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Progress in measuring the performance of baseball and softball bats

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The performance of baseball and softball bats has improved markedly over the past four decades. This has motivated many associations to develop test methods and measures to regulate bat performance. The present study reviews the progress of laboratory bat performance tests. The test involves an initially stationary bat that is allowed to recoil after being impacted by a ball. Bat performance was shown to be insensitive to changes in the way the bat was supported and sensitive to the rebound ball and bat speed. The rebound ball and bat speeds were in turn influenced by air turbulence and bat vibration, respectively. The common technique of normalizing the bat–ball coefficient of restitution (COR), by dividing it by the ball COR, was shown to overcorrect by more than the original effect of ball COR. Normalizing bat performance for the effect of ball weight, on the other hand, reduced its effect on bat performance. Measuring bat performance in the laboratory at impact speeds representative of play conditions had only a small effect on the relative performance between bats, but improved the correlation with field results. While laboratory bat performance tests are complex and experimentally challenging, they are robust and repeatable. © *2008 John Wiley and Sons Asia Pte Ltd*

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- softball
- baseball
- bats
- performance

1. INTRODUCTION

Technology has had a measurable impact on many sports improving player performance, endurance and safety. In the case of amateur baseball and softball modern bat design and materials have had a significant impact on the game. Non-metal bats are lighter and easier to swing than their wood predecessors. The benefit of lighter bats is particularly evident with young players. Learning the fundamentals of swinging is easier with a lower weight bat. Some are concerned, however, that hollow bats hit the ball faster than wood bats, changing the competitive balance of the game. Accordingly, nearly every baseball and softball regulating association controls bat performance in some way. In professional baseball the control is by material, where only solid wood bats are allowed. In softball and amateur baseball, bat performance is controlled through experimental testing. The following explores recent developments in measuring bat performance experimentally.

2. THE BALL

Bat performance is strongly dependent on the properties of the ball. The surface of the ball and even the number of stitches are controlled to ensure uniform flight characteristics. Weight and circumference affect the speed and distance of the ball and must be within specified limits. The coefficient of restitution (COR or e) is a measure of the dissipated energy from impact. Ball COR is regulated using a standard test method which has been developed for baseballs and softballs (ASTM F1887). The test involves firing the ball at 60 mph (26.8 m/s) at a flat rigid wall. The COR is found from the ratio of the rebound (v_r) and inbound (v_i) speeds as:

$$e_b = \frac{v_r}{v_i}. \tag{1}$$

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The COR of baseballs and softballs is approximately 0.50. Since the dissipated energy is $1-e^2$, baseballs and softballs lose approximately 75 per cent of their energy upon impact with a rigid wall. Modern bat evolution is largely driven by attempts to minimize the large energy loss of the ball.

Balls are also regulated by their stiffness. This is particularly true for softballs, which are made from a polyurethane core that can be formulated to provide a relatively wide range of COR and stiffness. The stiffness of baseballs and softballs is most commonly measured from a compressive force to displace the ball 0.25 inches (6.3 mm) between flat platens (ASTM F1888). In comparison to a bat impact, the displacement rate is relatively slow. A dynamic ball stiffness test has been proposed that measures ball stiffness during impact with a rigid cylinder. Dynamic stiffness has been shown to more accurately represent the ball's impact response with a bat than the quasistatic measure [1], but has not yet gained broad acceptance.

3. THE BAT

While the dependence of bat performance on the ball COR is straightforward, the effect of ball stiffness is more subtle [2]. The energy dissipated from colliding objects depends on its respective COR and deformation. A ball impacting a compliant elastic surface will deform less (and dissipate less energy) than a ball impacting a stiff surface. Bats are nearly elastic, dissipating comparatively little energy, particularly when impacted near their 'sweet spot'. Balls impacting hollow bats (with compliant barrels) dissipate less energy than balls impacting solid wood bats (with stiff barrels). The magnitude of this so-called 'trampoline effect' increases with the compliance of the barrel. Thus, the bat–ball COR depends on both the ball COR and ball stiffness. A 10 per cent change in ball COR or stiffness produced comparable ($\sim$1 per cent) change in hollow bat performance [3]. Since ball stiffness can differ by more than 100 per cent between models, while ball COR differs by only 10 per cent, the effect of ball and barrel stiffness can be a significant factor contributing to bat performance.

Bats are marketed by their weight and length. The structure of many hollow bats is sufficiently light, that weight is added to the bat. The so-called 'balance' of a bat is controlled by placing the weight in the knob or distal end of the bat. The weight distribution and length of a bat affect its mass moment of inertia (MOI or I). Although the MOI of a bat affects its swing speed more than weight, it is not commonly used in bat selection among players. Bat MOI has a measurable effect on bat performance and is commonly found from the period of oscillation (t) at about a point 6 inches (152 mm) from the knob as (ASTM F2398):

$$I = \frac{t^2 a W}{4\pi^2}, \tag{2}$$

where a is the distance from the pivot to the center of gravity, and W is the weight of the bat.

