

# Batting performance of wood and metal baseball bats

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## ABSTRACT

CRISCO, J. J., R. M. GREENWALD, J. D. BLUME, and L. H. PENNA. Batting performance of wood and metal baseball bats. *Med. Sci. Sports Exerc.*, Vol. 34, No. 10, pp. 1675–1684, 2002. **Introduction/Purpose:** Although metal baseball bats are widely believed to outperform wood bats, there are few scientific studies which support this. In a batting cage study, Greenwald et al. found that baseballs hit with a metal bat traveled faster than those hit with a wood bat, but the factors responsible for this difference in bat performance remain unidentified. The purpose of this study was to determine the effects of swing speed, impact location, and elastic properties of the bat on batted ball speeds. **Methods:** The pitched ball, batted ball, and swings of two wood and five metal baseball bats by 19 different players were tracked in three dimensions at 500 Hz using a passive infrared motion analysis system. **Results:** Increases in the batted ball speeds of metal bats over those of wood bats resulted from faster swing speeds and higher elastic performance with an apparent increase in the ball-bat coefficient of restitution. The contribution of these variables to batted ball speed differed with metal bat model. The “sweet spot” associated with maximum batted ball speeds was located approximately the same distance from the tip of wood bats as it was from metal bats. **Conclusions:** The variables that correlated with differences between metal and wood bat performance, and most notably differences in the percentage of faster batted balls, were identified using a novel kinematic analysis of the ball and bat. These variables and their correlation with bat performance should be applicable to other players and bats, although more skilled players and higher performing bats would likely result in even faster batted ball speeds. **Key Words:** BALL SPEED, BIOMECHANICS, FIELD STUDY, SPORTS

Performance of baseball bats has been an intriguing question since the traditional wood bat was first doctored or “corked” by a player. Currently, wood bats are used only in Major and Minor League Baseball, whereas in high school and college play, they have been completely replaced by aluminum and other metal alloy bats. Metal bats were originally introduced in the early 1970s as a cost-saving alternative to wood bats that were prone to break. They are especially practical in leagues with the smallest budgets, those least likely to be able to purchase bats made of higher quality wood. The performance of early metal bats was perceived to be limited, and actually lower than that of wood bats. By the early 1980s, however, there was a general consensus among players and coaches that metal bats could largely outperform wood ones. In the mid-1980s, the National Collegiate Athletic Association (NCAA) began considering guidelines for limiting bat performance, and in 1988, the first rule was established. That rule, known as the “minus 5” rule, stated that a bat could not weigh (in ounces) less than 5 units from its length (in inches). Since that time, the issue of regulating bat performance has been, and continues to be, a controversial one. At the heart of this con-

trovery is the debate over performance differences between wood and metal bats. Although there is a sweeping consensus among players and coaches with regard to the increased performance of metal bats, few scientific studies have documented these performance differences. Recently, the NCAA adopted a laboratory method for measuring bat performance, but the lack of data on actual bat performance raises concerns about the validity of this and other laboratory methods.

Although numerous scientists have examined the physics of pitching and batting (1,2,11,13), rigorous experimental studies on bat performance are limited. To the best of our knowledge, only one prior study has examined the performance difference between wood and aluminum baseball bats. In 1977, Bryant et al. (7) reported that aluminum bats outperformed wood bats by approximately  $1.8 \text{ m}\cdot\text{s}^{-1}$  (4 mph). However, the design and construction of metal bats has changed dramatically since that study was conducted. We measured batted ball speeds in a previous batting cage study (10) and reported that the batted ball speeds of some metal bats were significantly faster than those of wood bats, supporting long held beliefs of players, coaches, and fans. However, those properties of the bat and its swing responsible for this increase in batted ball speed were not identified.

Several variables are believed to contribute to a metal bat’s increased performance; metal bats are said to possess a “trampoline effect,” a larger “sweet spot,” and the ability to be swung faster. The trampoline effect is typically thought to be associated with elastic deformation of the

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TABLE 1. Physical specifications (mean  $\pm$  1 SD) of the various bat models used in the study; these measurements were made on the bats after the batting cage study; therefore, dented and broken bats were excluded; the weight-length difference is defined by the governing bodies of baseball as the weight in oz. minus the length in inches; center of gravity and MOI are measured from the bottom of the knob.

Bat Model	Weight - Length	Length (cm (in.))	Weight (kg (oz))	Center of Gravity (cm (in.))	MOI at 15.2 cm (6 in.) (kg-cm <sup>2</sup> (oz-in. <sup>2</sup> ))	Maximum Barrel Diameter (cm (in.))
W1/W2 (N = 7)	-3	86.4 (34)	0.87 $\pm$ 0.01 (30.9 $\pm$ 0.4)	58.4 $\pm$ 0.3 (23 $\pm$ 0.1)	2103 $\pm$ 177 (11516 $\pm$ 177)	6.6 (2.6)
M1 (N = 5)	-3	83.8 (33)	0.86 $\pm$ 0.0 (30.3 $\pm$ 0.1)	52.8 $\pm$ 0.3 (20.8 $\pm$ 0.1)	1761 $\pm$ 15 (9646 $\pm$ 81)	7.1 (2.8)
M2 (N = 6)	-5	83.8 (33)	0.83 $\pm$ 0.0 (29.2 $\pm$ 0.1)	52.6 $\pm$ 0.3 (20.7 $\pm$ 0.1)	1695 $\pm$ 18 (9282 $\pm$ 98)	7.1 (2.8)
M3 (N = 6)	-5	83.8 (33)	0.80 $\pm$ 0.0 (28.4 $\pm$ 0.1)	52.8 $\pm$ 0.3 (20.8 $\pm$ 0.1)	1695 $\pm$ 19 (9282 $\pm$ 103)	7.4 (2.9)
M4 (N = 5)	-5	83.8 (33)	0.81 $\pm$ 0.02 (28.6 $\pm$ 0.6)	54.4 $\pm$ 0.5 (21.4 $\pm$ 0.2)	1714 $\pm$ 36 (9388 $\pm$ 197)	7.1 (2.8)
M5 (N = 4)	-4	86.4 (34)	0.84 $\pm$ 0.01 (29.8 $\pm$ 0.2)	54.1 $\pm$ 0.3 (21.3 $\pm$ 0.1)	1864 $\pm$ 19 (10208 $\pm$ 102)	6.6 (2.6)

barrel wall upon contact with the ball. This deformation of the bat wall causes less deformation of the ball, resulting in less energy loss by the ball and higher batted ball speeds.

