On the potential of a chemical Bonds: Possible effects of steroids on home run production in baseball

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In recent years several baseball players have hit a remarkable number of home runs, and there has been speculation that their achievements were enhanced by the use of anabolic steroids. Basic mechanics and physiology, combined with simple but reasonable models, show that steroid use by a player who is already highly skilled could produce such dramatic increases in home run production. Because home runs are relatively rare events on the tail of a batter's range distribution, even modest changes in bat speed can increase the proportion of batted balls that result in home runs by 50–100%. The possible effect of steroid use by pitchers is briefly considered.
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I. INTRODUCTION

The use of performance-enhancing substances is probably as old as sport itself, but anabolic (muscle-building) steroids[1] have received increasing attention in recent decades, at least since the notorious systematic doping of East German female swimmers in the 1970s and 1980s.[2] Since 1990, international stars in track and field, cycling and cricket, among other sports, have been found to have used steroids.[3]

In the United States, intense attention has focused on steroid use in baseball.[4–7] The legitimacy of home run records has received particularly close scrutiny, in part because home runs have a special glamour for baseball fans, but also because the performances between 1995 and 2003 were so extraordinary. Babe Ruth's record of 60 home runs in a single season, set in 1927, stood for 34 years, until Roger Maris hit 61 in 1961. For the next 35 years no player hit more than 52 in a season. But between 1998 and 2006, players hit more than 60 home runs in a season six times. Mark McGwire shattered Maris's record by hitting 70 home runs in 1998, but his record was eclipsed just three years later when Barry Bonds hit 73 home runs in 2001.[8] Over a four year period a record that had stood unchanged for decades suddenly increased by 20%.

Figure 1 illustrates the explosion of home runs in the 1990s. It displays the average of the five highest individual home run totals in the major leagues for each year from 1960 to 2006 (omitting the strike-shortened seasons of 1981 and 1994), together with the number of players who hit more than 45 home runs in each season. An abrupt increase in the mid-90s is clearly visible, together with a drop back to historical levels in 2003, the year that Major League Baseball instituted steroid testing.[9]

Such dramatic changes in performance over a short period of time are rare in well-established sports.[10] Is there something special about home run hitting that makes it more amenable to performance enhancement than other athletic endeavors? And is it physically and physiologically plausible that steroids could produce effects of the magnitude observed—allowing a player who is capable of hitting 50 home runs per year without chemical assistance (a good year for an outstanding pre-steroid-era slugger) to increase that total to 70? I will argue that the answer to both of these questions is yes, because home runs fall on the tail of a statistical distribution, and so are especially sensitive to small changes in physical ability.

Hitting 50 home runs per year in the major leagues is a remarkable athletic achievement, reached so far by only 20 players. With or without steroids, it requires extraordinary skill, judgment, and coordination. Nevertheless, it is important to ask how much the use of illicit pharmacology could enhance the abilities of an already exceptional athlete.

To hit a large number of home runs, a player must put the ball in play (not strike out or walk) many times; and must hit a large fraction of the batted balls over the fence. Putting the ball in play is largely a matter of skill, and is not likely to be greatly affected by the use of strength-enhancing drugs. Hitting those balls over the outfield wall is a matter of both skill and physical strength, and could be influenced by the use of drugs that build muscle mass. A useful statistic is the fraction of balls put in play by a given hitter that are home runs. (This quantity is the number of home runs divided by the number of times the batter puts the ball in play. The latter is the number of official at-bats (which omits walks) minus the number of strikeouts.) Figure 2 shows this fraction as a function of the number of years in the major leagues for six of the ten hitters with the highest career home run totals. Figure 2(a) shows the data for the three most prolific sluggers whose careers ended before 1980, and who can therefore be assumed not to have used steroids. Figure 2(b) shows the top three home run hitters whose careers began after 1980 and included the period generally regarded as the "steroid era" of major league baseball.

