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Batting Cage Performance of Wood and Non-Wood Youth Baseball Bats

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Abstract

The purpose of this study was to examine the batting cage performance of wood and non-wood baseball bats used at the youth level. Three wood and ten non-wood bats were swung by 22 male players (13-18 yr.) in a batting cage equipped with a 3-D motion capture (300 Hz) system. Batted ball speeds were compared using a one-way ANOVA and bat swing speeds were analyzed as a function of bat moment of inertia by linear regression. Batted ball speeds were significantly faster for three non-wood bat models (p < 0.001), significantly slower for one non-wood model, and not different for six non-wood bats when compared with wood bats. Bat impact speed significantly (p < 0.05) decreased with increasing bat moment of inertia for the 13, 14, and 15 yr. age groups, but not for the other age groups. Ball-bat coefficient of restitution (BBCOR) for all non-wood were greater than wood but this factor alone did not correlate with bat performance. Our findings indicate that increases in BBCOR and swing speed were not associated with faster batted ball speeds for the bats studied whose moment of inertia was substantially less than that of a wood bat of similar length.

Key Words: Baseball, bat, wood, performance

Word Counts: Abstract = 200, Manuscript = 4,377
Introduction

Since the first non-wood bats were introduced to baseball in the early 1970s as an inexpensive and durable approach to address the cost and fragility of wood bats, there have been concerns with the effects of increased bat performance on safety and the balance between offense and defense. To address these concerns, governing bodies such as the National Collegiate Athletic Association (NCAA) and the National Federation of State High School Associations (NFHS) have a bat certification process that requires standardized laboratory testing. Standardized laboratory testing of baseball bats consists of measuring several physical properties, including weight, length, and the ball-bat coefficient of restitution (BBCOR). BBCOR is defined as the ratio of the relative ball–bat velocity after the collision to that before the collision and it is used to quantify what is commonly referred to as the “trampoline effect”. The trampoline effect is commonly used to describe the effectiveness of the bat-ball energy transfer, using a solid wood bat as the baseline. Therefore, if the BBCOR of a given bat is greater than the BBCOR of a solid wood bat, it is said to exhibit the trampoline effect, and will theoretically produce higher batted ball speed, if all other factors are equal.

In addition to BBCOR, other factors that determine the speed of the batted ball include the swing speed just prior to ball impact, the location of the ball impact on the bat, and the weight and moment of inertia (MOI) of the bat. Interestingly, these factors are not necessarily independent. Increases in swing speed have been found to be more closely related to MOI about the knob of the bat than to weight and has been attributed to increases in performance when compared to wooden bats. Decreases in bat MOI are also associated with higher BBCOR values because thinner barrel walls can result in less deformation of the ball, the greatest source of energy loss in the ball-bat collision. Composite materials provide manufacturers with even
more control over the design of a bat’s properties, allowing composite bats to have a low barrel stiffness (and possibly higher BBCOR values) and high flexural stiffness, which may play a role in further increasing bat performance. At the collegiate and high school levels, MOI and “weight drop” (bat length in inches minus bat weight in oz.) are tightly regulated, and therefore BBCOR becomes the primary factor affecting bat performance. Presently, the collegiate and high school rules require the weight drop to be no less than -3, but a bat with a drop of -3 is generally considered too heavy to be swung well by youth players. Many youth governing bodies do not regulate the weight drop and MOI with the intent that lighter bats (e.g. with weight drops of -12) are easier to swing by youth players and thus provide greater participation in play. With so little momentum to transfer to the ball, the batting performance of these substantially lighter bats is postulated to be adversely affected, regardless of their BBCOR value. These complex relationships between BBCOR, MOI and bat performance at the youth level have not been previously reported in an experimental setting.