The barrel of a wood bat is believed not to deform upon ball contact. But, deformation of the metal bat's barrel wall during ball impact has yet to be documented. In essence, the ball-bat coefficient of restitution (COR) is believed to be higher for metal bats than for wood bats, and the trampoline effect is the most common explanation for this higher elastic performance. The sweet spot is typically referred to as the location on the barrel of the bat that generates the fastest hits. Previous theoretical studies have predicted that this location corresponds to a node of the fundamental vibrational mode and/or the center of percussion (6,8,15). More recently, the sweet spot has been proposed to lie at a location where the vibrational energy is minimized (11). Whereas lighter bats can clearly be swung faster, swing speed has been shown to correlate more closely with moment of inertia (a measure of how the weight of the bat is distributed along its length) than with total weight (9). However, the principle of conservation of momentum stipulates that, for the same swing speed as the heavier wood bats, lighter metal bats must impart less momentum to the ball, and thus result in lower batted ball speeds. How these or other variables contribute to the increased performance of metal baseball bats is unclear.

The aim of this study was to determine whether specific variables analyzed from three-dimensional kinematic data of the bat and ball during actual batting cage sessions correlated with batted ball speed among five metal and two wood bat models. The variables we examined were batted ball speed, bat swing speed, and bat impact location. In addition, once we accounted for swing speed and impact location, we compared the elastic performance properties of the bats.

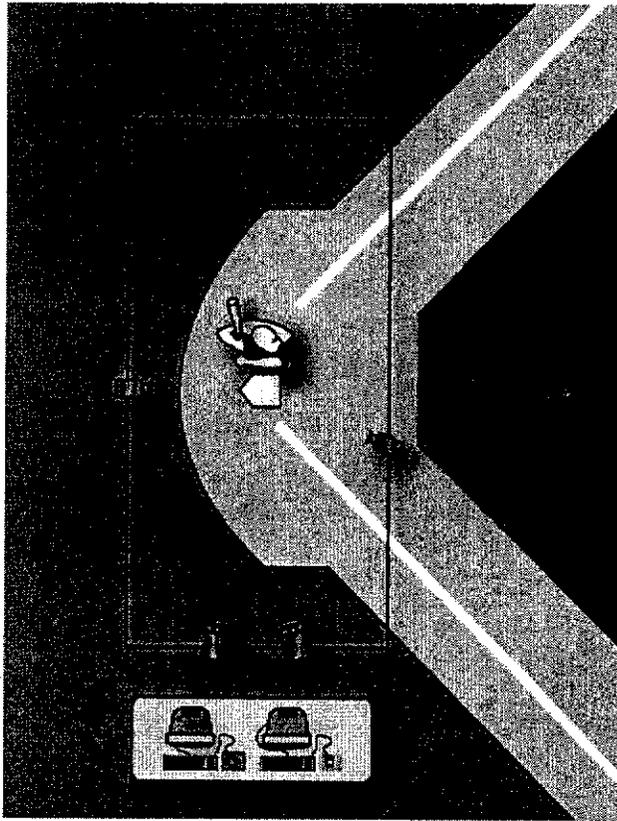
## METHODS

**Players, bats, and balls.** Nineteen right-handed male baseball players (mean age: 22, range 17-39) representing three skill levels (professional minor league, collegiate, and high school) participated in the batting cage study with informed written consent after IRB committee review. Differences in batted ball speed as a function of player skill level were examined in our previous study (10). In this study, we grouped the data from all players because our analysis of ball impact location on the bat and the speed of the bat at that location removed the influence of skill level.

Two wood and five aluminum bat models from four bat manufacturers were used (Table 1). Six identical bats of each model were prepared for testing by applying reflective tape (3M Corp, Minneapolis, MN) at five locations along the length of the bat. These locations were the bat tip, just above the handle, the knob, and 12.7 cm (5 in.) and 30.5 cm (12 in.) from the bat tip. The tip, handle, and knob were wrapped with 2.5 cm (1 in.) wide strips of tape, whereas each of the other two locations were provided with two 5.1 cm (2.1 in.) equilateral triangles on opposite sides of the bat barrel. Wilson (Chicago, IL) A1001 (N = 120) baseballs were used. All baseballs were covered with reflective tape leaving only the seams uncovered.

Testing took place indoors at a batting cage facility (Frozen Ropes Training Center, Franklin, MA) over a 3-d period. A schematic of the setup in the batting cage facility is provided in Figure 1. The entire batting cage was approximately 15.2 m (50 ft) long by 4.9 m (16 ft) wide and 3.7 m (12 ft) high. A pitching machine (Iron Mike, Master Pitching Machine, Kansas City, MO) delivered the ball at preset velocities of approximately 22.4, 26.8, or 29.5 m·s<sup>-1</sup> (50, 60, or 66 mph) from a distance of 13.8 m (45 ft) to the hitter. Ball speed was not found to be significantly different for the various pitch speeds (10); therefore, all pitches were grouped in this study. Both the order of the players and the bat they used were selected randomly. Each player faced 10-20 pitches with a single bat, including several warm-up swings, if desired, and was then replaced by another hitter. Not all bats were swung by every player. A breakdown of the hits per bat and player is provided in our previous study (10).

**Data collection and analysis.** Four 500-Hz infrared-sensing cameras (Qualisys Inc., Glastonbury, CT) were fixed to scaffolding around home plate so that the field of view included the trajectory of the bat before impact as well as the pitched and batted baseball (Fig. 1). ProReflex Motion Capture System software (Qualisys Inc.) was used to record and analyze the individual trials, consisting of a single pitch and swing. The standard deviation in the coordinates of the calibration system was 1.2 mm. A 1.5-s data collection period was triggered manually as the pitch left the rotating arm of the pitching machine. The path of the ball (a single marker) and each marker on the bat were defined using the automated algorithms and user interaction in Track 3D (Qualisys Inc., Glastonbury, CT). A single data file containing the three-dimensional coordinates of each marker in frame increments of 0.002 s was generated, exported from Track 3D, and then processed using a series of



**FIGURE 1**—An aerial schematic of the batting cage setup with four cameras and data acquisition computers. The four 500-Hz cameras were mounted on a scaffold  $3.4 \times 7.9 \times 3.7$  m ( $8 \times 16 \times 12$  ft) built about home plate. With this setup, only right-handed batters were studied. A pitching machine, located 13.7 m (45 ft) from the batter, was used throughout the study.

custom programs written in Borland C (SPSS Corp., Chicago, IL) and Matlab (The MathWorks, Natick, MA).