For the pre-1980 sluggers, home runs generally represented 5–10% of the balls put in play. Only Babe Ruth regularly surpassed 10% and even he never reached 15%. The best present-day sluggers are much more prolific. Mark McGwire's record is particularly remarkable, with seven seasons at or above 15%. (McGwire has acknowledged using the legal anabolic steroid androstendione.[11]) Other points of reference include 11.5% for Roger Maris when he broke Ruth's record in 1961, 12.5% for Hank Greenberg when he hit 58 home runs in 1938, and 14.0% for Ryan Howard when he hit 58 in 2006.[8]

The fact that present-day athletes achieve at a higher level than those of a previous generation is not unique to baseball, nor is it evidence of cheating. And there have been other changes in the game that could have affected home run rates,

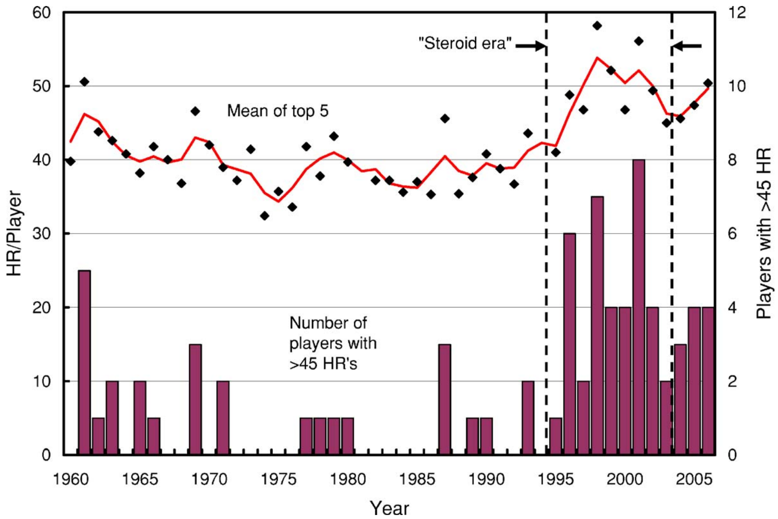

Fig. 1. (Color online) Historical progression of home run production from 1960 to 2006. Each data point represents the average number of home runs per season for the players with the five highest totals in each year (the strike-shortened seasons of 1981 and 1994 are omitted). The line is a three-point binomial smoothing of the data. The vertical bars show the number of major league players with more than 45 home runs in each year. The period conventionally regarded as the "steroid era"—from the mid-1990s to the imposition of mandatory steroid testing in 2003—is indicated. Data from Ref. 8.

including changes in ballpark dimensions, league expansions, the entry of African-American athletes, lowering of the pitcher's mound, and many other changes. (However, none of those changes coincide with the sudden burst of home run production in the mid-1990s shown in Fig. 1.) If the record-breaking performances of McGwire, Sosa, and Bonds are to be attributed in part to steroid use, then steroids must be able to account for an increase of ~50% in the fraction of balls put in play that are home runs, above the levels achieved without the use of steroids.

To see whether such a large increase is plausible, I will first consider the physiological evidence for the effects of anabolic steroids on muscle mass, and then use basic mechanics to examine the effect of such an increase in muscle on bat speed. The effect on the speed of the batted ball can be estimated with a simple model of the bat-ball collision. Using a model of the ball's trajectory and a crude estimate of the distribution of the speeds and angles of batted balls, the effect on home run production will then be estimated. Many of the models involved are uncertain and oversimplified, but because we are interested primarily in the differential effect of a small change in the initial conditions, the central result is insensitive to the details: A change of only a few percent in the average speed of the batted ball, which can reasonably be expected from steroid use, is enough to increase home run production by at least 50%. This disproportionate effect arises because home runs are relatively rare events that occur on the tail of the range distribution of batted balls. Because the distribution's tail is particularly sensitive to small changes in the peak and or width, home run records can be more strongly affected by steroid use than other athletic accomplishments.