The aim of this study was to determine the batting cage performance of wood and non-wood baseball bats at the youth level among various age groups. Specifically, we sought to test the hypothesis that the performance of non-wood bats was greater than wood bats. We quantified bat performance by batted ball speeds, and analyzed batted ball speeds as a function of bat model and player age. We note that batted ball speeds can be highly dependent on the cohort of players studied, so in order to provide a more specific measure of bat performance we utilized our previously established approach that computes ideal batted ball speeds by taking into account the swing speed of the bat and the impact location of the ball on the bat. We also examined the ability of lab measurements of BBCOR to predict the measured batted ball speeds.
Methods

Twenty two (n = 22) right-handed male players (mean age: 16, range 13-18) representing two different skill levels (little league and high school) participated in a batting cage study after IRB approval and informed written consent/assent were obtained. Thirteen bat models from six different manufacturers were used in this study (Table 1). The non-wood bats are used in league play that presently do not regulate bat specifications. Five bats of each model were prepared for testing by applying square markers (13 mm × 13 mm (0.5 in × 0.5 in)) of retro-reflective tape (3M Scotchlite High Gain Reflective Sheeting 7610) along the length of the bat. Four markers were evenly-spaced circumferentially at approximately 0, 9, 28, 38 and 76 cm (0, 3.5, 11, 15, and 30 inches) from the tip. Baseballs (R100, Rawlings, St. Louis, MO, n = 300) were prepared with six uniformly arranged square retro-reflective markers (13 mm × 13 mm (0.5 in × 0.5 in)).

Testing was held indoors in the Brown University Athletic Center (Providence, RI) over a two-day session. A portable batting cage was assembled (15.2 m × 3.0 m × 4.3 m (50 ft × 10 ft × 14 ft)) on the gymnasium floor. The pitching machine (Iron Mike MP5, Master Pitching Machine Kansas City, MO) was positioned within the cage 12.2 m (40 ft) from the hitter. Balls were pitched at a speed comfortable to the hitter (range 21.5 – 26 m/s (48-58 mph)) to maximize the number of hits. Players participated in multiple batting sessions consisting of approximately twenty-five pitches with a single bat. The order of bat models swung by players was selected randomly. Not all bat models were swung by all players.

Data Collection and Analysis

The pitched ball, batted ball and bat swing were tracked at 300 Hz using an eight-camera Oqus 5-series infrared sensing system (Qualisys, Gothenburg, Sweden). The cameras were mounted on tripods approximately 2.4 m (8 ft) high and positioned behind and to the right side of
the batter. Pitched and batted balls were tracked within 3 m (6 ft) of the front of home plate. The system was recalibrated following every 100 pitches, resulting in calibration tolerances less than 0.7 mm. Ball and bat markers were identified within Qualisys Track Manager and exported to Matlab (Mathworks Inc., Natick MA) for subsequent analysis.

Ball and bat positions and velocities were calculated using previously developed algorithms. Briefly, pitched and batted ball velocity were determined component-wise by a linear least-squares fit to the 3-D ball coordinates as a function of time. Batted ball speed (BBS) was computed as the magnitude of the batted ball velocity. Ball speed error was defined as the standard error of these linear fits and had a mean value of 0.6 m/s (1.3 mph) for the hits analyzed. Bat position was determined by fitting a least-squares 3-D vector to the bat markers at each time point. This approach does not permit the tracking of the rotations of the bat about its long axis.

The impact location of the ball on the bat was determined by intersecting the incoming pitch vector with the bat vector at the impact frame. The variation in computing impact location was defined as the orthogonal distance between the bat vector and the pitch vector and had a mean value of 0.02 m (0.78 in) for the hits analyzed. The sweet spot for each bat was defined as the average impact location of the top 10% batted ball speeds.

Bat swing speed was computed as the speed of the bat at the impact location. The impact location was tracked from the impact frame backwards to the frame at which the bat speed first exceeded 8.9 m/s (20 mph). The 3D path of the impact location was fit with a second-order polynomial, and then differentiated to obtain the bat swing speed at the instant of impact. As an estimate of error in bat swing speed, we computed bat speed one frame prior to, and one frame
after, the selected impact frame. The mean difference in these speeds was 1.3 m/s (2.8 mph) for the hits analyzed.