The three-dimensional kinematics of the ball and bat for each trial were calculated from the three-dimensional coordinates of the ball marker and each bat marker recorded using several assumptions. To determine the inbound (pitched) and outbound (batted) ball velocities, we assumed that the velocity of the ball was constant in each inbound and outbound segment, which covered a distance of less than 1.8 m (6 ft). Ball velocity was then calculated as the slope of the linear least-squares regression of ball marker position over time. The variables describing bat motion were calculated using the two frames just before the time of impact, defined as the time at the end of the ball inbound segment. To calculate the important bat variables, two assumptions were required: the bat moved as a rigid body, and bat motion was planar between successive time frames of 0.002 s. The complete three-dimensional kinematics of the bat were then described using the helical axis of motion (also referred to as the screw axis) variables (14). The intersection of this axis with the instantaneous plane of bat motion is the instantaneous center of rotation (ICOR). Bat impact location (i.e., where the ball hit the bat) was defined by the intersection of the inbound ball segment and the central axis of the bat. Once this point on the bat was defined, rigid body

kinematics were used to calculate the speed of the bat at the impact location (referred to as the bat impact speed).

**Statistical analysis.** The performances of the two wood bat models were first compared. Then, the performance differences among the metal and wood bats were compared on batted ball speed, bat impact speed, and location of bat impact. Finally, we sought to compare the elastic performance of the bat models after adjusting for bat swing speed and impact location. Because we cannot experimentally control these variables in a field study, statistical methods were used to perform this adjustment and subsequently quantify the effect of these variables.

We hypothesized that the performance of the two wood bat models was not different. Batted ball speeds of hits within  $\pm 1$  standard deviation of the mean of the ball impact location on the bat were compared. A total of 54 hits and 53 hits for wood bat models W1 and W2, respectively, were then analyzed for differences in the mean batted ball speed using a Student's *t*-test. There was not a significant difference between the mean batted ball speed ( $P = 0.101$ ) for the two wood bat models; therefore, the data were pooled for the remainder of the analysis and referred to as model W.

Survival (cumulative) distributions for batted ball speed were calculated and analyzed to determine the percentage of balls that traveled at a certain speed or faster. Here "survival" refers to a ball speed attaining a particular speed. For example, the survival distribution at  $31.3 \text{ m}\cdot\text{s}^{-1}$  (70 mph) gives the observed percentage of balls that traveled at  $31.3 \text{ m}\cdot\text{s}^{-1}$  (70 mph) or faster. We tested the hypothesis that the survival distributions were equal using a log-rank test. To characterize the difference between two survival distributions with a single summary measure, we estimated all pairwise probabilities that the batted ball speed for one bat would exceed that for another bat. Specifically, if  $X$  is the batted ball speed for bat A and  $Y$  is the batted ball speed for bat B, we estimated  $P(X < Y)$ . (Note that if A and B are the same bat, then this probability is 0.5). Thus, the deviation of  $P(X < Y)$  from 0.5 measures the degree to which one bat tends to hit balls faster. Moreover, we provided the *P*-value for testing the null hypothesis that  $P(X < Y) = 0.5$ , and we estimated the constant "d" such that  $P(X + d < Y) = 0.5$ . Here "d" represents the shift (in batted ball speed) in the survival distribution of ball speed from one bat to another. Essentially, this distribution shift is the average increase in batted ball speed, but is less sensitive to distributional assumptions and outliers than the overall mean difference.

The "sweet spot" of a bat was defined as the range of impact locations associated with the highest batted ball speeds. We defined the two groups of highest batted ball speeds as those in the top 10% and top 20% from each bat model. These groups were compared among bat models by using the Wilcoxon rank sum test. Here the null hypothesis is that the impact locations of the highest batted ball speeds do not differ among the bat models (i.e., the "sweet spot" is not different among models).

To quantify the individual effects of bat model, bat swing speed, and impact location on the batted ball speed, we modeled batted ball speed (dependent variable) as a function

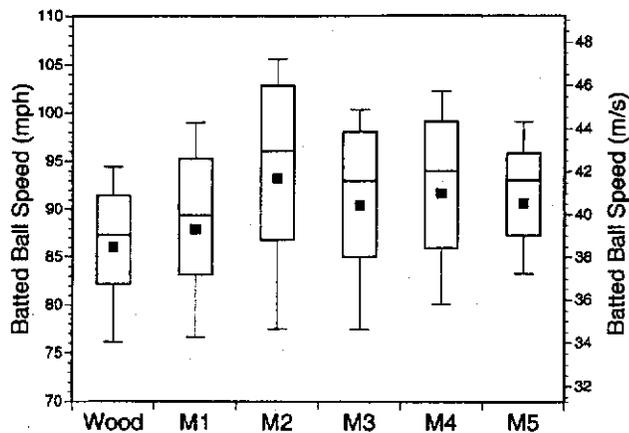


FIGURE 2—Box plots of the batted ball speed distributions for each bat type. The center line on the box plot represents the median, and the top and bottom of the box are the 75th and 25th percentile, respectively. The whiskers describe the tails (10th and 90th percentile) of the distributions. The average batted ball speed is indicated by the single data point.

of these three independent variables (bat model indicator, bat swing speed, and impact location) by using standard regression ANCOVA techniques. (Modeling note: we included an additional term in our regression model, impact location squared, that accounted for the nonlinear relationship between impact location and batted ball speed.) We report the multiple coefficient of determination ( $R^2$ ), which is the percentage of variability in batted ball speed that is explained by our model, as a measure of model accuracy. This statistical model allowed us to control for bat speed and impact location and therefore permitted us to determine the differences, from wood bats, in batted ball speed that were associated with an inherent property of each metal bat model. Although the specific nature of this inherent property is unknown, we postulate that it is dominated by the elastic performance of the bat and the ball-bat COR.

Due to the long history and continued use of English units in the sport of baseball, we have also reported the data in English units (1 inch equals 2.54 cm; 1 mph equals 0.44704  $m \cdot s^{-1}$ ; and 1 ounce equals 0.0283 kg).

## RESULTS

**Number of hits analyzed.** A total of 1079 pitches were recorded. Of these, 538 hits were eligible for analysis, as the remaining pitches resulted in foul balls, pop-ups, or missed pitches. In the current analysis, if all of the considered variables were not recorded, then a hit was removed from analysis. This left a total of 502 hits: 153 from wood (W), 85 from metal 1 (M1), 89 from metal 2 (M2), 43 from metal 3 (M3), 56 from metal 4 (M4), and 76 from metal 5 (M5).