II. WHAT DO STEROIDS DO?

Anabolic (muscle-building) steroids are a class of testosterone derivatives that enhance protein synthesis in muscle cells by promoting the production of messenger RNA in the nucleus.[11,12] Physiological pathways involving the interaction of steroids with the stress hormone cortisol have also

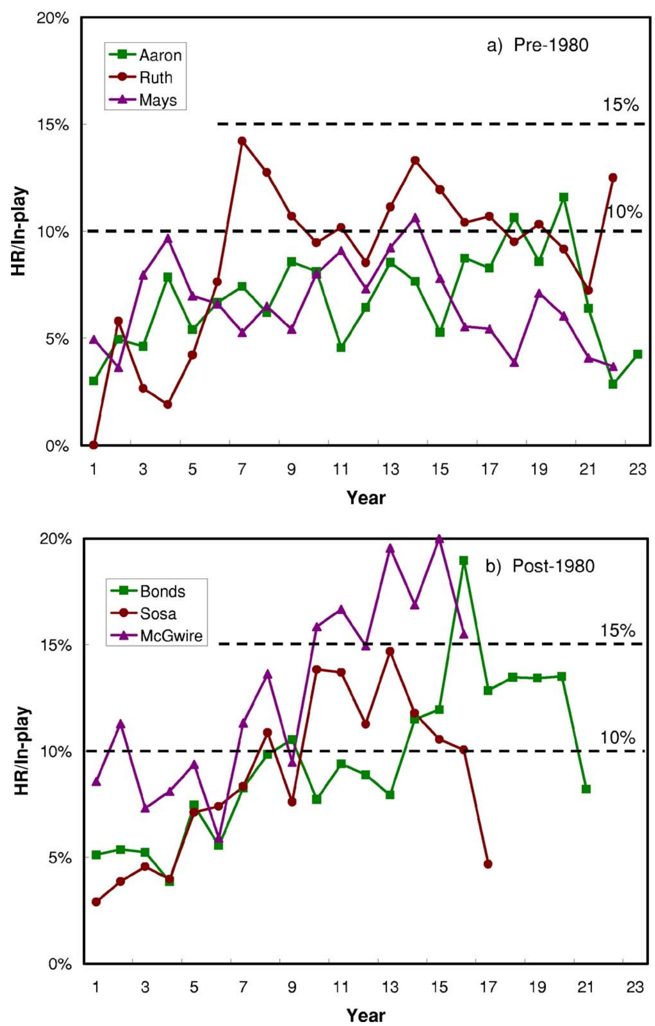

Fig. 2. (Color online) Home runs per ball put in play, as a function of years in the major leagues, for the three players with the highest career home run totals among (a) players whose careers ended before 1980 (pre-steroids), and (b) players whose careers began after year 1980 and encompassed the "steroid era." All are among the top 10 all-time. Data from Ref. 8.

been proposed.[13] In combination with adequate nutrition and exercise, steroid supplements are effective in increasing lean muscle mass in individuals suffering from AIDS, cancer, and other debilitating conditions.[11,12,14,15] In a controlled, double-blind study of undernourished male patients with chronic obstructive pulmonary disease patients given steroids over a period of 27 weeks increased lean body mass by 6%, while those given a placebo showed no increase.[16]

In view of the known influence of anabolic steroids on protein synthesis and their well-studied muscle-building efficacy in medical applications, most experts are convinced that they also enhance lean muscle mass in healthy adults and specifically in athletes, at least when combined with adequate nutrition and a rigorous program of weight training.[11,12,14] Rigorous controlled experiments demonstrating such an effect are scarce, and studies directly investigating effects on athletic performance (other than weightlifting) do not exist.[12,14] There are major practical, legal, and ethical obstacles to controlled direct investigation of the issues at relevant dosage levels and in the relevant populations.[11] In a 1991 meta-analysis of 16 prior studies, Elashoff *et al.*[17] found no clear evidence for steroid-induced strength enhancement, but most of the studies were small, often not well controlled, and used steroid doses well below those commonly used by athletes. The dose is particularly significant, because there is evidence for a threshold dose, below which only a minor increase in lean body mass is observed, but above which the increase becomes much more substantial.[12] All of the studies reviewed in Ref. 17 used subthreshold doses. Other key parameters that must be controlled, but often were not, include nutrition and training regimen.