The angular swing speed of the bat was computed as the time derivative of the helical rotation \(^8\) (also referred to as the screw rotation) for the two frames prior to ball impact. To examine the validity of this calculation of angular swing speed, bat swing speed was recomputed as the product of angular swing speed and the distance from the impact location to the closest point on the helical axis. A linear regression analysis compared these two, independent bat swing speed calculations. The regression line had an \(R^2\) and slope of 0.94 and 0.9 \(\pm\) 0.005 respectively.

Ideal batted ball speed (BBS) is defined as the maximum possible batted ball speed at a given bat swing speed and was computed in three steps for each bat model at a selected bat swing speed of 24.6 m/s (55 mph). First, the 98\(^{th}\) percentile value of the batted ball speeds were computed for each bat swing speed bin of 0.22 m/s (0.5 mph). Then, a linear regression was performed on these 98\(^{th}\) percentile batted ball speed values as a function of bat swing speed. Finally, at the specified bat swing speed of 24.6 m/s (55 mph) the regressed batted ball speed was computed along with its 95% confidence interval.

**BBCOR, MOI and \(vf\)**

For each bat model, the laboratory BBCOR value was measured using the standardized ball velocity of 51.4 m/s (115 mph) and impact location of 0.13 m (5 in.) for the certification of baseball bats by sports governing bodies\(^9,10\). Moment of inertia of the bat was measured using standard laboratory procedures\(^11\) and then computed about the knob (MOI). Using equations derived by Nathan et al.\(^3\), we computed the predicted batted ball speed (\(vf\)) for each bat using its measured BBCOR and MOI, a baseball pitched at 23.7 m/s (53 mph), an impact location at 12.7
cm (5 in.) from the tip, and a bat swing speed of 24.6 m/s (55 mph). These values were chosen as representative values of our dataset.

**Number of Hits Analyzed**

A total of 1,638 hits were analyzed from 3,405 pitches. All hits that were visually noted as clearly being foul tips were excluded from the analysis. Not all players successfully hit with all bat models (Table 2) and there was a protocol bias in which 17 and 18 yr. players did not swing bat model H because it was found to be quickly damaged by these older players.

**Statistical Analysis**

Consistent with our previous study, we did not find any significant differences among the various wood bat models, so the data from the three wooden bats were pooled and referred to as Wood. Differences in batted ball speed, bat impact speed, and angular speed of all non-wood bat models were first compared to Wood without considering any other factors using three separate one-way ANOVAs with a Dunnett’s multiple comparison test (Wood as control) in Prism (V5, GraphPad, La Jolla, CA). Significance was set at a $P < 0.05$.

Differences in batted ball speed, bat impact speed, and angular speed between all non-wood and Wood bat models within each age group were analyzed with unpaired t-tests. Significance was set at a $P < 0.00625$ (0.05/8), to account for multiple comparisons among age groups.

Bat linear and angular swing speeds were analyzed as a function of bat MOI by first regressing each player’s hits. These values were then grouped by the player’s age group and subsequent linear regression was used to examine any correlation with bat MOI by age group. Sweet spots and BBCORs were compared using a one-way ANOVA with a post-hoc Dunnett’s multiple comparison test using Wood as the control. Comparison among all bat models was
performed with post-hoc Bonferroni’s multiple comparison. The ability of the MOI and BBCOR values to predict ideal BBS and vf were examined using linear regression. All analyses were performed in Prism (GraphPad Software, Inc., La Jolla, CA).