**Batted ball speeds.** The average batted ball speed was fastest for bat M2 ( $41.7 m \cdot s^{-1}$  (93.3 mph)) and slowest for bat W ( $38.5 m \cdot s^{-1}$  (86.1 mph)) (Fig. 2). Bat M2, as well as bats M3, M4, and M5, with average batted ball speeds of 40.4, 41.0, and 40.5  $m \cdot s^{-1}$  (90.4, 91.7, and 90.6 mph),

respectively, were each significantly faster than bat W, whereas M1, with an average batted ball speed of  $39.3 m \cdot s^{-1}$  (88 mph), was not statistically different from bat W. At a 95% confidence level, the estimated difference in the average batted ball speed between wood and metal was  $-0.3$  to  $2.0 m \cdot s^{-1}$  ( $-0.7$  to  $4.5$  mph) for bat M1,  $1.9$  to  $4.6 m \cdot s^{-1}$  ( $4.2$  to  $10.3$  mph) for bat M2,  $0.4$  to  $3.4 m \cdot s^{-1}$  ( $1.0$  to  $7.6$  mph) for bat M3,  $1.2$  to  $3.9 m \cdot s^{-1}$  ( $2.6$  to  $8.7$  mph) for bat M4, and  $0.8$  to  $3.2 m \cdot s^{-1}$  ( $1.9$  to  $7.2$  mph) for bat M5.

The survival curves for metal bats were almost uniformly shifted to the right of the curve for wood bats (Fig. 3). This means that for any given batted ball speed, metal bats produced a larger proportion of balls exceeding this speed when compared with wood bats. The log-rank test indicated that the six survival curves were not statistically equal ( $P < 0.001$ ) and therefore these differences were not due to random variability. Pairwise comparisons indicated that the survival distribution of batted ball speed for each metal bat was statistically different from that of wood bats ( $P < 0.001$  for each pair-wise log-rank test). The average shift ("d" in our earlier notation) in batted ball speed for metal bats M1 through M5 over wood bat W was approximately 1.1, 4.0, 2.4, 2.8, and 2.2  $m \cdot s^{-1}$  (2.5, 9.0, 5.3, 6.2, and 5.0 mph), respectively. The probability that the batted ball speed off of a metal bat was faster than that off of a wood bat was 58%, 73%, 67%, 70%, and 70%, respectively, for metal bats M1 through M5.

The most striking difference in the performance of the metal bats compared with wood bats was not the increase in average batted ball speeds but rather the difference in the cumulative distributions of the speeds. For example, consider balls hit at  $42.5 m \cdot s^{-1}$  (95 mph) or faster (Fig. 3). With wood bats, 9% of the hits were faster than  $42.5 m \cdot s^{-1}$  (95 mph), whereas 52% of the hits with bat M2 were faster than  $42.5 m \cdot s^{-1}$  (95 mph). Similarly, only 2% of the hits with wood bats were faster than  $44.7 m \cdot s^{-1}$  (100 mph), whereas 37% of the hits with bat M2 were faster than  $44.7 m \cdot s^{-1}$  (100 mph).

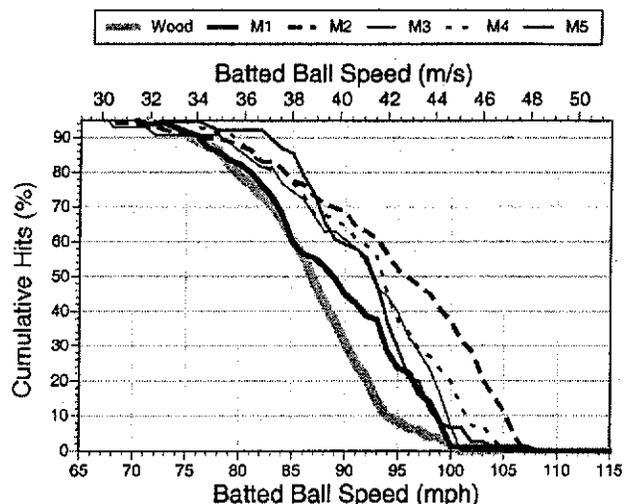
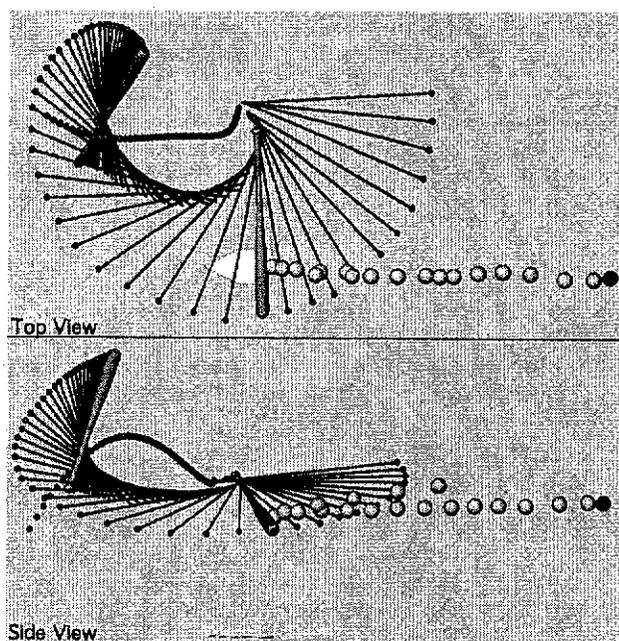


FIGURE 3—Cumulative distributions (survival curves) of the batted ball speeds for the six bat models. For each specific batted ball speed (located on the x-axis), the survival curve indicates the percentage of batted balls traveling faster than that specific speed.



**FIGURE 4**—Top and side views of a typical bat swing. The positions of the bat and ball are drawn at 4-ms intervals, with the first image of the pitched ball highlighted. The spheres indicate the three-dimensional location of the instantaneous center of rotation in the plane of each successive bat position. After hitting the ball, the wrists roll over, and this is associated with the sharp curve in the path of the instantaneous center of rotation at the end of the swing.