The most definitive evidence to date comes from a controlled, double-blind study of 43 healthy male recreational weight lifters.[18] This study differs from earlier, inconclusive experiments in its use of much higher doses (600 mg/week of testosterone enanthate), comparable to those reportedly used by athletes, its control of nutrition and exercise regimens, and its careful design. Over ten weeks the subjects given steroids increased muscle mass by 9.3% compared to 2.7% for the control group (both groups had the same exercise regimen). The steroid users increased the maximum weight they could bench-press by 23% and that they could squat by 37%, compared to 9% and 20% for the control group. It is possible that athletes attain even greater gains in muscle mass, because they may use higher doses for longer periods, “stack” multiple drugs, and may be able to increase their level of training as a result of steroid use.[11,12,18]

Steroids are known or believed to have other effects that may be relevant to athletic performance, including increased aggressiveness and the ability to recover more quickly from exercise and therefore train harder.[11] These effects have not been quantified, and it is not clear whether greater aggressiveness would be beneficial or harmful to a hitter in baseball. There is some evidence that steroids decrease reflex reaction time, although there do not appear to be indications of a significant effect, either positive or negative, on such factors as hand-eye coordination.[11]

For purposes of this article, I will assume that the basic effect of steroids is to increase muscle mass by about 10%, with other aspects of the player’s performance remaining constant.

III. HOW MUCH CAN MORE MUSCLE ENHANCE HOME RUN PRODUCTION?

The increase in muscle mass due to steroids must take place primarily by increasing the cross-sectional area of the muscle through the addition of new muscle fiber. It is well established that the maximum force a muscle can exert is proportional to its cross-sectional area—muscles from a wide range of creatures from mollusks to mammals produce maximum stresses ~200 kPa.[19,20] It is therefore reasonable to assume that a 10% increase in an athlete’s muscle mass will also increase the force exerted by those muscles by about 10%. The increases in maximum voluntary force found in the weight-lifting study of Ref. 18 were even greater, possibly because of steroid-induced behavioral effects that led to more intense effort.[18] In view of those results, my assumption that the increase in force is proportional to the increase in muscle mass is conservative. If we assume that the length and technique of a batter’s swing remain the same, it follows that the work done by muscles on the bat, and therefore the kinetic energy of the bat, can also be increased by about 10% through the use of steroids. If the bat’s mass is constant, the speed of the bat as it strikes the pitched ball will be roughly 5% higher than without the use of steroids. (Because we are making rather rough estimates here, it will not make much difference if the batter uses a slightly heavier or lighter bat.)

Determining the effect of this increase in bat speed on the speed of the batted ball requires a model of the bat-ball collision. Nathan and others have given sophisticated treatments,[21–23] but for balls hit near the bat’s “sweet spot”—which is the case for most home runs—the results are well approximated by a simple one-dimensional, partially elastic collision, with the bat treated as a rigid body:[22]

$$v = \left(1 + \frac{MC_R - m}{M + m}\right) v_{bat} + \left(\frac{MC_R - m}{M + m}\right) v_{pitch}, \quad (1)$$

where M and m are the masses of the bat and ball, respectively, v_{bat} and v_{pitch} are their speeds just before the collision, and C_R is the coefficient of restitution. For the reasonable values $M=0.96$ kg, $m=0.145$ kg, $C_R=0.5$,[21–24] $v_{pitch}=40$ m/s, $v_{bat}=30$ m/s (see Ref. 23), a 5% increase in bat speed leads to an increase of 4% in the speed of the ball as it leaves the bat. The ratio of ball-speed increase to bat-speed increase changes by 10% or less when the parameters are varied within realistic ranges.