Results

Across all players, batted ball speed (BBS), bat impact speed, and angular speed for bat models A and K were significantly faster ($p < 0.001$) than for Wood (Figure 1). Mean differences were 4.0 and 3.6 m/s (8.9 and 8.1 mph), 1.4 and 2.5 m/s (3.1 and 5.6 mph), and 166 and 309 deg/s, respectively. BBS for model J were also significantly faster by a mean of 1.5 m/s (3.4 mph), while batted ball speeds for model H were significantly slower than Wood by a mean of 2.0 m/s (4.5 mph). Bat impact speeds for models D and L were also significantly faster when compared with Wood by a mean difference of 1.1 and 1.7 m/s (2.5 and 3.8 mph), respectively, but there were no differences in angular speed among these bat models.

Within age groups, there were significant increases in the non-wood BBS, bat impact speed, and angular rate when compared to Wood (Figure 2). Mean BBS was significantly ($P < 0.001$) faster with non-wood than Wood by 1.8, 2.5, 3.5, and 3.5 m/s (4.0, 5.6, 7.8, and 7.8 mph) in the 13, 14, 17, and 18 yr. age groups, respectively. Mean speed at the impact location was significantly ($P < 0.001$) faster by 1.5, 2.2, 0.9, and 2.1 m/s (3.3, 4.9, 2.0, and 4.7 mph) in the 13, 14, 16, and 17 yr. age groups, respectively. The angular swing speed was significantly ($P < 0.001$) faster for non-wood than Wood by 152, 252, and 128 deg/s in the 13, 14 and 16 yr. age group, respectively.

Across all bat models, BBS increased by 1.5 ± 0.3 m/s (3.4 ± 0.7 mph) ($R^2 = 0.87$, $P < 0.005$) with each increasing year of player age. The differences in mean batted ball speed among non-wood bat models compared to Wood were fairly consistent within each age group (1.4 ± 1.0
m/s). The largest increases in mean BBS over Wood within each age group were for model A with values of 3.3, 4.8, 3.9, and 5.2 m/s (7.4, 10.7, 8.7, and 11.6 mph) for the 13, 14, 17, and 18 yr. age groups, respectively.

Bat impact speed significantly ($P < 0.05$) decreased with increasing MOI for the 13, 14 and 15 yr. age groups (Figure 3). The slopes of the regression for each of these age groups was $-24.4 \pm 1.4$, $-28.3 \pm 7.7$, and $-28.7 \pm 4.3$ m/s per kgm$^2$ (54.6 ± 3.1, 63.3 ± 17.2, and 64.2 ± 9.6 mph per kgm$^2$), respectively. There was no significant change in bat impact speed with bat MOI for 16, 17, and 18 yr. age groups (slope = 7.6 ± 12.5 m/s per kgm$^2$, $P = 0.56$). Angular swing speed decreased significantly (slope = $-3807\pm507$ deg/s per kgm$^2$, $P < 0.001$) with increasing MOI only for the 14 yr. age group.

The sweet spot on the Wood bat models was located a mean (± 1 SD) of 13.4 ± 3.2 cm (5.3 ± 1.3 in.) from the tip of the bat. The location of the sweet spot on the non-wood bat models did not differ significantly from Wood ($P = 0.196$). However, the sweet spot of model C (10.7 ± 2.8 cm (4.2 ± 1.1 in.)) was significantly ($P = 0.008$) closer to the tip of the bat then model H (15.6 ± 2.0 cm (6.1 ± 0.8 in.)).

