

Corked bats, juiced balls, and humidors: The physics of cheating in baseball

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Three questions of relevance to Major League Baseball are investigated from a physics perspective. Can a baseball be hit farther with a corked bat? Is there evidence that the baseball is more lively today than in earlier years? Can storing baseballs in a temperature- or humidity-controlled environment significantly affect home run production? These questions are subjected to a physics analysis, including an experiment and an interpretation of the data. The answers to the three questions are no, no, and yes, respectively. © 2011 American Association of Physics Teachers. [DOI: 10.1119/1.3554642]

I. INTRODUCTION

Baseball is rich in phenomena that are ripe for a physics analysis. In the last decade there has been an explosion in the number of papers addressing interesting issues in baseball from a physics perspective. In this paper we address three issues of relevance to Major League Baseball. Although the issues are seemingly separate, they all involve the kinematics of the ball-bat collision, a topic particularly well suited for introductory physics classes as a real-life example of inelastic two-body collisions. Such collisions are characterized by non-conservation of kinetic energy, which leads to the introduction of the phenomenological coefficient of restitution (COR). The COR is the ratio of the outgoing to the incoming relative velocities of the two bodies and is unity if kinetic energy is conserved. Oftentimes in introductory courses, discussion is limited to the cases where the COR is either 1 (an elastic collision) or zero (a completely inelastic collision). The ball-bat collision provides a more realistic and interesting example in that the COR is equal to about 0.5. An additional feature of the ball-bat collision not usually treated in introductory courses is that the bat is an extended object rather than a point object. As a result, the kinematics involves both linear and angular momentum conservation. Therefore, the ball-bat collision is an interesting example of more generalized two-body collisions. Although the experiments that we will discuss involve specialized equipment not generally available in undergraduate laboratories, simple low-speed versions of the same experiments are possible.

The three topics we will address all involve the COR in the ball-bat collision, and are explored using variations of the same experimental technique described in Sec. II. We investigate in Sec. III whether or not a baseball can be hit harder and therefore farther with an illegally modified corked bat. We next investigate in Sec. IV whether there is any evidence that baseballs of today are more or less lively than baseballs of yesteryear. Finally we investigate whether a baseball stored at reduced temperature or elevated humidity leads to fewer home runs (see Sec. V). We conclude with a brief summary in Sec. VI.

II. DESCRIPTION OF THE BAT AND BALL TEST FACILITY

All the experimental work for these studies was done at the bat-ball test facility at the Sports Science Laboratory at Washington State University.¹ The experimental setup is depicted schematically in Fig. 1. The measurements consisted of firing a baseball from a high-speed air cannon onto a stationary impact surface. While inside the barrel of the cannon, the ball travels in a sabot which allows control of the ball speed and orientation. An arresting plate at the end of the cannon captures the sabot while allowing the ball to continue unimpeded. Three light screens were placed between the cannon and impact surface to measure the speed of the incident (v_i) and rebounding (v_f) balls. The location of the impact surface relative to the cannon was adjusted so that the ball rebound path was within 5° of the inbound path. The air pressure to the cannon was adjusted to achieve an incident speed within 1 mph of the target speed. The laboratory was maintained at fixed 72°F temperature and 50% relative humidity for all of the impact measurements.

Three different impact surfaces were used in the studies: A baseball bat shown in Fig. 1, a fixed rigid flat surface, and a fixed rigid cylindrical surface. The bat was used for the corked-bat studies and for some of the juiced-ball studies. The bat was mounted horizontally and supported by clamping it at the handle to a structure that was free to pivot about a vertical axis located 6 in. from the knob. For an impact with an initially stationary bat, the collision efficiency q is defined as the ratio of outgoing to incoming speeds v_f/v_i . For the collision of a ball of mass m with a bat that is free to pivot, a straightforward application of angular momentum conservation about the pivot and the definition of COR results in the relation²

$$\text{COR} = q(1 + m/M_{\text{eff}}) + m/M_{\text{eff}}, \quad (1)$$

where $M_{\text{eff}} = I/z^2$ is the effective mass of the pivoted bat, I is the moment of inertia of the bat about the pivot, and z is the distance from the impact location to the pivot. For fixed rigid surfaces, $M_{\text{eff}} \rightarrow \infty$, so that the COR is just the ratio of the outgoing to the incoming speeds. Under these conditions, the COR is referred to as the “ball COR” for the flat surface or