4. BAT SPEED

Laboratory measures of bat performance are of limited value without comparisons to field performance. Surprisingly, little data exist to compare laboratory and field measures of bat performance, however. While the motion of the bat during the swing is complex, only its speed just prior to contact with the ball is needed. (Shaft flex prior to impact and player grip during impact are negligible [4].) Since the bat–ball contact duration is short ($\sim$1 ms), its motion may be described by an instantaneous center of rotation over this period. Field studies have shown this instantaneous center to be close to the knob, near the batter's lower wrist [5,6].

Bat speed decreases with increasing MOI and has a large effect on the batted ball speed in play. Accordingly, an understanding of the effect of MOI on bat speed is needed. Unfortunately, the dependence of bat speed on MOI is nontrivial. Empirical studies have shown bat speed (v_b) to depend on MOI according to:

$$v_b = v_n \frac{q}{q_n} \left(\frac{I_n}{I}\right)^n, \tag{3}$$

where v_n and I_n are the nominal bat speed and MOI, respectively [6,7]. The impact location (q) is taken from the bat center of rotation. The nominal bat speed (v_n) is taken at q_n. The exponent n is approximately 0.25.

5. THE LABORATORY

A variety of methods have been employed to simulate a bat–ball impact in the laboratory. All use a bat pivoted at about a fixed point. The tests are designed to measure the maximum bat performance, which involves a colinear rebound (i.e. line drive). The devices may be described in three broad categories by the speed of the bat and ball before impact: (i) stationary bat–pitched ball; (ii) stationary ball–rotating bat; and (iii) pitched ball–rotating bat. While experimentally quite different, the methods are identical when viewed from a consistent frame of reference. The most complex device involves a pitched ball and rotating bat. To achieve the desired impact location, the bat and ball must be positioned precisely while traveling at a high speed and the timing of their motion must be carefully controlled. The National Collegiate Athletic Association (NCAA) used this type of device for nearly 5 years to certify baseball bats for collegiate play.

Some manufacturers test bats using a stationary ball and a rotating bat. The method presents experimental challenges for both the bat and the ball. The bat speed is increased to achieve a relative bat–ball speed that is comparable to play conditions. The greater bat speed often requires multiple bat rotations to avoid bat failure during acceleration before impact and deceleration after impact. Accordingly, delivery of the 'stationary' ball may need to be timed. In addition, the hit-ball speed (from the pitched ball or laboratory frame of reference) will be relatively high. This complicates ball capture and encourages ball damage, which could have an adverse effect on the results.

Currently, all associations that govern bat performance through laboratory testing use a pitched ball and stationary bat test. The ball speed is usually increased to achieve a bat–ball speed that is comparable to play conditions. Using an air cannon, it is easier to increase the ball speed than it is to increase the bat speed. Ball capture is also simplified with this method, since the hit-ball speed (from the bat or laboratory frame of reference) is relatively slow.

6. THE APPARATUS

A schematic of the bat test apparatus used herein is shown in Figure 1. Ball speed was controlled indirectly by the supply pressure through an electronic regulator. To help control speed and position, the ball traveled in a sabot, depicted in Figure 2. The sabot minimized ball wear and speed variation due to friction between the ball and barrel wall. It also allowed control of the ball surface impacting the bat.

An arresting plate at the end of the barrel stopped the sabot while allowing the ball to pass unimpeded. The arresting plate was padded and recoiled to minimize the impact forces to the sabot. The design of the sabot must balance the need for reduced weight (to allow rapid acceleration) with strength (to withstand the impact forces from contacting the arresting plate). The spokes of the sabot were shaped to place the ball in a repeatable location at the center of the barrel.

After the ball exits the air cannon, it passes through light screens which measure its inbound speed. The bat pivot is positioned along two axes to achieve the prescribed impact location along its length and a colinear (line drive) rebound. From the conservation of angular momentum about the pivot, we obtain:

$$r(v_i - v_r) = V_r, \tag{4}$$

where V_r is the bat rebound speed at the impact location:

$$r = \frac{mq^2}{I}, \tag{5}$$

and m is the ball mass. Accordingly, the bat–ball test involves measuring five parameters: the ball mass, bat MOI, inbound and rebound ball speed, and the recoiling bat speed. Ball mass and bat MOI are readily measured to a greater accuracy than ball or bat speed. Since angular momentum about the pivot point of the ball–bat system is conserved during the impact, two speeds are typically measured, and Equation 4 is used to determine the third. The preferred approach is to measure the rebound ball speed as it passes back through the light screens after impact. Since the ratio of the ball speeds is used to describe performance, errors in the light screen spacing cancel. In some cases, the rebound ball speed is too slow to pass through the light screens, necessitating a bat-speed measurement. In cases where a ball rebound speed can be measured, the bat speed provides a redundant measure to check for experimental errors.