The next ingredient in the analysis is a model for the trajectory of the baseball. In addition to gravity, the significant forces on the ball are air resistance (drag) and the lift force due to the ball’s spin, and neither is well understood for a rapidly spinning baseball. In particular, there is disagreement about whether the drag coefficient drops precipitously with the onset of turbulence in a particular range of speeds. Adair is skeptical about the existence of such a “drag crisis” for baseballs,[24] but Sawicki *et al.*,[23] drawing on empirical data for pitched balls, conclude that there is a pronounced drag crisis for speeds near 32 m/s (~72 mph). I have done calculations using models with and without a drag crisis (see Fig. 3). There are significant differences of detail. For example, the launch angle for maximum range is about 26° for the Sawicki model and about 34° for the Adair model. The Sawicki model also shows lower sensitivity of the home run rate to the average initial ball speed, because once the ball leaves the bat the speed drops rather quickly into the range

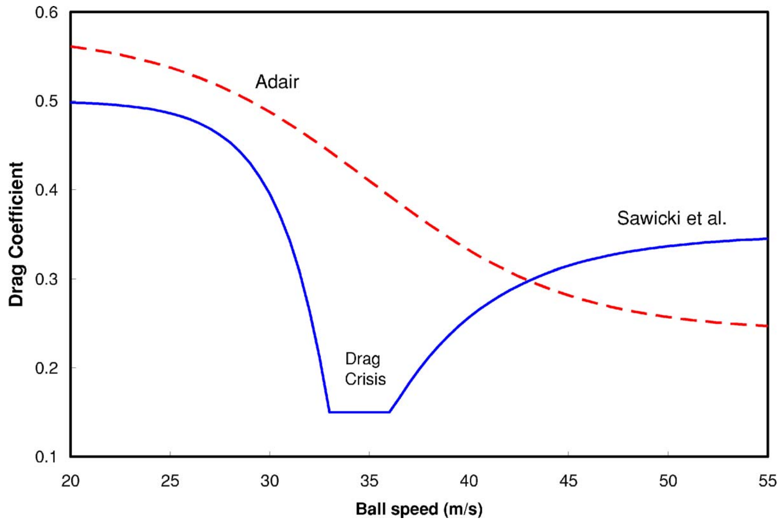

Fig. 3. (Color online) Two models of the drag coefficient as a function of speed of a rapidly spinning baseball, based on Refs. 23 and 24.

where the drag coefficient is minimal, and then remains there for much of the flight. Nevertheless, both models lead to the same qualitative conclusion.

Batted balls hit in the air have considerable backspin, with angular speeds of several hundred rad/s. The resulting lift can be on the order of one third of the ball's weight.[21,23,24] There is uncertainty, however, regarding both the actual angular speed of batted balls and the dependence of the lift force on both the linear and angular speeds of the ball. I have used both a simple model due to Adair[24] and a more involved semiempirical model from Sawicki *et al.*[23] As for the drag force, the different models give trajectories that differ in detail, but the overall conclusions regarding the differential effect of changes in ball speed are not greatly affected.

Given the initial velocity, angle, and angular velocity of the batted ball, its trajectory can be calculated (neglecting wind and sidespin, which is significant mainly for balls hit very near the foul lines). Whether that trajectory results in a home run depends on the direction of the hit and the dimensions of the ballpark. For this discussion, I assume that a ball is a home run if its trajectory has a height of at least 3 m (9 ft) at a distance of 115 m (380 ft) from its starting point—reasonable values for the height and distance of major league outfield walls.

The final necessary ingredient in the model is a distribution of the angles and speeds of batted balls (the angular speed is assumed to be related to angle[23]). In the absence of empirical data, I assume a Gaussian distribution of angles and an asymmetrical Gaussian distribution of ball speeds:

$$P(v,\theta) = \frac{1}{2\pi\sigma_\theta(\sigma_{v\ell}+\sigma_{vh})} e^{-(v-v_0/2\sigma_{v\ell})^2} e^{-(\theta-\theta_0/2\sigma_\theta)^2} \quad v \leqslant v_0$$

$$= \frac{1}{2\pi\sigma_\theta(\sigma_{v\ell}+\sigma_{vh})} e^{-(v-v_0/2\sigma_{vh})^2} e^{-(\theta-\theta_0/2\sigma_\theta)^2} \quad v > v_0. \qquad (2)$$

