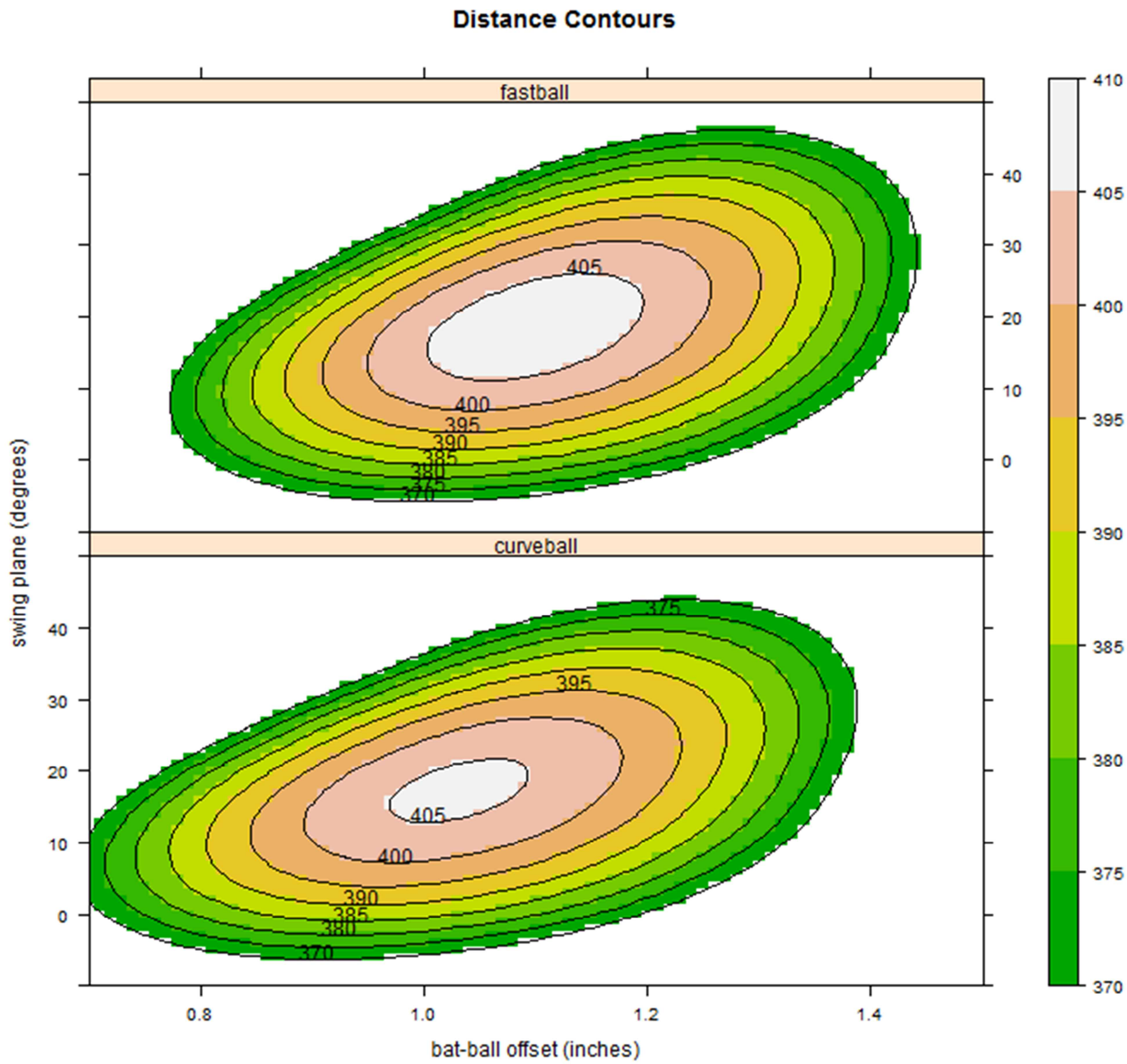


Table 2 Optimum swing parameters for maximum distance.

Pitch type	**offset (in)**	**centerline angle (deg)**	**attack angle (deg)**	**exit speed (mph)**	**launch angle (deg)**	**spin (rpm)**	**distance (ft)**
Fastball	1.09	23.6	18.8	100.6	29.6	2421	408.4
Curveball	1.03	22.3	17.8	100.4	30.3	2285	406.2
tee	1.60	36.1	25.0	88.4	33.3	1212	338.7

The first surprising result is that the exit speed for fastball and curveball are essentially identical. How is that possible since, all other things equal, I would have expected about a 3 mph greater exit speed for the fastball? The reason has to do with the so-called Coefficient of Restitution (COR), which is a measure of the bounciness of the ball, and how it depends on speed. In fact, the COR is larger at the lower impact speed of the curveball than at the fastball speed. That fact alone accounts for most of the additional 3 mph. The rest is buried in even more obscure details of the collision which I won't bore you with.

The second surprising result is that the backspin on the fastball is actually a little bit larger than that on the curveball, despite the qualitative argument given earlier that the backspin on the curveball should be larger. How is that possible? The key to understanding this result is to realize that because of smaller descent angle (see Table 1), the incoming ball moves along a direction further from the centerline for the fastball than for the curveball. As a result, there is a greater sliding speed for the fastball, so that friction acts over a longer period of time, resulting in a much greater change in the spin. In fact, for both the fastball and curveball, the outgoing spin depends far more on things related to how the ball and bat directions are aligned with the centerline than it does on the spin of the pitch. The collision model that leads to that result comes from experimental work done subsequent to the SHS article.