**Bat swing speed and bat swing kinematics.** Metal bats were swung significantly faster than wood bats. The median bat swing speed at the location of the ball impact with wood was  $30.4 \text{ m}\cdot\text{s}^{-1}$  (67.9 mph). This increased on average by 0.5, 1.3, 1.2, 1.2, and  $1.4 \text{ m}\cdot\text{s}^{-1}$  (1.2, 3.0, 2.7, 2.7, and 3.2 mph) for metal bats M1 through M5, respectively. The relationship between angular bat speeds was somewhat analogous. The median angular bat speed was  $2460^\circ\cdot\text{s}^{-1}$  for wood bats and increased by 30, 70, 53, 78, and  $32^\circ\cdot\text{s}^{-1}$  for the metal bats, whereas the average value for wood was  $2477^\circ\cdot\text{s}^{-1}$ , which increased on average by 89, 207, 155, 229, and  $89^\circ\cdot\text{s}^{-1}$  for metal bats M1 through M5, respectively.

The point about which the bat rotated (the instantaneous center of rotation (ICOR)) just before impact did not differ with bat model. This point was statistically analyzed by individually comparing the component along the central axis and the component off of the central axis ( $P = 0.14$  and  $0.78$ , respectively). The ICOR was located  $81.3 \pm 9.4 \text{ cm}$  ( $32.0 \pm 3.7 \text{ in.}$ ) from the tip of the bat along the central axis and  $8.4 \pm 4.1 \text{ cm}$  ( $3.3 \pm 1.6 \text{ in.}$ ) off of the central axis of the bat. This placed the ICOR at approximately the center of the wrist of the bottom hand in all players. The path of the ICOR moved forward (most likely as the player's weight shifted from back foot to front foot) with bat swing, and followed a complex curve in three-dimensional space (Fig. 4). The paths of the ICOR were not analyzed further in this study.

**The "sweet spot".** For wood bats, the scatter plot of batted ball speed versus impact location demonstrated a

curvilinear (inverse parabolic) relationship, demonstrating the existence of a region on the barrel associated with the fastest batted ball speeds (Fig. 5). This sweet spot was located approximately 10.2 to 17.8 cm (4 to 7 in.) from the tip of the wood bat. The performance within this sweet spot appeared constant. Outside of this sweet spot, maximum batted ball speed decreased at a rate of approximately  $4.5 \text{ m}\cdot\text{s}^{-1}$  (10 mph) with every 2.5 cm (1 in.). Hits within the sweet spot that resulted in lower batted ball speeds (data within the inverted parabolic envelope) were associated with slower bat swing speeds and with impacts slightly off of the bat's central axis of the bats.

The sweet spots of wood and metal bats were statistically compared using the top 10% and top 20% of the fastest hits from each bat model (Tables 2 and 3). There was no statistical difference between wood and any of the metal bat models in the location of these hits (e.g.,  $P$ -values of the top 10% hits were 0.43 and 0.93 for M1 vs W and M2 vs W, respectively).

**Bat speed and batted ball speed.** Plots of bat impact speed versus batted ball speed demonstrated a surprisingly complex relationship and clear differences between wood and metal bats (Fig. 6). In first considering wood bats (Plot Wood in Fig. 6), there is an upper boundary of batted ball speeds for the bat impact speeds ranging between  $24.6$  and  $31.3 \text{ m}\cdot\text{s}^{-1}$  (55 and 70 mph). In this range of bat speeds, the dense upper boundary of data are optimal hits: the maximum batted ball speed obtainable for a given bat speed. Within this same range of bat speeds, there are data with lower batted ball speeds. These data correspond to nonoptimal hits: hits outside the sweet spot and/or hits within the sweet spot that were not squarely on the central axis of the bat. In the range of bat speeds above approximately  $31.3 \text{ m}\cdot\text{s}^{-1}$  (70 mph), the upper boundary of hits was not present, possibly because it is more difficult to make an optimal hit at higher bat swing speeds. The character of the scatter plots for each metal bat was similar to that of wood. However, the data for bats M2 and M4 appear to be shifted with respect to the wood plots. For M4, the data appears shifted along the y-axis. For bat M2 the data appears to be shifted along both the x- and the y-axes. Differences between the wood plot and the plots of bats M1, M3, and M5 were less evident.

**"Elastic performance".** In the range of bat speeds between  $29.1$  and  $31.3 \text{ m}\cdot\text{s}^{-1}$  (65 and 70 mph), M2 batted ball speeds were faster than wood at any specified bat speed (Plot M2 in Fig. 6). Assuming that the batted balls speeds are at a maximum in this range of bat speeds for both bats M2 and W (i.e., the hits are optimal), then this increase in batted ball speeds suggests an inherent difference in the elastic performance of bat M2 over bat W. This increase in performance is attributed to a higher ball-bat COR with bat M2, but may be due also to additional unknown factors. This conclusion is generally supported by our statistical model ( $R^2 = 0.52$ ), which indicated significant increases in batted ball speed with bat model after controlling for swing speed and impact location.

The increases over wood in batted ball speed after controlling for bat speed and impact location were  $1 \text{ m}\cdot\text{s}^{-1}$  (2.2

TABLE 2. Distributions of the hit locations, measured from the tip of the bat, for the top 10% of the fastest batted ball speeds.

Bat Model (Hits)	Distribution of Hit Locations (cm (in.))					
	Min	1st Quarter	Median	3rd Quarter	Max	Mean
W1 (N = 16)	10.2 (4.0)	12.2 (4.8)	13.5 (5.3)	15.7 (6.2)	17.8 (7.0)	14.0 (5.5)
M1 (N = 9)	11.7 (4.6)	14.5 (5.7)	14.5 (5.7)	16.0 (6.3)	17.3 (6.8)	14.7 (5.8)
M2 (N = 9)	11.9 (4.7)	11.9 (4.7)	14.5 (5.7)	14.5 (5.7)	17.5 (6.9)	14.0 (5.5)
M3 (N = 5)	14.2 (5.6)	15.0 (5.9)	15.7 (6.2)	16.5 (6.5)	18.5 (7.3)	16.0 (6.3)
M4 (N = 6)	12.7 (5.0)	14.2 (5.6)	14.5 (5.7)	15.2 (6.0)	17.8 (7.0)	15.0 (5.9)
M5 (N = 8)	14.7 (5.8)	14.7 (5.8)	15.5 (6.1)	17.3 (6.8)	17.5 (6.9)	16.0 (6.3)

mph) with M1 ( $P = 0.046$ ),  $2.1 \text{ m}\cdot\text{s}^{-1}$  (4.8 mph) with M2 ( $P < 0.001$ ), and  $1.2 \text{ m}\cdot\text{s}^{-1}$  (2.7 mph) with M4 ( $P = 0.030$ ). Increases in batted ball speeds with M3 and M5 by  $1.2 \text{ m}\cdot\text{s}^{-1}$  and  $0.9 \text{ m}\cdot\text{s}^{-1}$  (2.6 mph and 2.0 mph), respectively, were not significant compared with wood. Because not all hits were optimal, these differences may underestimate the increase in batted ball speed associated with each specific metal bat model.