The procedure for testing a bat first involves careful selection of the test balls. They are typically selected to have similar weight, stiffness, and COR. The bat is impacted at discrete locations until a location with maximum performance is found. The performance at each location is the average from six impacts, and the impact locations are typically spaced 0.50 inches (13 mm) apart. A representative performance curve is shown in Figure 3. The error bars represent the standard deviation of the mean at each location. With an appropriate environmental control and ball selection, the performance results are typically repeatable within the laboratory and reproducible between laboratories to within 1 per cent.

7. BAT PERFORMANCE METRICS

The foregoing has described how a bat may be tested in a laboratory environment. Equally important is determining how the data from the test may be used to quantify and compare performance. This topic has been addressed in detail elsewhere [8], and will be briefly reviewed here for completeness. The COR of two impacting bodies is the ratio of their speed after impact to before impact. For a bat–ball impact, this may be described as:

$$e_{bb} = \frac{V_r - v_r}{v_i - V_i}, \tag{6}$$

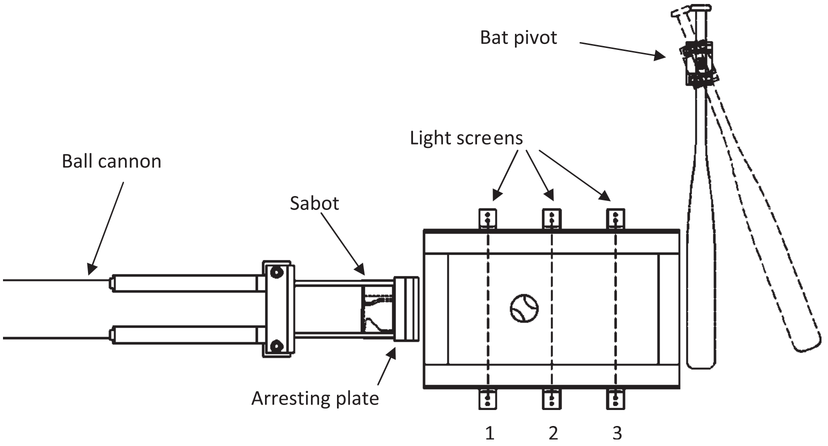

Figure 1. Scheme of bat test apparatus.

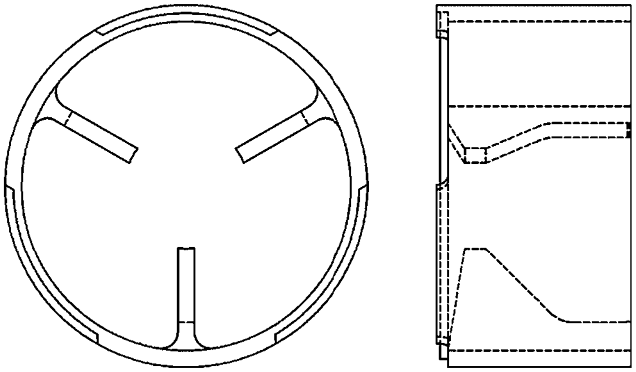

Figure 2. Scheme of ball sabot.

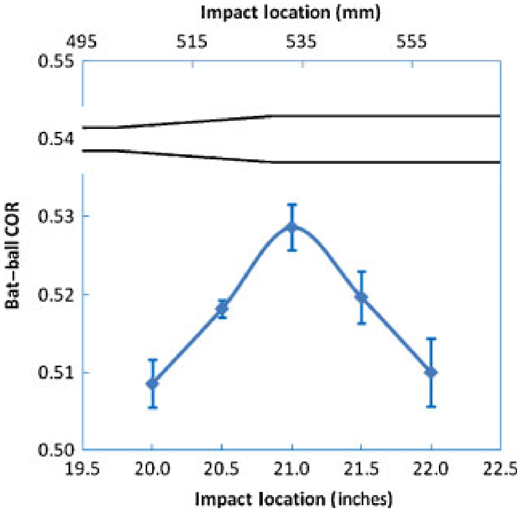

Figure 3. Representative bat performance curve. COR, coefficient of restitution,

where e_{bb} is the bat–ball COR, v and V are the ball and bat speeds at the impact location, respectively, and the subscripts i and r refer to inbound and rebound, respectively.

The speed of a ball hit by a bat in play (v_h) may be found from [8]:

$$v_h = e_a v_p + (1 + e_a) V_b, \tag{7}$$

where v_p and V_b are the pitch and bat speeds of interest on the field, respectively, and e_a is the so-called collision efficiency. The collision efficiency may be found from the bat–ball COR as:

$$e_a = \frac{e_{bb} - r}{1 + r}. \tag{8}$$

More conveniently e_a may be found from the ball inbound and rebound speeds from an initially stationary laboratory bat test as:

$$e_a = \frac{v_r}{v_i}. \tag{9}$$

The measures used to quantify bat performance (e_{bb}, v_h and e_a) may be distinguished by the effect of changing the bat's MOI. The bat–ball COR is independent of MOI for a given bat model [9], while e_a and v_h have a non-linear dependence. Bat speed will increase with decreasing MOI. Consider a player who swings a high MOI bat and an otherwise identical bat with low MOI. It is not obvious if the angular momentum (and in turn v_h) of the low MOI bat will be higher due to a faster swing speed or lower due to its reduced MOI. The competition between swing speed and angular momentum has been considered in field studies [6], where angular momentum had a slightly larger effect than swing speed. The effect of MOI on v_h is determined by the empirical exponent (n) in Equation 3. Thus, to achieve higher v_h, a batter should select a high MOI bat. The ideal bat MOI is limited by the ability of a player to make contact with the ball.