When you put it all together, the eye-catching result of SHS that an optimally hit curveball travels farther than an optimally hit fastball is not confirmed by my own analysis. In fact, the fastball beats the curveball but only by a little bit. My takeaway from this analysis is that the distances are comparable.

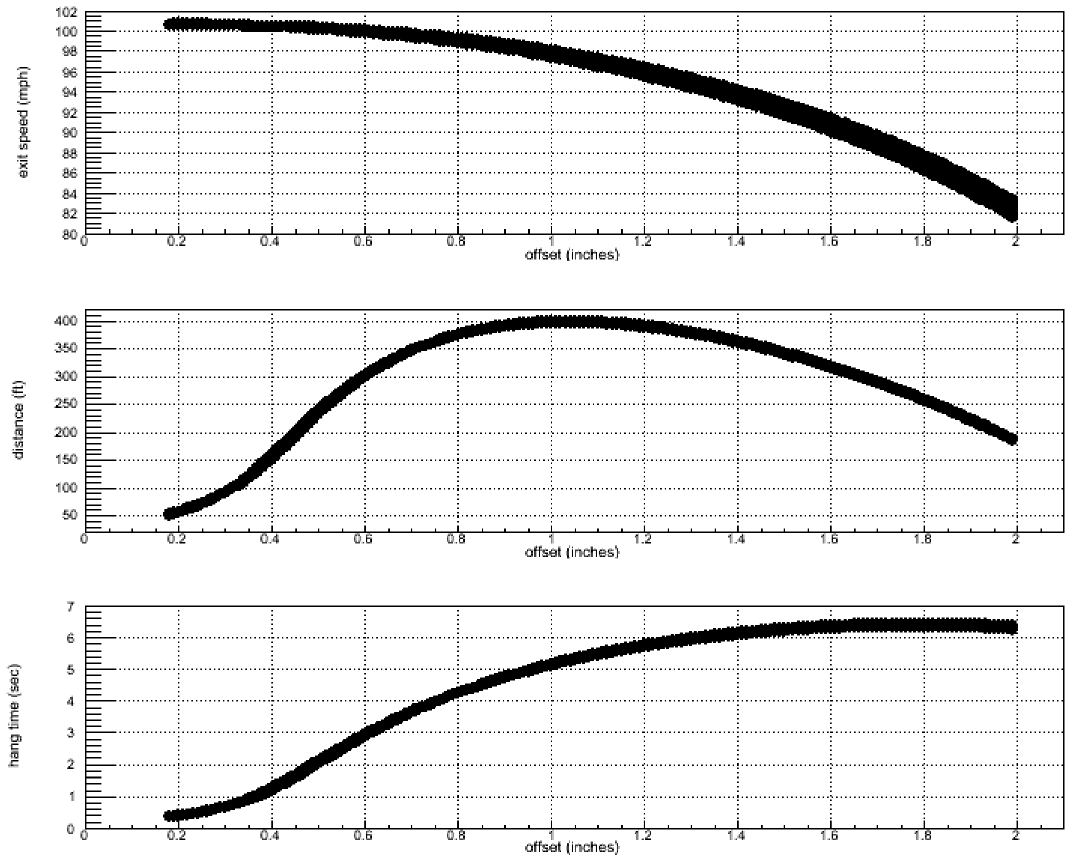
One additional thing can easily be seen from the contour plots: If your goal is to hit the ball as far as possible, swinging down on the ball—i.e., with a negative attack angle—does not appear to be a good idea.

Next take a look at the result for hitting off a tee in Table 2. If one attempts to hit the ball as far as possible, it requires an attack angle and an offset that are significantly larger than are optimum for hitting a pitch. I mention this as a cautionary tale that swinging the bat to maximize the distance off a tee can lead to bad habits.

There is undoubtedly much more to be gleaned from this analysis, particularly the contour plots. Rather than do that, however, I want to turn to a slightly different topic. Note from Table 2 that the optimum attack angle is about 18^0, which is significantly greater than the descent angle of 6^0 for a fastball. While such a swing might optimize the batted ball distance, it is not too forgiving if the swing is mis-timed.

This suggests that another way to optimize the swing is for the attack angle to be essentially identical to the descent angle, so that good contact can still result even if the timing is a little off. Coaches often refer to that as a “level swing”, although in this context level means that the upward plane of the swing coincides with the downward plane of the ball. So I took a look at the process where the two planes coincide and the results are summarized in the plots below, assuming a fastball.

The top plot shows exit speed versus offset and demonstrates that a high exit speed can be achieved with a wide range of offsets. The middle plot shows that maximum distance is achieved with an offset around 1 inch. That would be the hitting strategy if the goal is to hit a home run. The bottom plot shows that short hang time (along with high exit speed) is achieved with offsets less than 0.5 inch. In effect, this type of hit is a hard hit line drive with a low launch angle, leading to a safe hit with high probability. These plots demonstrate quantitatively what most people already realize. Namely, that the two different goals (home runs versus on base) require two different hitting strategies.



Let me return to the question that was posed to me: Is the claim that a curveball can be hit farther than a fastball ``fact, theory, or nonsense"? As already mention, it is not nonsense and it is theory. But it is not fact. Moreover, while I very much like qualitative arguments, since they often help us see through the details to get at the essential results, there are times when the details really do matter. This is one of those times..