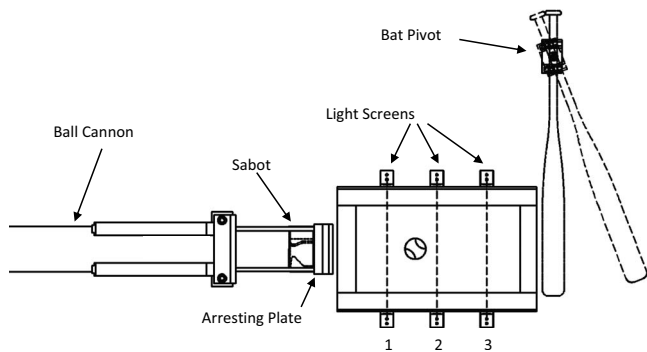


Fig. 1. Top view of the bat and ball testing facility at the Sport Science Laboratory at Washington State University with a bat as the impact surface. For some of the studies the bat was replaced by a fixed rigid surface, either flat or cylindrical.

the “ball cylindrical COR” for the cylindrical surface. The flat surface was used for some of the juiced-ball studies to measure the ball COR. The cylindrical surface was used in the humidor studies for determining the ball cylindrical COR, which is a better approximation to the forces and deformation encountered in a ball-bat collision. The 2.63 in. diameter of the impact surface was chosen to closely approximate the diameter of a baseball bat.

III. CAN A BASEBALL BE HIT FARTHER WITH A CORKED BAT?

In early June during the 2003 Major League Baseball season, an event occurred that dominated the sports news for several days. Sammy Sosa, the Chicago Cubs slugger, was caught using an illegally “corked” bat during a game. This event offered a rare opportunity for scientists to comment on events in sports by addressing the question of whether corking a bat gives the batter an advantage.

A corked bat is a wood bat in which a cylindrical cavity is drilled axially into the barrel of the bat. Typically the diameter and length of the cavity are approximately 1 and 10 in., respectively. The cavity is filled with a light inert material such as cork. By removing weight from the barrel region, the batter can achieve a higher swing speed. However, the lower barrel weight implies a lower collision efficiency. If the goal of the batter is to achieve as high a batted-ball speed as possible, the increased swing speed is at least partially compensated by the less effective collision. One goal of the present study is to investigate the tradeoff between swing

speed and collision efficiency to determine whether a batter can achieve a higher batted-ball speed with a corked bat.

Corking a bat may offer another advantage, the “trampoline effect,”³ at least according to anecdotal claims by some batters. The trampoline effect occurs in hollow metal bats due to the ability of the thin wall of the bat to compress when in contact with the ball, thereby increasing the elasticity of the collision. The increased elasticity results in a larger collision efficiency and, all other things equal, a larger batted-ball speed. Another goal of this study is to determine whether a trampoline effect exists for a hollow or corked wood bat.

A. Experimental procedures

These issues were addressed at the ball-bat test facility described in Sec. II. Impact measurements were performed consisting of firing a baseball from the air cannon at a speed of 110 mph onto a stationary bat. The speed of the incoming and rebounding baseball were measured, their ratio taken to determine the collision efficiency q , and Eq. (1) applied to determine the ball-bat COR. The properties of the bats used are given in Table I, with the weight, center-of-mass, and moment of inertia measured using standard techniques.¹

The unmodified bat had a length of 34 in. and a weight of 30.6 oz. First, the unmodified bat was impacted a total of six times. Then a cavity 1 in. in diameter and 10 in. deep was drilled into the barrel of the bat, reducing the weight to 27.6 oz. This hollow bat was impacted six times. Then the cavity was filled with crushed-up pieces of cork, raising the weight to 28.6 oz. The corked bat was impacted 12 times. Then the cork was removed and the hollow bat was impacted again five times. Unfortunately, the bat broke at the handle on the last impact. We had intended to fill the cavity with superball material, but that part of the experiment was cut short by breaking the bat. All impacts used the same baseball and all were at the same location, 5 in. from the barrel end of the bat. A twin control bat, with properties nearly identical to those of the unmodified bat, was impacted at various times throughout the measurement cycle to verify that the properties of the ball did not change during the course of the measurements.