The collision efficiency is related to the bat–ball COR through Equations 5 and 8, so that e_a increases as the bat MOI increases. Thus, two bats with the same collision efficiency will only have the same field performance if their MOI is also the same. In other words, if two bats have the same collision efficiency but differ in MOI, the bat with the lower MOI will have the higher field performance.

8. NORMALIZATION

The balls used to test bats are not identical, but differ in weight, COR, and stiffness. Normalizing the variation in these properties can improve bat performance accuracy. A method commonly used to normalize for ball COR is termed the 'bat performance factor' (ASTM F1890) or k_F, defined as:

$$k_F = \frac{e_{bb}}{e}. \tag{10}$$

To consider the effect of COR normalization, three balls of varying COR were used to test four bats of varying performance. The balls and bats are described in Tables 1 and 2, respectively. The bat–ball COR from each of the bats is shown in Figure 4. Bat performance generally increased with the bat–ball COR. A notable exception occurred with the two highest performing bats (C and D) with the 0.41 COR ball. The dynamic stiffness of this ball was 20 per cent higher than the other balls, which enhanced the trampoline effect for this case. The effect of the stiffer 0.41 COR ball is not apparent for bats A or B. The low performance of bats A and B was due to a stiffer barrel with a diminished trampoline effect.

The bat performance factor is also included in Figure 4. While the normalizing method worked well for the wood bat (A), it overcorrected more than the effect of ball COR for the high performing bats (C and D). This is a serious shortcoming of the bat performance factor, since the highest performing bats are generally of most interest. The difficulty of the bat performance factor to normalize for ball COR is likely related to the interdependence of the bat–ball COR with the bat and ball stiffness [10].

The effect of the variation in test ball weight can be normalized though Equation 8 by using a constant nominal ball weight in Equation 5. The four bats in Table 2 were tested using balls of varying weight in Table 1. The collision

Table 1. Ball properties used to measure bat performance.

Group	COR	Weight (oz)/(g)	Static stiffness (lb/inches)/(kN/mm)	Dynamic stiffness (lb/in)/(kN/mm)
Weight	0.462	6.44/183	1808/317	6545/1149
Weight	0.468	6.79/193	1820/319	6808/1195
Weight	0.449	7.06/200	1792/314	7257/1274
COR	0.411	6.73/191	1864/327	7342/1289
COR	0.459	6.73/191	1828/321	6029/1058
COR	0.509	6.74/192	1872/329	5979/1050

COR, coefficient of restitution.

Table 2. Mass properties of bats.

Bat	Material	Weight (oz)/(g)	MOI (oz in^2)/(kg m^2)	Length (in)/(mm)
A	Wood	32.63/927	10623/0.195	34.19/868
B	Aluminum	35.69/1014	10401/0.191	33.88/860
C	Composite	26.50/753	7897/0.145	34.06/865
D	Composite	30.64/870	9036/0.166	34.00/864

MOI, mass moment of inertia.

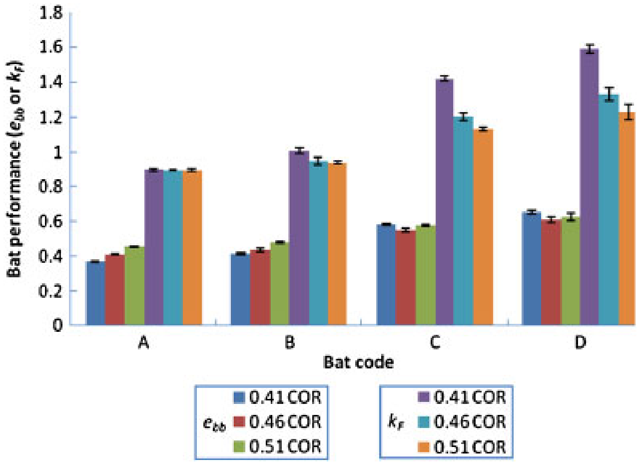

Figure 4. Effect of ball coefficient of restitution (COR) on bat performance. e_{bb}, bat–ball COR; k_f, bat performance factor.