## DISCUSSION

In this batting cage study, four metal bats hit the ball significantly faster than wood bats, whereas one metal bat was more similar to wood. The most dramatic difference between the wood bats and the higher performing metal bats was an increase in the distribution of hits above any given batted ball speed. In this study, we analyzed several variables associated with increases in batted ball speed. Previously, Bryant et al. (7) measured only batted balls speeds and reported that an aluminum bat model outperformed a wood bat by an average speed of  $1.7 \text{ m}\cdot\text{s}^{-1}$  (3.9 mph). We found greater differences between wood and some metal bats, mostly likely due to recent design and construction advances in modern metal bats. In contrast to our results, Weyrich et al. (16) reported that wood bats produced greater postimpact ball velocities and these velocities were maximized with a tight grip and an impact at the center of percussion (COP). The discrepancies between our findings and those of Weyrich et al. (16) arise almost assuredly from their study of stationary bats held by players. Furthermore, they compared impacts at different locations on wood and metal bats that corresponded to a COP for each bat (15.2 cm (6 in.) and 11.2 cm (4.4 in.) from the tip for wood and metal bats, respectively). It should be noted that the COP is a function of the axis of rotation, which they assumed was located above the hands, 17.8 cm (7 in.) from the knob and on the central axis of the bat. This location is in contrast to our finding that the axis of rotation was located in the center

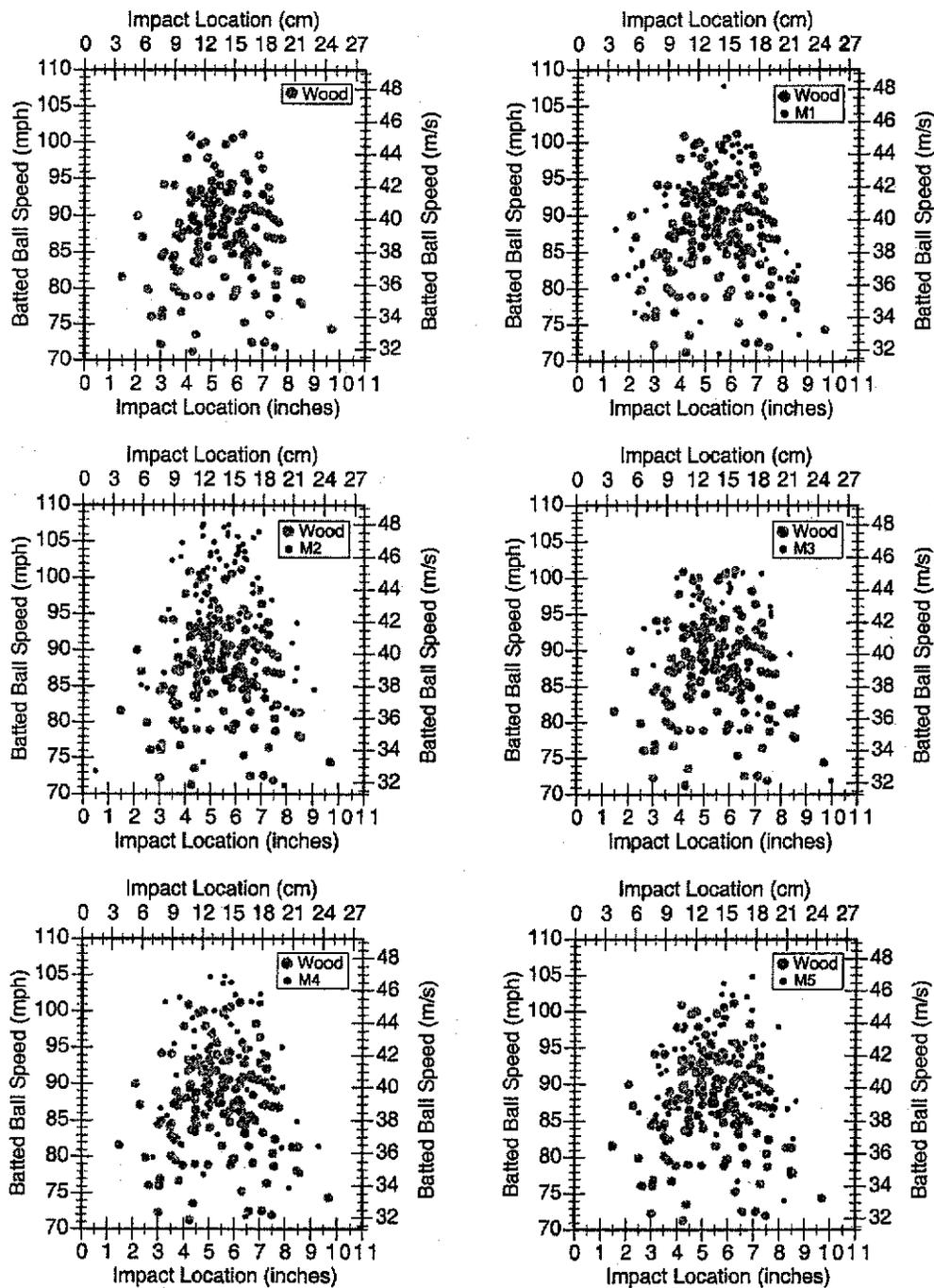
of the wrist of the bottom hand, which is much closer to the knob and off of the central axis of the bat. Their finding that a tighter grip increased batted ball speed is not in agreement with more recent works, e.g., Brody (5) and Nathan (11), who modeled the bat with a free-end condition at the handle. The free-end condition (i.e., no reaction force by the hands on the bat at the instance of impact) is supported by the experimental finding that the ball is in contact with the bat for about only 2 ms, so the ball has left the bat before the impact vibrations have reached the handle.

In general, the lighter bats were swung faster and were associated with faster batted ball speeds. These bats also had a lower moment of inertia (MOI), which correlates better with bat swing speed than simply bat weight (9). The MOI can be considered a measure of swing weight: the higher the MOI, the heavier the swing weight. The bats with highest MOIs (W and M1) had the lowest batted ball speeds. Bahill and Karnavas (3,4) and Bahill and Freitas (2) have reported that there is an optimal bat weight for each player, but we studied too few players and bat models to examine this issue. Applying the principle of conservation of momentum to the ball-bat impact, one would conclude that batted ball speeds would be faster with a heavier bat swung at the same speed as a similarly constructed lighter bat. However, the law of conservation of momentum does not incorporate the biomechanics of swing speed, and, therefore, it is possible that a lighter bat may outperform a heavier bat of the same construction due to an increase in swing speed. We did not explicitly test this in our study, and it is unlikely that two bats of different weights and MOIs, but with the same construction exist, because it is the various constructions (i.e., the material and wall thickness) that typically dictate bat weight and MOI.