B. Results and discussion

The average values of the collision efficiency q and the ball-bat COR for each bat are given in Table I. The measured ball-bat COR for 54 total impacts, including all bats, closely approximated a normal distribution with a mean of 0.489 and a standard deviation of 0.009. From these results, we con-

Table I. Properties of the Rawlings 34 in bats used in the studies and the results of the measurements. The hollow and corked bats are modifications of the “unmodified” bat. The control bat is a similar but different bat. The weight is in ounces, the center-of-mass (CM) is measured in inches from the knob end of the bat, and the moment of inertia I is with respect to a point 6 in from the knob and in units of oz in.². The collision efficiency q , the ratio m/M_{eff} , and the ball-bat COR are measured at an impact location 29 in from the knob. Estimated uncertainties in the least significant digit are given in parentheses.

Bat	Weight	CM	I	m/M_{eff}	q	COR
Unmodified	30.6	23.5	11635	0.2269	0.214(2)	0.490(2)
Hollow	27.6	22.9	10044	0.2628	0.173(2)	0.481(2)
Corked	28.6	23.2	10659	0.2477	0.193(2)	0.488(2)
Control	31.1	23.6	12106	0.2181	0.227(1)	0.494(2)

clude that to within about 0.01 (or about 2%), the ball-bat COR is identical for all four bats listed in Table I, despite the fact that the spread in q values is considerably larger, of order 0.05 (or over 20%). The ball-bat COR values for the corked and unmodified bats are even closer in value and are statistically indistinguishable to better than 0.6%. By comparison, the ball-bat COR of a typical hollow aluminum bat exceeds that of a wood bat of comparable dimensions by at least 10%.¹ We conclude that there is no evidence for a trampoline effect in a corked bat.

We next investigate the tradeoff between higher swing speed and lower collision efficiency, utilizing the formalism described by Nathan.² The batted-ball speed v_{hit} may be found using

$$v_{\text{hit}} = qv_{\text{pitch}} + (1 + q)v_{\text{bat}}, \quad (2)$$

which relates v_{hit} to the pitch speed, the bat speed, and the collision efficiency q . Equation (2) is derived by transforming to the bat rest frame, applying the definition of q , and then transforming back to the original frame. To compare a corked and unmodified bat, we use the measured values of the collision efficiencies (see Table I), along with a typical pitch speed $v_{\text{pitch}} = 85$ mph and a prescription for bat speed²

$$v_{\text{bat}} = 70 \text{ mph} \left(\frac{I_0}{I_{\text{knob}}} \right)^n, \quad (3)$$

where I_{knob} is the moment of inertia of the bat about the knob and I_0 is a reference moment of inertia. The value of I_{knob} is determined from I , the location of the center-of-mass (see Table I), and the parallel axis theorem. We take I_0 to be the moment of inertia about the knob of the unmodified bat (19213 oz in.²). The exponent n , which characterizes how the bat speed depends on I_{knob} , is not known from first principles. However, as discussed by Adair,⁴ we can confidently set two extreme limits for n . A lower limit $n=0$ is realized when the batter swings the bat at the same speed, independent of I_{knob} , and the limit $n=0.5$ is realized when the kinetic energy imparted to the bat is independent of I_{knob} . Experimental data from baseball^{5–7} and slow-pitch softball⁸ are consistent with $n \approx 0.25$, or halfway between the limits. By utilizing Eqs. (2) and (3), we find that v_{hit} for the unmodified bat exceeds that of the corked bat for all values of n in the range between 0 and 0.5. For example, with $n=0.25$ corking would reduce v_{hit} by 1.5 mph. We conclude that there is no advantage to corking a bat if the goal is for v_{hit} to be as large as possible, as is the case for a home run hitter. Said a bit differently, a baseball cannot be hit farther by corking a bat. We actually draw the opposite conclusion, namely that corking almost always results in a lower v_{hit} and therefore a shorter fly ball distance. This type of analysis would make a good homework problem or classroom discussion exercise in an introductory physics course.

However, there are other reasons why a batter might choose to cork a bat. The smaller moment of inertia results not only in a higher bat speed but most likely in a higher bat acceleration. That is, in the parlance of baseball, the batter can “get around quicker,” allowing the batter to wait longer on the pitch as well as more easily adjust the swing after the swing has already begun. So, while corking may not allow a batter to hit the ball farther, it may well allow a batter to hit the ball solidly more often. In a recent study of bats used in NCAA baseball, Cross and Nathan⁹ show that batters tend to select bats with I that is less than optimum from the point of

view of maximizing v_{hit} , seeming to prefer frequency of good contact to higher maximum v_{hit} . Although the present study shows that corked bats do not result in longer home runs, it makes no statement about whether home runs might be hit more often with a corked bat.