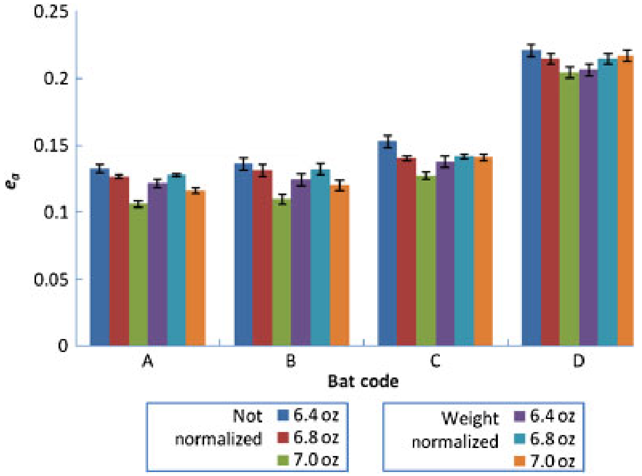

Figure 5. Effect of ball weight on bat performance. e_a, collision efficiency.

efficiency is shown in Figure 5, which without normalization, decreased with increasing ball weight. The effect of ball weight was reduced in the normalized results, which tended to magnify other features of the balls. In contrast to the k_F, the differences in the weight normalized results are consistent with the properties of the test balls. Since the 6.8 oz ball had the highest COR, the normalized performance of the low performance bats (A and B) had the highest performance with this ball. Since the 7.0 oz ball had the highest dynamic stiffness, the highest performing bat (D) had the highest normalized per formance with this ball.

9. MEASURING BALL SPEED

Ball speed was found from the time for a ball to pass through successive light screens, spaced at a known distance. The accuracy of the measurements is influenced by the error in the screen spacing, the repeatability of the light screens, and the circuit used to time the screen signals. Redundant speed measurements from bat tests provide a means of evaluating the ball speed measurements. In the following, the screens were kept stationary so the reported variation is not due to changes in screen spacing.

Softballs were fired though three light screens spaced 6 inches (152 mm) apart (Figure 1). The balls were fired at 110 mph (49.2 m/s) ,500 times from which two speed measurements were taken (screen 1 to 2 and screen 2 to 3). The data used to evaluate the light screens were taken from bat tests, which involved a ball rebound speed on the order of 10 mph (4.5 m/s). The change in ball speed between the screens was consistent with drag effects at the inbound and rebound speeds. The change in ball speed over the short distance between the screens was small, but nearly double the expected amount [11]. Air friction with the walls of the duct, through which the ball traveled as the screens measured speed, likely contributed to the increased drag.

The correlation of the redundant ball speeds was nearly unity, so they were compared by examining the coefficient of variation (COV) of their difference. The inbound COV was 0.05 per cent, which was considerably higher than the 0.007 per cent repeatability of the screens at this speed. The effect of drag between the screens was on the order of 0.2 per cent. Turbulent airflow from the ball likely caused non-uniform drag, contributing to the variation.

At the lower rebound speed, the COV of the speed difference was 1.5 per cent. The higher variation is not due to the light screens, since their repeatability improves at lower speeds. Turbulent airflow likely plays a role here as well, since the rebounding ball is traveling through the turbulent flow created by the incoming ball. Thus, when evaluating the effect of ball speed accuracy on laboratory bat performance, airflow effects should be considered.

10. MEASURING BAT SPEED

In cases where the ball does not rebound through the light screens, the bat speed must be measured. Some test methods find bat speed from the time required for the bat to rotate through discrete locations (ASTM F1890). Since the bat tends to vibrate as it rotates, the time between the discrete locations is sensitive to the vibration of the bat. An improved bat speed has been obtained by recording its location continuously after impact using an optical encoder, as shown in Figure 6. Bat speed may be found from the slope of the bat angle versus time over a suitable range (5 to 95 degrees). The collision efficiency of 30 bats was found from the rebound ball speed (Equation 9), and compared to the collision efficiency from the bat speed (Equations 4–6,8), using the optical encoder, as shown in Figure 7. Given the complexities involved in the test, the comparison is remarkable where the two measures of e_a had a correlation coefficient of 0.984.

The collision efficiency was also found from the ball inbound and bat rebound speeds (Equations 5,6,8) and compared to the ball rebound collision efficiency in Figure 7, where the correlation coefficient improved to 0.999. For most bats, $r \approx 0.3$. When Equation 4 is solved for v_r, V_r is divided by r, which tends to magnify experimental error. Solving Equation 4 for V_r, v_i and v_r are multiplied by r, which tends to reduce the effect of experimental error. The problem of magnified experimental error is compounded if bat speed is measured from discrete locations. The correlation coefficient between the collision efficiency from the ball rebound speed and bat speed using discrete bat locations was 0.635.