The ideal BBS at a bat swing speed of 24.6 m/s (55 mph) were 34.7 ± 0.1, 34.4 ± 0.2, 32.7 ± 0.4, 33.8 ± 0.3, 33.9 ± 0.3, 31 ± 0.3, 33 ± 0.3, 35.4 ± 0.2, 34.8 ± 0.2, 32.8 ± 0.2, and 33.8 ± 0.2 m/s for Wood, A, C, D, G, H, I, J, K, L and M, respectively. These ideal BBS increased significantly (slope = $41.0 \pm 8.7$ m/s per kgm$^2$, $R^2 = 0.71$, $P = 0.001$) with increasing MOI (Figure 4). The relationship between ideal BBS and bat impact speed was explored further by a regression model based on Wood, and it was found that the envelope of ideal BBS increased linearly with swing speed by a factor $1.4 \pm 0.02$ ($R^2 = 0.98$, $P < 0.001$) (Figure 5).
BBCOR values for all non-wood bats were significantly (P < 0.0001) higher than Wood’s value of 0.5 ± 0.006. As expected BBCOR values alone did not predict ideal BBS (R² = 0.1330, P = 0.27, Figure 6A), while computed batted ball speed (vf) was overall strongly predictive of ideal BBS (slope = 1.0 ± 0.01, P < 0.001) (Figure 6B). vf was explored further for Wood by computing its values for a range of bat swing speeds with vf increasing linearly with swing speed by a factor of 1.2 (Figure 5).

Discussion

This study was undertaken to examine the batting cage performance of non-wood bats compared with Wood bats. We focused on bat models used in youth play that have a drop (length in inches – weight in oz.) of -3 to -11 because these bats have previously been unregulated at the youth level. We found that batted ball speeds (BBS) were significantly faster for three non-wood bat models, significantly slower for one non-wood model, and not different from Wood for four bat models. Bat impact speed significantly decreased with increasing MOI for the 13, 14 and 15 yr. age groups. Decrease in angular speed with increasing MOI occurred only in the 14 yr. age group. The laboratory BBCOR values for all non-wood bats were greater than the Wood bats, but this did not correlate directly with batted ball speeds, as expected. Rather, vf computed from BBCOR with a swing speed of 24.6 m/s (55 mph) did correlate relatively strongly with the ideal BBS.

There are numerous weaknesses and strengths to consider when interpreting our findings. A weakness of our approach is that we do not measure a player’s batting performance, so our findings cannot be extrapolated to predict batting percentages in actual play. This weakness arises because we do not analyze strikes or foul tips and we used a pitching machine, which is an oversimplification of a pitcher. These approaches were intentional in order to maximize the
number of hits. It must also be appreciated that the batted ball speeds we recorded (Figures 1 and 2) are specific to the cohort of the players participating in this study and may not reflect the batted ball speeds across a different cohort of players. Moreover, not all players swung all bats because of external time constraints on the subjects’ participation. This limitation may have influenced our values for absolute batted ball speed and swing speed (Figure 1). The influence of the cohort of player on the absolute batted ball speeds values will always be a factor in studies where human performance is a factor. Analyzing all non-wood bats as a group (Figure 2) partially addresses this limitation because it increases the sample size, but then limits analysis by bat models. Both of these limitations are however addressed in our approach that computes and analyzes ideal BBS and $v_f$ because the influence of player age, strength, and skill are removed.

In our previous study we found that the center of rotations of the bat, at the instant of impact, was located fairly consistently near the knob of the bat. At this instant, linear speed would be directly proportional to the rotational speed. In present study we found weak correlations between linear and rotational bat speeds, and further analysis demonstrated a substantially higher variation in the center of rotation than we previously observed. We conjecture that the swing kinematics in this study were far more varied across subjects than in the previous study. To demonstrate this an analysis of all six degrees of freedom of the bat throughout the entire swing would be required, but such an analysis is beyond the scope of this manuscript.