The sweet spot of a bat has long been a topic of debate. From a physics perspective, precise definitions of the sweet spot have varied and have included the COP, the node of the lowest vibration, the location that minimizes the total energy going to bat vibrations, the location that gives maximum rebound en-

TABLE 3. Distributions of the hit locations, measured from the tip of the bat, for the top 20% of the fastest batted ball speeds.

Bat Model (hits)	Distribution of Hit Locations (cm (In.))					
	Min	1st Quarter	Median	3rd Quarter	Max	Mean
W1 (N = 31)	7.9 (3.1)	11.9 (4.7)	13.5 (5.3)	15.2 (6.0)	18.3 (7.2)	13.5 (5.3)
M1 (N = 17)	11.4 (4.5)	14.2 (5.6)	14.5 (5.7)	15.5 (6.1)	17.5 (6.9)	14.2 (5.6)
M2 (N = 18)	9.9 (3.9)	13.0 (5.1)	14.5 (5.7)	15.5 (6.1)	17.5 (6.9)	14.2 (5.6)
M3 (N = 9)	9.9 (3.9)	11.9 (4.7)	15.0 (5.9)	15.7 (6.2)	18.5 (7.3)	14.2 (5.6)
M4 (N = 12)	8.4 (3.3)	13.7 (5.4)	14.5 (5.7)	17.0 (6.7)	17.8 (7.0)	14.5 (5.7)
M5 (N = 16)	10.9 (4.3)	13.7 (5.4)	14.7 (5.8)	16.0 (6.3)	20.1 (7.9)	14.7 (5.8)

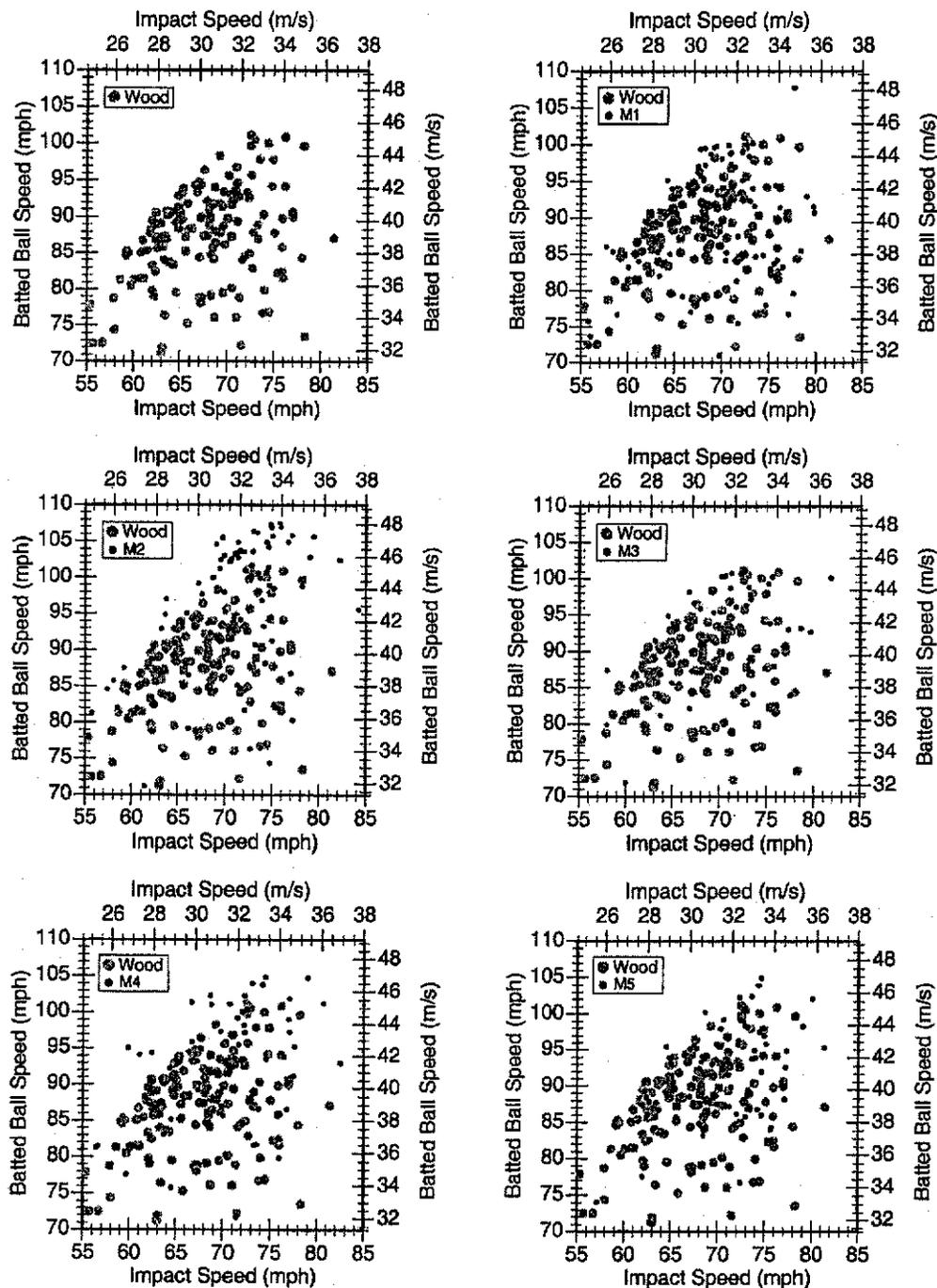


**FIGURE 5**—Batted ball speed versus the location of impact (impact location) for the six bat models. The location of the impact is measured from the tip of the bat and the “sweet spot” was defined as the region of impacts with the highest batted ball speeds (i.e., maximum performance). Data within the inverted parabolic envelope were not the fastest hits and were associated with hits at lower swing speeds and hits not squarely on the central axis of the bat.

ergy, and the location that gives the maximum batted ball speed (11). Our data clearly demonstrate the existence of a sweet spot in terms of maximum batted ball speeds. This warrants a detailed correlation of our data with the physical properties of each bat model, such as stiffness and vibrational properties, but such a correlation is beyond the scope of this study. It is interesting to note that Bryant et al. (7) reported that the COP was wider in aluminum bats than in wood bats and it was

located approximately 20.3 cm (8 in.) from the tip of the bat; these findings are not in agreement with our results. The more recent dynamic model by Nathan (11), which predicts that the maximum batted ball speed would occur in the neighborhood of 13.7 cm (5.4 in.) from the tip of a wood bat, is in good agreement with our results.