IV. IS THE BASEBALL JUICED?

Is today’s baseball juiced? That is, is the baseball used in the game today more lively than the baseball of yesteryear? Or in more scientific language, is the COR of today’s baseballs larger than that of earlier eras? Regardless of which version of the question is posed, the underlying issue periodically arises in baseball, usually during times when there is a marked increase in the rate of home run production. The rules of Major League Baseball are not very discriminating regarding the COR. The rules specify that the COR of official baseballs must be in the range 0.514–0.578 when the ball is impacted on a flat plate at an incident speed of 58 mph. That range of acceptable values of $\pm 6\%$ leads to a significant difference in performance when extrapolated to the higher speeds that are relevant to the game. Our estimate is that such a range would amount to a spread of approximately 35 ft on the distance of a long fly, in agreement with an earlier estimate by Kagan.¹⁰

The issue of juiced baseballs attracted widespread attention during the early part of the 2000 Major League Baseball season. During April and May of that season, home runs were hit at a rate markedly higher than the rate over the same time period in the previous year. There was much speculation among baseball observers that the increase was due to the juicing of the ball. As a result, Major League Baseball commissioned a study by the Baseball Research Center at the University of Massachusetts at Lowell to compare the COR of baseballs from years 1998–2000. Although not published in the refereed literature, the report was widely disseminated.¹¹ Interestingly, the measurements done at 58 mph were clustered at the upper end of the range allowed by Major League Baseball. The principal conclusion of the study was that there were no significant performance difference among the three sets of baseballs. A subsequent study commissioned by the Cleveland Plain Dealer reached the same conclusion.¹² However, the Cleveland Plain Dealer study reported that the COR of present-day baseballs is significantly higher than the COR measured at the National Bureau of Standards in 1945.¹³ This conclusion was based on a comparison of the COR of 2000 balls at 89 mph (0.54, according to Ref. 12) to the value of 0.46 for 1938 balls from the NBS study, which was done at a slightly higher speed of 104 mph.¹⁴

The purpose of the present study is to compare the COR of baseballs from different eras at the highest practical speed. The main difficulty in any measurement of this type is finding a supply of unused baseballs from earlier years. Serendipitously we were able to find unopened boxes of baseballs from the late 1970s. These baseballs were provided to us by the family of Charlie Finley, then owner of the Oakland A’s, and were official American League baseballs bearing the facsimile signature of then American League President Lee MacPhail and manufactured by Rawlings. These facts constrain the baseballs to the period 1976–1980.¹⁵ The present-day baseballs were purchased directly from Rawlings in 2004, the year the measurements were performed. Interest-

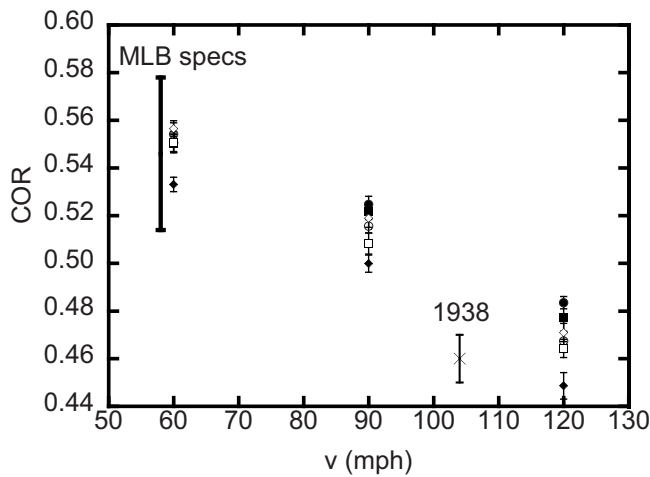


Fig. 2. Measured values of the COR versus the incident speed for three 1970s balls (closed symbols) and three 2004 balls (open symbols), with different plotting symbols corresponding to different balls. The vertical line at 58 mph is the range of COR specified by Major League Baseball. The x at 104 mph is the measurement of Briggs¹⁵ on 1938 baseballs.

ingly, the mean number of home runs per game was 1.4 and 2.1 in 1976–80 and 2000–2003, respectively.¹⁶

A. Experimental procedures

In the present study, baseballs were fired at speeds in the range 60–125 mph onto either a massive and rigid flat steel plate or onto a wooden bat. The same techniques described previously were used to extract the ball COR or the ball-bat COR. It was assumed that the ball COR is close to the peak ball-bat COR for which energy losses due to bat vibrations are minimal. The peak location was found in a supplemental experiment using a different set of baseballs to scan across the barrel of the bat. All baseballs used in this study were conditioned by storing them in a controlled 50% relative humidity environment for at least two weeks prior to the measurements.