We have previously established that ideal batted ball speed increases linearly with increasing bat impact speed and that relationship is independent of the skill level of the player. The data collected in this study further confirms these findings. Using Wood as the example (Figure 5), as bat swing speed increases the envelope of ideal batted ball speed at each bat swing speed increases linearly. These batted ball speeds at each bat swing speed are referred to as
“ideal” because they are associated with hits located within the sweet spot of the bat and squarely on the long axis of the bat. Given these conditions, the ideal batted ball speed is the maximum batted ball speed that can be generated, regardless of the skill of the player swinging the bat. Our previous study\(^7\) included players with a mean age of 22 yrs. By plotting both sets of data (Figure 5) we demonstrate that the performance of Wood bats does not differ (a single line for ideal BBS envelope is plotted for both data for demonstration), despite the large variation in age, strength and skill. For a given bat swing speed, hits outside of the sweet spot and/or not squarely on the central axis of the bat result in decreased batted ball speeds. These are the data points below the ideal batted ball speed envelope (Figure 5). We also demonstrated that the computed velocity \(v_f\) for the range of bat speeds underestimated the batted ball speed that was measured at higher bat swing speeds. Presently the reason for the difference between the measured batted ball speed and computed \(v_f\) is not known but may be related to the fact that BBCOR values reported here were measured at one speed and a single impact location.

In our study, we observed an approximate 2 m/s increase in bat impact speed as bat MOI about the knob decreased from 0.24 to 0.16 km\(^2\). This finding is in close agreement with the data reported by Fleisig et al.\(^6\) on softball bats. In our study, bat impact speed significantly decreased with increasing MOI for the 13, 14, and 15 yr. age groups by an average rate of 27 m/s per km\(^2\). We observed no effect on swing speed with various MOI for the 16, 17, and 18 yr. age groups. This may be due to under sampling with not enough players at these age groups; however, we postulate that it is more likely that these bats are so light that variations in the MOI in the range that we studied do not have a detectable effect on the swing speed for the older and stronger players in this study. Our linear bat swing speeds were substantially lower than those reported by Inkster et al.\(^{12}\). While they swung at a ball on a tee and the point on the bat at which
linear velocity was computed was not reported may explain the differences, the most likely explanation is the older age of their subjects (22.2 ± 5.3 yr.) \(^{12}\). We also found no significant change in angular swing rate with bat MOI, as discussed above.

To the best of our knowledge, there have not been previous studies on the performance of youth bats. Previous studies of high school and college level bats have reported ball speed without accounting for swing speed or impact location. In one study, the maximum batted ball speed was 47.4 m/s (106 mph) for metal bats compared to 45.2 m/s (101 mph) for wooden bats, and the average batted ball speed was up to 4 m/s (9 mph) higher for metal bats \(^{13}\). These differences are comparable to the composite models A and K that hit the ball an average of 3.8 m/s (8.5 mph) faster than wooden bats in our study. Batted ball speeds of model J over Wood were similar to metal bat models studied in the late seventies in which Bryant et al. \(^{14}\) found speed increases of approximately 1.8 m/s (4 mph).

It is important to note that the laboratory BBCOR alone did not correlate directly with batted ball speed (Figure 6A). BBCOR is a measure of the ball-bat coefficient of restitution, or trampoline effect, and does not take into account the effects of MOI or swing speed at time of impact. The theoretical work of Nathan et al. \(^3\) was used to compute batted ball speed \((v_f)\) from BBCOR and the bat’s other physical properties. In order to compare \(v_f\) with batted ball speed data, we computed the ideal BBS, the actual maximum ball speed at a bat speed of 24.6 m/s (55 mph), and found an overall strong relationship between \(v_f\) and ideal BBS (Figure 6B). We note that \(v_f\) for bat models A and C overestimated the ideal BBS. These discrepancies may be due to a lack of high quality hits by our cohort. It must be emphasized that predicting batted ball speeds from the physical properties of bats is challenging, because \(v_f\) is highly dependent on bat swing speed.
In summary, this study examined the performance of various non-wood youth baseball bats and compared this performance to that of wood bats. With our approach we were able to track the complete 3-D kinematics of the bat and ball, and thus were able to analyze batted ball speed as a function of bat speed at the point of impact and location of the ball impact on the bat. This enabled us to compute an ideal batted ball speed for direct comparison of bat performance by normalizing for player skill and strength. We found that even though all non-wood bats had higher BBCOR values than Wood, the substantially lower MOIs resulted in batted ball speeds similar to or less than Wood for seven of the ten bats studied. Placed in the context of the previous studies in which small decreases in bat MOI can result in faster batted ball speeds\textsuperscript{5,6}, substantial decreases in bat MOI can result in slower batted ball speeds. The findings also emphasize that selecting bat swing speed for computing $vf$ from BBCOR remains a critical issue. These findings may have broad application in the regulation of youth baseball bats, indicating that substantially lighter bats, which permit more play participation by a wider range of players, do not hit the ball faster than wood bats, even though the barrels have higher BBCOR values.
REFERENCES