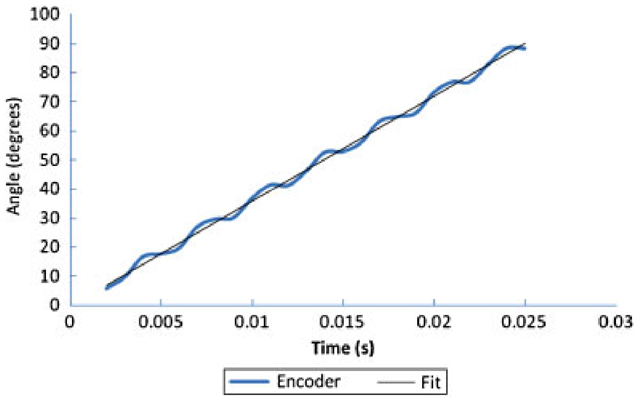

Figure 6. Bat angle as a function of time after impact.

11. EFFECT OF MEASUREMENT ERROR ON BAT PERFORMANCE

While the positive correlation of the collision efficiency between the bat and ball rebound speed in Figure 7 is encouraging, it is helpful to consider the effect of measurement errors on bat performance. The following considers errors in the five measured parameters used in Equation 4. Accordingly, a representative error, with a normal distribution for each measure, was applied. The COV from the light screen study were used for v_i and v_r (0.05 and 2 per cent, respectively). The COV for ball mass, MOI, and impact location (0.4, 0.2, and 0.15 per cent, respectively) were taken from the calibrations of these measures.

The errors in bat speed were primarily due to a non-integer number of oscillations and their magnitude over the period that the bat speed measured. Bats impacted near their sweet spot typically have a vibrational amplitude less than two degrees. Consider a bat with a swing speed of 2000 /s, a vibrational amplitude of two degrees, and a frequency that varies from 120 to 200 Hz (a common range for bats). Fitting the slope of the oscillating bat (Figure 6) provides an estimate of the bat-speed error, which for the range of frequencies considered had a COV of 4 per cent. A Monte Carlo simulation was conducted to reproduce Figure 7 in concert with the errors above. The correlation of e_a between the bat and ball rebound speeds from the Monte-Carlo simulation agreed with Figure 7. Thus, for the apparatus used here, errors in the five parameters in Equation 4 should be within the bounds outlined earlier.

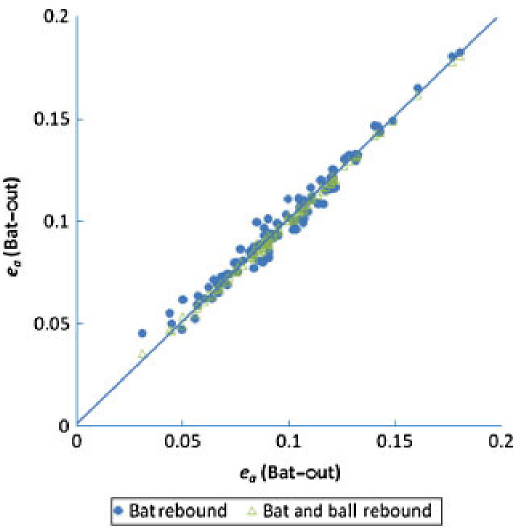

Figure 7. Comparison of the collision efficiency (e_a) found from the ball rebound speed to the collision efficiency found from the bat rebound speed and the bat and ball rebound speed.

The performance (e_{bb}, e_a, and v_h) of a representative softball bat ($I = 9500$ oz in$^2 = 0.174$ kg m^2, $v_i = 110$ mph $= 49$ m/s, $v_r = 18$ mph $= 8$ m/s, $m = 7$ oz $= 200$ g, and $q = 21$ in $= 533$ mm) was computed. The performance was again computed by adding one standard deviation to each of the measures in Equation 4. The percentage of change in performance for each measure is reported in Figure 8 for the cases of measuring the ball rebound speed, the bat rebound speed, and the ball and bat rebound speed. Errors in ball weight were observed to have the smallest effect, while errors in the rebound speed (ball or bat) had the largest effect. Of the three performance measures, e_a was the most sensitive to experimental errors, while v_h was the least sensitive. Measuring the bat rebound speed was most sensitive to errors, while measuring the ball rebound speed was the least sensitive. Note that a positive error in the measurement can produce a positive or negative change in performance.

12. THE BAT–BALL COR

The results of two field studies were used to evaluate the laboratory performance test. The field studies were conducted on outdoor regulation fields and involved 16 men (slow pitch) and 33 women (fast pitch) players [6]. Ball and bat motion were recorded using high-speed video. An aim of both field studies was to determine the effect of bat MOI on swing speed. Accordingly, bats of the same design or shell were selected with similar weight and varying MOI. The field hit-ball speeds are the average from all players from each field study, taken from the top 50 per cent for each player–bat combination, as shown in Figure 9.

The performance of sister bats to those used in the field study was measured in the laboratory. The laboratory bat performance results were evaluated using Equation 7 to provide direct comparison with the field hit-ball speeds. A pitch speed (25 mph and 60 mph (11.1 and 26.8 m/s) for the slow and fast pitch, respectively) and nominal bat speed (85 mph and 60 mph (38 and 26.8 m/s) for the slow and fast pitch, respectively) from the field studies were used in Equation 6. The bat speed was found from Equation 3 with $q_n = 22$ inches (559 mm). The nominal bat MOI was 8000 and 9000 oz in^2 (0.147 and 0.165 kg m^2 and measured about the pivot) for the fast and slow pitch studies, respectively.