The COR of three baseballs from each set was first measured by impacting the flat plate at incident speeds of 60, 90, and 120 mph. The results are presented in Fig. 2, where each point is an average of four impacts. Second, the COR of three additional balls from each set was measured in the same manner at the fixed incident speed of 120 mph, each ball being impacted four times. Third, the same balls tested in the second part were tested again by impacting a wood bat with a 125 mph initial speed.

B. Results and discussion

The primary conclusion evident from an inspection of Fig. 2 is that there is nothing in the current measurements to suggest any significant difference in the COR of the baseballs tested from the two different eras. Averaging the results from the ball-flat plate collisions (120 mph) yields nearly identical results for the two sets of balls, 0.470 ± 0.002 and 0.468 ± 0.002 . Similarly, averaging the ball-bat collision (125 mph) results yields 0.487 ± 0.002 and 0.491 ± 0.002 for the older and newer balls, respectively.

Some interesting secondary conclusions emerge from the data. From Fig. 2 we see that all baseballs fall within the rather broad range allowed by Major League Baseball at 60

mph. With one exception, the COR of the balls tested at 60 mph are within 0.01 of each other, a spread significantly smaller than the 0.064 range allowed by Major League Baseball. The spread in values approximately doubles at 120 mph, showing that baseballs performing identically at 60 mph do not necessarily do so at higher speeds. The data also confirm the result from the Cleveland Plain Dealer study regarding the comparison with the National Bureau of Standards measurement (see Fig. 2). If the present data are interpolated to find the expected result at 104 mph, that result is larger than the National Bureau of Standards result by about 0.03. We note that the ball-bat COR at 125 mph is slightly larger (0.49) than the ball-flat plate COR at 120 mph (0.47), despite the fact that the COR decreases with increasing velocity. This seemingly contradictory result is resolved when it is realized that in the ball-bat case the center-of-mass energy—the only energy available for deforming the ball—is 10% lower than in the ball-flat plate case.¹⁴

Although our principal finding is the lack of evidence that today's baseball is not more lively than that of an earlier time, we caution readers that this result applies only to the very small sample of balls that we tested. It is not possible to extrapolate this result to more general statements about the relative liveliness of baseballs without more extensive testing. Given the difficulty of obtaining older unused baseballs, we will likely never be able to make such statements.

V. WHAT'S THE DEAL WITH THE HUMIDOR?

Coors Field, home of the Colorado Rockies in mile-high Denver, is well-known to be a pitcher's nightmare and a batter's paradise. Because the air density in Denver is approximately 80% of that at sea level, fly balls carry farther and there is less movement on pitches, both of which contribute to an increase in a variety of offensive statistics. Starting in 2002 the Colorado Rockies began storing their baseballs in a humidor, which was kept at a constant 70 °F temperature and 50% relative humidity. Since that time, various offensive statistics have dropped, such as home runs or total runs per game.¹⁷ Hence, the question posed in the title to this section arises. Rephrasing the question more scientifically, is it plausible that the humidor accounts for the decrease in offensive statistics at Coors Field since 2002?

Two recent studies have addressed this question. Meyer and Bohn¹⁷ investigated the effect of the humidor on the aerodynamics of official Major League baseballs, specifically on the flight of a fly ball. Elevated humidity is expected to increase both the weight and the diameter of a baseball. The authors investigated these effects at relative humidity values of 33, 56, and 75%, and used their findings along with models for the drag and lift to calculate trajectories of batted and pitched baseballs. For batted balls, the expectation is that elevated humidity produces two partially compensating effects. An increased diameter results in a larger drag force while an increased weight results in a smaller drag acceleration. Their net result was an increase of 2 ft in the distance traveled by a fly ball on a typical home run trajectory when the relative humidity is changed from 30 to 50%. Not only is the effect too small to be significant, it goes in the wrong direction to account for the decrease in offensive statistics. For pitched balls, the same two effects result in slightly less movement on a pitched baseball for a given velocity and spin. However, the authors speculated that the ability of the pitcher to impart spin to the ball might be greatly improved

at the higher humidity, giving rise to more movement on the pitch. There is anecdotal information suggesting that balls stored at very low relative humidity tend to feel slippery to the pitcher, making it difficult to put spin on the ball.