**Figure 1.** Batted ball speed, bat impact speed and angular speed computed across all age groups for each bat model. Significant differences ($P < 0.001$) when compared to wood bat models are noted (*). Box denotes median and interquartile range, whiskers denote minimum and maximum values.
Figure 2. Batted ball speed, speed of the bat at impact location, and the angular swing rate computed across wood and all non-wood bat models for each age group. In general, the ball and bat speeds tended to be greater for non-wood bats when compared to Wood within age groups. Significant increases in mean speeds are denoted (*, $P < 0.001$) for several of the age groups.
**Figure 3.** The relationships between bat MOI and swing speed. Mean (SD) bat impact speed significantly ($P < 0.05$) decreased with increasing bat MOI for the 13, 14, and 15 yr age groups. MOI was not a significant factor in bat speed for the older age groups (16, 17 and 18 yr)
Figure 4. The ideal BBS computed at a constant swing speed of 24.6 m/s (55 mph) increased significantly (slope = 41.0 ± 8.7 m/s per kgm², $R^2 = 0.71$, $P = 0.001$) with increasing bat MOI.
**Figure 5.** For any given bat speed, balls that are hit squarely in the sweet spot are hit the fastest. These ideal batted ball speeds are indicated here for Wood bats (Ideal BBS envelope). These ideal batted ball speeds increased approximately linearly with bat impact speed and this relationship is consistent with our previous study that examined different wood bats swung by college and post-college players⁷. A single envelope (Ideal BBS) is plotted for both of these experimental data set. The computed $vf$ values are also shown for Wood ($vf$ envelope).
Figure 6. The laboratory BBCOR value alone was not predictive of ideal batted ball speed (ideal BBS), defined as the actual maximum ball speed at a swing speed of 24.6 ms (55 mph) (A). However, using BBCOR with the equations developed by Nathan et al. ³, dramatically improved the correlation (slope = 1.0 ± 0.01, P < 0.001) between the theoretical batted ball speed (vf) and the ideal BBS (B).
Table 1. Physical properties of the bat models tested (values listed are the averages of 5 bats per model). The “drop” is a term used in baseball bat regulation and refers to the difference between bat length (defined in in.) and bat weight (defined in oz.). The center of gravity (C.G.) is measured from the tip of the bat. The MOI is computed about the bat’s knob. The center of gravity (C.G.) is measured from the tip of the bat.