Here v_0 is the most probable speed. The width of the distribution for speeds below the peak is $\sigma_{v\ell}$ and the width for speeds above the peak is σ_{vh}. Because we are concerned with the game's most accomplished home run hitters, I assume that the angular distribution is centered on the angle that gives maximum range. (The value depends on the choice of drag and lift model.) The values for the other variables, v_0, $\sigma_{v\ell}$, σ_{vh}, and σ_θ, were chosen by requiring that the fraction of balls that are home runs should be 10% and that fewer than 5% of the home runs should travel farther than 140 m (460 ft). (Adair[24] reports that only two of about 2000 measured major league home runs in 1988–1989 traveled more than 140 m. For the best home run hitters the fraction of very long balls is presumably somewhat higher.)

These requirements strongly constrain the possible distributions, but the answer is still not unique. For each drag and lift model, I considered a range of parameter sets that met all the above constraints. For each satisfactory parameter set, the peak velocity v_0 and widths $\sigma_{v\ell}$ and σ_{vh} were all increased by the same percentage, and the change in home run rate was calculated. (The results are not appreciably different if only the peak velocity is increased, with the widths held constant.) Figure 4 displays the results for several model distributions, using both models of the drag and lift forces. There is considerable variation among the models, but the salient point is that a 4% increase in ball speed, which can reasonably be expected from steroid use, can increase home run production by anywhere from 50 to 100%.

Figure 5 shows the distribution of ranges for a typical model distribution of ball speeds and angles. The solid line shows the original distribution, which by design has 10% home runs. The dashed line shows the distribution when both the peak ball speed and the width of the speed distribution are increased by 4%. Although the overall change in the distribution is modest, the fraction of balls hit more than 115 m increases to 16.6%.

IV. WHAT ABOUT THE PITCHERS?

Most of the attention paid to steroid use in baseball has focused on batters, and power hitters in particular. But when the first results of drug testing in professional (mainly minor league) baseball were announced in 2005, 31 of the 68 suspended players—46%—were pitchers.[25] It is not difficult to understand why. By the same mechanical analysis, a 10% increase in muscle mass should increase the speed of a thrown ball by about 5%, or 4–5 mph for a pitcher with a

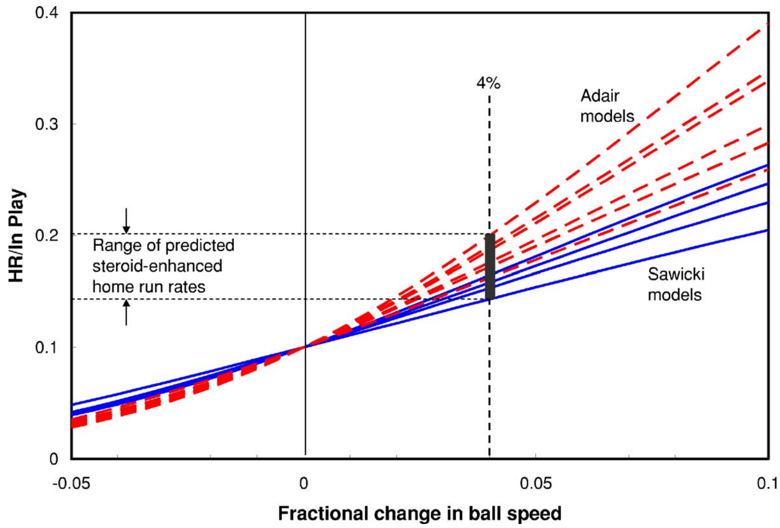

Fig. 4. (Color online) Dependence of the home run rate (home runs per ball put in play) on the fractional change in the average speed of a batted ball, for a variety of speed and angle distributions and using the Adair (Ref. 24) (dashed lines) and Sawicki *et al.* (Ref. 23) models for the drag and lift forces. All models were constrained to give an initial rate of 0.1. For a 4% increase in ball speed the home run rate increased by 50–100%.