Meyer and Bohn recognized that a much larger effect on fly ball distances comes from the change in the COR of the ball. This effect had been investigated by Kagan and Atkinson,¹⁸ who measured the COR of an NCAA-approved baseball at 61 mph over the range 0–100% in relative humidity. They found that the COR decreased by 0.054 over that range, from which they estimated a decrease in fly ball distance by about 6 ft between 30 and 50% relative humidity.

It is suspected that the COR increases with increasing temperature, leading to anecdotal reports of equipment managers manipulating the COR of baseballs by using “hotter” balls when their team is batting and “cooler” balls when the opposing team is batting. The only experimental data addressing this issue of which we are aware are those of Drane and Sherwood,¹⁹ who find that the flat-plate COR of a standard NCAA baseball measured at 60 mph increases from 0.524 to 0.548 when the temperature is increased from 25 to 120 °F. To our knowledge, there are no comparable data for a Major League baseball.

The present experiment seeks to extend the work of Kagan and Atkinson with higher precision measurements of the cylindrical COR of official Major League baseballs at more values of the relative humidity. In addition new data are presented on the temperature dependence of the cylindrical COR.

A. Experimental procedures

Eight groups of official Major League baseballs were given a controlled humidity exposure, after which their weight and cylindrical COR were measured. A relatively slow 60 mph incident speed was used for these measurements to minimize ball degradation during the study. Four dozen baseballs were placed in a 50% relative humidity conditioning environment for four months. The balls were then divided into eight groups of six baseballs and placed in separate conditioning chambers ranging from 11 to 97% relative humidity and at a fixed temperature of 72 °F for six weeks. The humidity was controlled by suspending the balls over saturated salt solutions in sealed containers. Humidity sensors were placed in half of the containers to verify the target humidity level was maintained throughout the study. A control group was left in the initial 50% relative humidity environment for the duration of the study. To determine when the balls had reached saturation, the weight of three baseballs (separate from the primary study) at 33 and 97% relative humidity was continuously monitored. The balls in the 33% relative humidity environment reached saturation in just over a week, while the balls at 97% relative humidity required upward of three weeks. The average weight for each group is shown in Fig. 3 as a function of the humidity level.

The error bars represent the standard deviation for each group. Meyer and Bohn¹⁷ reported a weight gain of 3.4% for Major League baseballs when the humidity was increased from 33 to 75%, in agreement with our measurement of 3.8%.

To study the effect of temperature on the cylindrical COR, the balls were conditioned at 50% relative humidity and 72 °F for 4 months, then heated or cooled for 24 h prior to testing. The cylindrical COR of the balls were then quickly

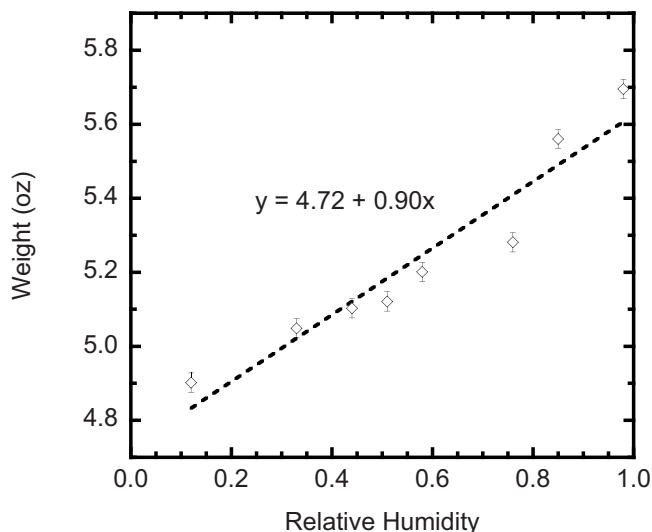


Fig. 3. Ball weight as a function of relative humidity, showing that the weight increases by 3.8%, as the relative humidity is increased from 0.33 to 0.75.

measured before any appreciable temperature change could occur. Because the oven and cooler used for the temperature tests were surrounded by air at 72 °F and 50% relative humidity and the temperature change was relatively brief, the moisture content of the balls was similar to their 50% relative humidity conditioned state.