<table>
<thead>
<tr>
<th>Bat Model</th>
<th>Material / Construction</th>
<th>Max. Barrel Diam. (cm (in))</th>
<th>Length (cm (in))</th>
<th>Weight (kg (oz))</th>
<th>Drop</th>
<th>C.G. (cm (in))</th>
<th>MOI (kgm(^2) (ozin(^2)))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Composite</td>
<td>7.0 (2.8)</td>
<td>78.7 (31)</td>
<td>0.74 (26)</td>
<td>-5</td>
<td>29.3 (11.5)</td>
<td>0.2190 (11,992)</td>
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<tr>
<td>B (Wood)</td>
<td>Maple</td>
<td>5.7 (2.3)</td>
<td>78.7 (31)</td>
<td>0.74 (26)</td>
<td>-5</td>
<td>27.5 (10.8)</td>
<td>0.2193 (12,014)</td>
</tr>
<tr>
<td>C</td>
<td>Composite</td>
<td>7.0 (2.8)</td>
<td>78.7 (31)</td>
<td>0.62 (22)</td>
<td>-9</td>
<td>27.4 (10.8)</td>
<td>0.1965 (10,764)</td>
</tr>
<tr>
<td>D</td>
<td>Composite</td>
<td>6.7 (2.6)</td>
<td>78.7 (31)</td>
<td>0.60 (21)</td>
<td>-10</td>
<td>30.7 (12.1)</td>
<td>0.1718 (9,409)</td>
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<tr>
<td>E (Wood)</td>
<td>Bamboo</td>
<td>6.4 (2.5)</td>
<td>76.2 (30)</td>
<td>0.77 (27)</td>
<td>-3</td>
<td>26.0 (10.2)</td>
<td>0.2314 (12,673)</td>
</tr>
<tr>
<td>F (Wood)</td>
<td>Maple</td>
<td>6.4 (2.5)</td>
<td>76.2 (30)</td>
<td>0.77 (27)</td>
<td>-3</td>
<td>25.3 (9.9)</td>
<td>0.2322 (12,719)</td>
</tr>
<tr>
<td>G</td>
<td>Composite</td>
<td>7.0 (2.8)</td>
<td>78.7 (31)</td>
<td>0.64 (22.5)</td>
<td>-8.5</td>
<td>28.2 (11.1)</td>
<td>0.1998 (10,944)</td>
</tr>
<tr>
<td>H</td>
<td>Composite</td>
<td>5.7 (2.3)</td>
<td>78.7 (31)</td>
<td>0.57 (20)</td>
<td>-11</td>
<td>30.9 (12.2)</td>
<td>0.1609 (8,815)</td>
</tr>
<tr>
<td>I</td>
<td>Composite</td>
<td>6.7 (2.6)</td>
<td>76.2 (30)</td>
<td>0.57 (20)</td>
<td>-10</td>
<td>27.7 (10.9)</td>
<td>0.1678 (9,192)</td>
</tr>
<tr>
<td>J</td>
<td>Composite</td>
<td>6.7 (2.6)</td>
<td>81.3 (32)</td>
<td>0.57 (27)</td>
<td>-5</td>
<td>30.3 (11.9)</td>
<td>0.2395 (13,117)</td>
</tr>
<tr>
<td>K</td>
<td>Composite</td>
<td>6.7 (2.6)</td>
<td>78.7 (31)</td>
<td>0.74 (26)</td>
<td>-5</td>
<td>30.9 (12.2)</td>
<td>0.2151 (11,781)</td>
</tr>
<tr>
<td>L</td>
<td>Composite</td>
<td>6.7 (2.6)</td>
<td>78.7 (31)</td>
<td>0.60 (21)</td>
<td>-10</td>
<td>28.2 (11.1)</td>
<td>0.1852 (10,144)</td>
</tr>
<tr>
<td>M</td>
<td>Aluminum</td>
<td>6.7 (2.6)</td>
<td>78.7 (31)</td>
<td>0.61 (21.5)</td>
<td>-9.5</td>
<td>28.5 (11.2)</td>
<td>0.2000 (10,952)</td>
</tr>
</tbody>
</table>
Table 2. Number of hits analyzed by age group and bat model.

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<thead>
<tr>
<th>Age Group</th>
<th>Wood</th>
<th>A</th>
<th>C</th>
<th>D</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>M</th>
<th>Sum by Age</th>
</tr>
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<td>34</td>
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<td>30</td>
<td>34</td>
<td>29</td>
<td>309</td>
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<td>20</td>
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<td>40</td>
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<td>11</td>
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<td>12</td>
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<td>100</td>
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<td>22</td>
<td>5</td>
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<td>29</td>
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<td>13</td>
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<td>313</td>
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<tr>
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<td>11</td>
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<tr>
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<td>112</td>
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