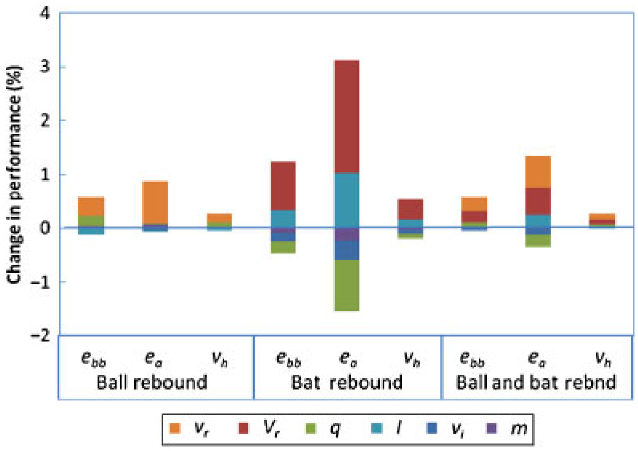

Figure 8. Effect of test measurement error on bat performance (e_{bb}, e_a, v_h) for tests where either the ball rebound speed, bat rebound speed, or ball and bat rebound speeds were measured. e_a, collision efficiency; e_{bb}, bat–ball coefficient of restitution; I, mass moment of inertia; m, ball mass; q, impact location; v_h, speed of a ball hit by a bat in play; v_i, incoming ball speed; v_r ball rebound speed.

The field and laboratory results are compared in Figure 9 and are in good agreement. Laboratory tests can better achieve collinear ball rebounds than field conditions, which result in a higher collision efficiency. Thus, the laboratory results represent the upper bound that would occur in play. The comparison demonstrates the ability of laboratory tests and field studies to identify even subtle effects, such as MOI, on bat performance.

For a given bat design, the bat–ball COR is typically assumed to be constant [9]. The effect of weight on bat performance occurs through Equations 3, 5, 7, and 8. The bats in each field study differed only in their weight distribution, which allowed the effect of MOI on the bat–ball COR to be considered. The fast- and slow-pitch bats had an average bat–ball COR of 0.475 and 0.464, respectively. The lines in Figure 9 were found from Equations 7 and 8 using the average bat–ball COR from each field study to obtain the collision efficiency. The effect of MOI was included through Equation 5. The agreement between Equation 7 and the field data demonstrates the independence of the bat–ball COR to bat weight (for a given bat design).

13. THE BAT PIVOT

All standardized tests pivot the bat about a point 6 inches (152 mm) from the knob. The selection of the pivot location was made before empirical evidence showed it to be near the knob (instantaneous center, just prior to impact). It is believed that the bat–ball contact duration is sufficiently short (~ 1 ms) that the location of the laboratory bat pivot does not affect the measured performance. Apparently, during the bat–ball

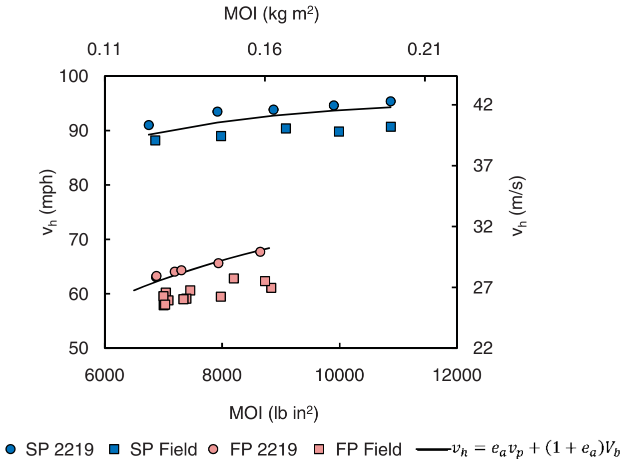

Figure 9. Comparison of field and laboratory bat performance of women's fast pitch and men's slow pitch players. MOI, mass moment of inertia; v_h, speed of ball hit by a bat in play.

contact, the bat is sufficiently compliant and bat flexure is sufficiently small that the pivot constraint does not affect the impact conditions at the barrel [4,12].