B. Results and discussion

The cylindrical COR is shown as a function of humidity level and temperature in Fig. 4. We find that the slope of the cylindrical COR versus the relative humidity for Major League baseballs is -0.122 ± 0.010 , which is considerably

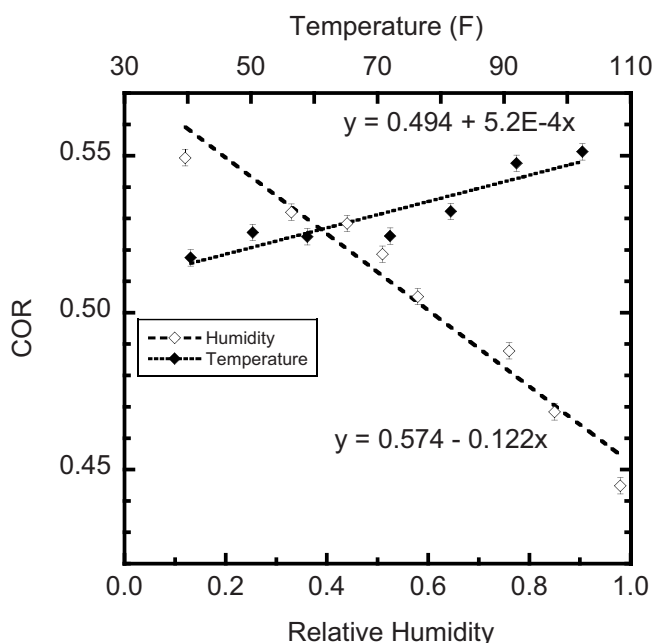


Fig. 4. Cylindrical COR as a function of relative humidity and temperature. These data show that the ball COR decreases by 4.5% when the relative humidity is increased from 0.3 to 0.5 and by 3.3% when the temperature is decreased from 70 to 35 °F.

larger than the flat-plate COR slope of -0.054 measured by Kagan and Atkinson¹⁸ for NCAA baseballs. The slope of the cylindrical COR versus temperature is $(5.2 \pm 1.0) \times 10^{-4} \text{ }^\circ\text{F}^{-1}$, which is about twice that measured for an NCAA baseball.¹⁹

In view of the large difference between the present measurement of the effect of relative humidity on the cylindrical COR for the Major League baseball and that found by Kagan for a NCAA baseball,¹⁸ it is worthwhile recalculating the effect of the humidior on a long fly ball. If the relative humidity is increased from 30 to 50%, the cylindrical COR decreases by 0.024, which is about 4.5%. We assume a similar decrease occurs at the higher speeds of the ball-bat impact. For a typical Major League bat, pitch speed, and bat speed, we estimate a decrease in batted-ball speed by about 2.5 mph, corresponding to a decrease in fly ball distance by about 14 ft. Adair estimated that each percent change in fly ball distance changes the probability of hitting a home run by about 7%.⁴ Taking 380 ft as a typical home run distance, a reduction of 14 ft corresponds to a reduction in home run probability by about 25%, a significant result and one that is not inconsistent with the numbers quoted by Meyer and Bohn.¹⁷ We conclude that it is plausible that the humidior can account for the decrease in offensive statistics at Coors Field since 2002.

A similar analysis can be done for the temperature dependence of the cylindrical COR. Balls stored at $70 \text{ }^\circ\text{F}$ have a larger cylindrical COR by 0.018 (or 3.3%) than those stored at $35 \text{ }^\circ\text{F}$. Assuming the same fractional change at higher speeds, a reduction of the temperature from 70 to $35 \text{ }^\circ\text{F}$ would lead to a decrease in fly ball distance by about 10 ft, corresponding to a decrease in home run production by about 19%.

VI. SUMMARY

We have addressed three questions at the intersection of baseball and physics. We have shown that there is no measurable trampoline effect with a corked bat and that it is unlikely that a batter can hit a baseball harder by using a corked bat. We have found no evidence that baseballs of today are more or less lively than baseballs used in the late 1970s. Finally, we have shown that storing baseballs in humidors at 50% relative humidity in Denver can lead to a marked reduction in home run production. A similar effect can be achieved by storing the baseballs at a temperature of $35 \text{ }^\circ\text{F}$.