Contrary to the generally accepted belief among players, coaches, and bat manufacturers, we found no differences in the



**FIGURE 6**—Batted ball speed versus bat impact speed for the six bat models. Bat impact speed was defined as the speed of the bat at the location of impact of the ball. The data below the maximum batted ball speed for a given impact speed were associated with hits outside the “sweet spot” (see Fig. 5) and with hits on the “sweet spot” but not squarely on the central axis of the bat.

location and in the size of the sweet spot between metal and wood bats. However, it is important to appreciate that we defined the sweet spot as the locations on the bat that was associated with the top 10% and 20% of the fastest hits. We postulate that the belief in an enlarged sweet spot on metal bats may be associated in part with the significant decrease in MOI that allows for a faster swing and easier control, giving the player more time to react to a pitch. It is also possible that our definition of the sweet spot is not consistent with that of players, coaches, and bat manufacturers.

There did appear to be a difference between wood and metal bats with hits outside the sweet spot, but there were not enough data to warrant a statistical analysis. For example, in the plots of bats M2 and M5 of Figure 5, there were hits located at 21.6 cm (8.5 in.) that were almost  $3.6 \text{ m}\cdot\text{s}^{-1}$  (8 mph) faster than wood. On the other side of the sweet spot, there were also a few elevated hit speeds, for example, at 7.6 cm (3 in.) with bat M4 and at 8.9 cm (3.5 in.) with bat M2 (Fig. 5). These few data points suggest a marked increase in performance along the length of some metal bats.

Differences in the maximum batted ball speed correlated with bat swing speed and an inherent property of the bat, which we postulate is most likely the ball-bat COR. A limitation of this study was that we did not calculate the ball-bat COR directly. Increases in ball-bat COR have most often been attributed to the "trampoline effect," but we were unable to confirm this because we could not measure the deformations of the barrel wall. Vibrational behavior (11) or bat flex (12), as observed in the whipping action of golf club shafts, may also contribute to an increase in elastic performance. However, if bat flex did occur, we were unable to detect it with our methods.

The relative contribution of bat swing speed and elastic performance to batted ball speed varied among the five metal bat models. Bat M2 had the greatest contribution of both. Swing speed had a minimal contribution to bat M1, whereas the contribution of the elastic performance was significant. The relationship between bat swing speed and batted ball speed (Fig. 6) demonstrated an upper boundary of optimal hits for bat swing speeds up to about  $31.3 \text{ m}\cdot\text{s}^{-1}$  (70 mph). With wood, for example, hits at a swing speed of  $33.5 \text{ m}\cdot\text{s}^{-1}$  (75 mph) did not reach batted ball speeds that would be predicted by this upper boundary; it is likely that these wood hits were not optimal. The single data point of the fastest hit of M1 in Figure 5 lends some further insight. This point appears to be an outlier, but when examining the plot of bat M1 in Figure 6, we see that this hit was associated with an unusually high bat swing speed of nearly  $35.8 \text{ m}\cdot\text{s}^{-1}$  (80 mph).

The higher skilled players in our study hit the fastest balls (10). Had we recruited players with even higher skills, we would expect the batted ball speeds to have been even faster, but we cannot estimate how much faster. Our methods were not designed to evaluate the characteristics of the player or their swings that would account for differences with skill level. The influence of skill level on batted ball speed was removed in the current analysis by measuring the location and the bat speed at the point of impact. We did calculate the location of the instantaneous center of rotation of the bat just before impact and found that it was located consistently near the wrist of the bottom hand. This location is notably different than what is currently used in the laboratory methods adopted by the NCAA and the ASTM for evaluating baseball bat performance.

The bats categorized as  $-5$  and  $-4$  weight-length (bats M2, M3, M4, and M5 in Table 1) are no longer allowed in collegiate or high school play in the United States. The governing bodies at these levels (the NCAA and the National Federation of High Schools (NFHS)) have implemented  $-3$  as the maximum allowable difference between weight and length. The performance capabilities of baseball bats currently in use at the high school and collegiate levels

are unknown. There are other limitations to this study. The full motion of the swing was not consistently recorded because of the limited field of view of the cameras. Initially, an aluminum ring (0.6 cm (0.25 in.) thick, 6.4 cm (2.5 in.) diameter) with triangulated markers was attached via three set screws to the bat above the grip. During preliminary testing, the rings became badly deformed, even though no balls struck the rings directly. This necessitated applying marker tape directly to the bat along its central axis, resulting in colinear markers. Because colinear markers cannot be used explicitly to calculate the three-dimensional kinematics of bat, we made the assumptions that the bat rotated within a plane for consecutive sampling frames of  $2 \text{ m}\cdot\text{s}^{-1}$ , that the bat was a rigid body, and that it did not rotate about its central axis. In evaluating the error of these assumptions, we found that the bat translation orthogonal to this plane averaged  $0.3 \pm 0.8 \text{ cm}$  ( $0.1 \pm 0.3 \text{ in.}$ ) for all bat swings. The root mean square distance from the linear fit of the central axis of the bat to each marker was  $0.8 \pm 0.5 \text{ cm}$  ( $0.3 \pm 0.2 \text{ in.}$ ), suggesting that the bat did behave as a rigid body within the frames we analyzed. Additionally, we grouped all pitched speeds. There was no statistical correlation between pitched ball speeds, which ranged between  $21.5 \text{ m}\cdot\text{s}^{-1}$  and  $29.5 \text{ m}\cdot\text{s}^{-1}$  (48 mph and 66 mph), and either batted ball speed or bat swing speed (10). However, over a wider range of pitched ball speeds, we would expect a trend toward increased batted ball speed with increased pitched ball speed.

In summary, we have shown that some metal bats can significantly outperform wood bats. Our analysis indicated that this increase in performance is due to increases in swing speeds and an inherent elastic property. In addition, we found only minimal differences among bats in the size of the sweet spot associated with maximum batted ball speeds. Identifying the role of these variables leads to a better understanding of differences in bat performance and should greatly aid in the investigation of current bat models and in the development of laboratory test methods for measuring bat performance.

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