90 mph fastball. Although there is far more to pitching than speed (just as there is far more to hitting than bat speed), there is a significant correlation between average fastball speed and earned run average (ERA), with an increase of 4–5 mph translating to a reduction in ERA of about 0.5 runs/game.[26,27] That is enough to have a meaningful effect on the success of a pitcher, but it is not nearly as dramatic as the effects on home run production. The unusual sensitivity of home run production to bat speed results in much more dramatic effects, and focuses attention disproportionately on the hitters.

V. CONCLUSION

Physics cannot tell us whether a particular home run was steroid-assisted, or even whether an extraordinary individual performance indicates the use of illicit means. But physics, combined with physiology, can constrain the extent of performance enhancement that could be attributed to the use of drugs. Basic mechanical principles, in combination with simple but plausible models, show that relatively modest increases in muscle mass, well within the range that can reasonably be expected from steroid use, can dramatically in-

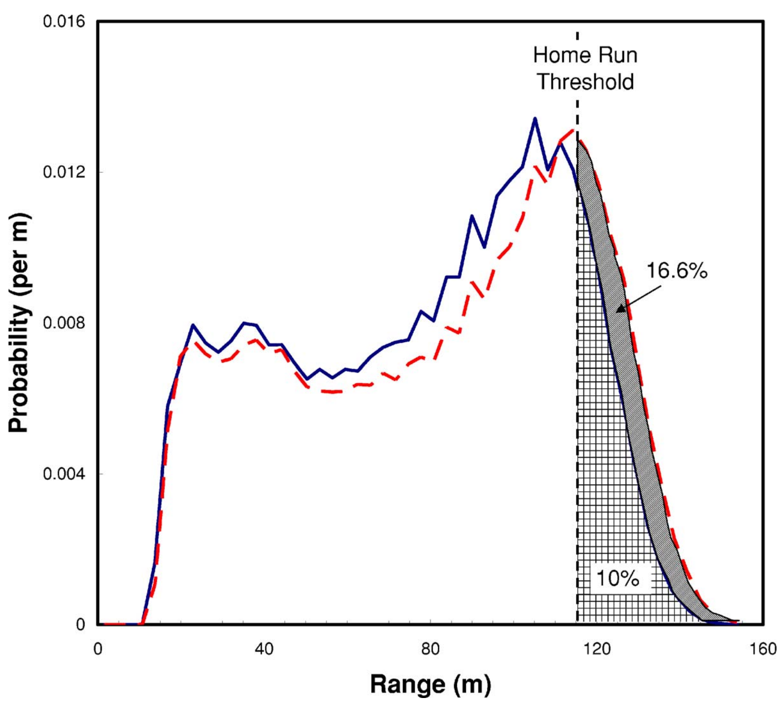

Fig. 5. (Color online) Distribution of ranges. The solid line is the probability distribution for the original distribution of ball speeds and angles, and by design gives a home run rate of 10%. The dashed line shows the distribution when the peak velocity and width of the velocity distribution are each increased by 4%. The fraction of balls with ranges beyond the home run threshold is increased by 66%.

crease home run production. Specifically, a 10% increase in muscle mass can increase the fraction of balls put in play that result in home runs by 50% or more. This increase is comparable to the differences in home run rate between the most productive sluggers of the "steroid era" and those of earlier generations. These results certainly do not prove that recent performances are tainted, but they suggest that some suspicion is reasonable.

Note added in proof. The estimated increases in bat and pitch speed in Secs. III and IV neglect the energy required to move the player's additional body mass. Including that effect, and assuming that muscle accounts for 50% of total body mass, reduces the estimated speed enhancements by about 25%. The increase in batted-ball speed resulting from a 10% gain in muscle mass is reduced from 4% to 3% and the increases in home-run rate (see Fig. 4) range from 30 to 70%. Similarly, a pitcher's fastball can be expected to gain 3–4 mph. The major conclusions of the paper are not affected. The author thanks Alan M. Nathan for pointing out the omission and for other insightful comments.

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[1]The chemicals of interest are considered anabolic-androgenic steroids because they affect both muscle development and sexual characteristics. In the context of sport they are often simply called "anabolic steroids" or just "steroids." In this article the terms are used interchangeably.

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