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¹L. V. Smith, "Progress in measuring the performance of baseball and softball bats," *Sports Technology* **1**, 291–299 (2008).

²A. M. Nathan, "Characterizing the performance of baseball bats," *Am. J. Phys.* **71**, 134–143 (2003).

³A. M. Nathan, D. A. Russell, and L. V. Smith, "The physics of the trampoline effect in baseball and softball bats," *Engineering of Sport 5* (International Sports Engineering Association, Sheffield, England, 2004), Vol. 2, pp. 38–44.

⁴R. K. Adair, *The Physics of Baseball*, 3rd ed. (HarperCollins, New York, 2002), pp. 29–38, 97.

⁵R. M. Greenwald, L. H. Penna, and J. J. Crisco, "Differences in batted ball speed with wood and aluminum bats: A batting cage study," *J. Appl. Biomech.* **17**, 241–252 (2001), J. J. Crisco (private communication).

⁶G. S. Fleisig, N. Zheng, D. F. Stodden, and J. R. Andrews, "Relationship between bat mass properties and bat velocity," *Sports Eng.* **5**, 1–8 (2002).

⁷K. Koeing, N. Mitchell, T. Hannigan, and J. Clutter, "The influence of moment of inertia on baseball/softball bat swing speed," *Sports Engineering* **7**, 105–114 (2004).

⁸L. Smith, J. Broker, and A. Nathan, in *Sports Dynamics Discovery and Application*, edited by A. Subic, P. Trivailo, and F. Alam (RMIT University, Melbourne, Australia, 2003), pp. 12–17.

⁹R. Cross and A. M. Nathan, "Performance versus moment of inertia of sporting instruments," *Sports Technology* **2**, 7–15 (2009).

¹⁰D. T. Kagan, "The effects of coefficient of restitution variations on long fly balls," *Am. J. Phys.* **58**, 151–154 (1990).

¹¹The report from the University of Massachusetts at Lowell study is available at (go.illinois.edu/physicsbaseball/UML2000.pdf).

¹²The Cleveland Plain Dealer study was performed at the Lansmont Corporation's bat and ball testing facility. The results were published in the September 29, 2000 issue of the newspaper and is available online from their archives. A more technical report is available at (go.illinois.edu/physicsbaseball/ClevelandPlainDealerReport.pdf).

¹³L. J. Briggs, "Methods for measuring the coefficient of restitution and spin of a ball," *J. Research NBS* **34**, 1–23 (1945) The NBS study found that at about 100 mph, the COR of 1938 baseballs was 0.46 and those of 1943 baseballs was significantly lower at 0.40. The latter baseballs were almost certainly constructed from inferior wartime materials.

¹⁴L. V. Smith and A. M. Nathan, "A determination of the dynamic response of softballs," *Sports Eng.* **12**, 163–169 (2010) It is shown that the relevant quantity that determines the COR is the initial kinetic energy in the center-of-mass frame. The National Bureau of Standards studies¹³ were performed by projecting a 16 oz block of wood at 119 mph onto a stationary ball. Such an incident speed would have the same center-of-mass energy as a baseball projected at 104 mph onto an infinite mass.

¹⁵Rawlings became the official supplier of Major League baseballs starting in 1976. Finley owned the A's in 1960–1980. MacPhail was American League President in 1974–1984.

¹⁶P. Palmer and G. Gillette, *The Baseball Encyclopedia* (Barnes & Noble, New York, 2004), pp. 1552–1607.

¹⁷E. L. Meyer and J. L. Bohn, "Influence of a humidior on the aerodynamics of baseball," *Am. J. Phys.* **76**, 1015–1021 (2008) (See Table I for a comparative study of various statistics before and after implementation of the humidior.).

¹⁸D. T. Kagan and D. Atkinson, "The coefficient of restitution of baseballs as a function of relative humidity," *Phys. Teach.* **42**, 89–92 (2004).

¹⁹P. J. Drane and J. A. Sherwood, in *Engineering of Sport 5*, edited by M. Hubbard, R. D. Mehta, and J. M. Pallis (International Sports Engineering Association, Sheffield, England, 2004), Vol. 2, pp. 59–65.