Since the bat–ball COR has been shown to be independent of bat MOI, it may be used to consider the constraint of the pivot. This was done by placing a weight at discrete locations along the length of the bat and calculating the peak bat–ball COR at each location [13]. The bat–ball COR was found by solving Equation 8 for e_{bb}, where e_a was found from Equation 9. The weight was adjusted at each location to increase the bat MOI by a uniform 10 per cent. The bat–ball COR is shown as a function of weight location in Figure 10. The solid line represents the initial bat–ball COR before weight was added. For weight locations greater than 12 inches (305 mm) from the pivot, the bat–ball COR was relatively constant and close to the unweighted bat. For weight locations closer to the pivot, however, the bat–ball COR was observed to decline measurably. The bat–ball COR was recalculated using the MOI of the unweighted bat in Equation 5. As shown in Figure 10, the bat–ball COR found with the original MOI returned to the value of the unweighted bat. Thus, weight added inside of 12 inches (305 mm) from the pivot did not affect the bat–ball collision. Similarly, the type of constraint or weight of the pivot (near the knob) should not affect bat performance.

14. TEST SPEED

Since the bat–ball impact is non-linear, laboratory tests have been designed to replicate impact forces and displacements occurring in play. Consider, for instance, a performance test in which a baseball is dropped from a relatively low height onto a solid wood bat and a hollow metal bat. Under this relatively low impact force, the barrel deformation and performance of the two bats would be similar.

While the aim of many bat and ball tests is to replicate play speeds, the effect of speed on bat performance is rarely considered. As shown in Figure 11, three bats of varying performance were tested at three speeds. Bat performance decreased with increasing test speed, since the ball deforms more and dissipates more energy at higher speeds. The relative performance of the bats was surprisingly similar, however, given the experimental effort needed to achieve test speeds representative of play. The primary advantage of testing at play speeds is apparently to provide a v_h representative of play (Figure 9).

The effect of test speed on bat performance diminished as the bat performance increased (i.e. the lines of Figure 11 are not parallel). This is another example of the trampoline effect. The lowest performing bat has the stiffest barrel, and is thus more dependent on speed-related changes in the energy dissipated by the ball.

15. SUMMARY

Significant effort and progress have been made in measuring the performance of baseball and softball bats. The most widely used test involving an initially stationary bat and a pitched ball is experimentally more expeditious that other methods and less likely to damage the ball. Bat performance found from the rebound ball speed was shown to be less sensitive to experimental errors than from the bat rebound speed. Bat performance obtained from the rebound ball or bat speed agreed when the bat speed was taken from a continuous rather than a discrete angular measurement. Of the three commonly used bat performance measures, v_h was the least sensitive and e_a was the most sensitive to experimental errors. The common practice of normalizing bat performance by dividing the bat–ball COR by the ball COR was shown to overcorrect by more than the effect of the ball COR, while normalizing for ball weight reduced its effect on bat performance. Ball speed measurements were shown to be sensitive to air turbulence effects inherent with high ball speeds and a primary contribution to variations in laboratory bat performance. The laboratory test speed was shown to have a measurable effect on the magnitude of the measured bat performance, but only a small effect on the relative bat performance. In spite of the noted sensitivities to experimental errors, bat performance measures have remarkable repeatability and reproducibility, which is generally within 1 per cent.

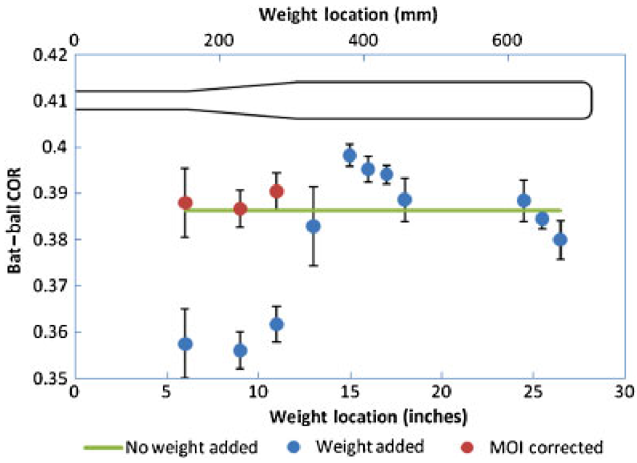

Figure 10. Bat–ball coefficient of restitution (COR) as a function of added weight location, relative to the pivot point.

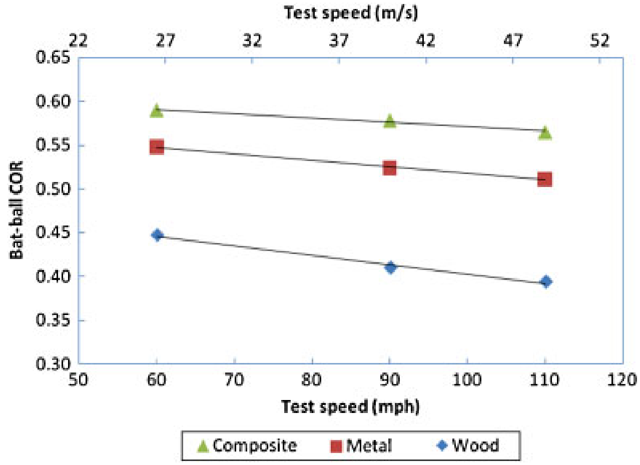

Figure 11. Effect of laboratory test speed on bat performance.

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