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Bat Kinematics in Baseball: Implications for Ball Exit Velocity and Player Safety

Rochelle L. Nicholls[1,2], Bruce C. Elliott[1], Karol Miller[2], and Michael Koh[1,3]

[1,2]University of Western Australia; [3]Nanyang Tech University

Ball exit velocity (BEV) was measured from 17 experienced baseball hitters using wood and metal bats of similar length and mass but different moments of inertia. This research was conducted in response to safety issues for defensive players related to high BEV from metal baseball bats reported in the literature. Our purpose was to determine whether metal bats, with their lower swing moment of inertia, produce a higher linear bat tip velocity than wooden bats swung by the same players. Analysis using high-speed videography indicated significant differences in the x-component of velocity for both the proximal (metal = 5.4 m s^{-1}; wood = 3.9 m s^{-1}) and distal ends of the bats (metal = 37.2 m s^{-1}; wood = 35.2 m s^{-1}), $p < 0.01$. The orientation of the bats with respect to the horizontal plane was also significantly more "square" 0.005 s prior to impact (270°) for the metal (264.3°) compared with the wood bat (251.5°), $p < 0.01$. Mean BEV from metal bats (44.3 m s^{-1}) was higher than the 41 m s^{-1} velocity which corresponds to the minimum movement time for a pitcher to avoid a ball hit in his direction (Cassidy & Burton, 1989).

Key Words: equipment design, injury risk, field performance

Introduction

Wooden bats have been used in baseball since the inception of the game, and are still exclusively used by professional players. More durable metal bats were introduced into college and youth baseball in 1972. Metal bat performance has been the subject of recent research, as concern has arisen over ball exit velocity (BEV) and its link to player safety. The closest infielder to the hitter, the pitcher, is at greatest risk of being struck by a batted ball. Such impact injuries comprise about 3% of all

[1]School of Human Movement and Exercise Science, and [2]Dept. of Mechanical and Materials Engineering, The University of Western Australia: Crawley, Perth, WA 6009, Australia; [3]Physical Education and Sports Science Academic Group, National Institute of Education, Nanyang Technological University, Singapore.

injuries to pitchers (Dick, 1999), but they can be devastating. A full 35% of baseball fatalities from 1973 to 1985 were caused by a pitcher being struck in the head or chest by the ball (Viano, Andrzejak, & King, 1992). The National Center for Catastrophic Sports Injury Research indicated that baseball had the highest fatality rate of 13 men's sports surveyed in U.S. colleges (*NCAA News*, June 8, 1998).

The risk to pitchers may be increased when facing hitters who use metal bats rather than wooden bats. At an average distance of 16.5 m from the batter when the ball is hit, an adult pitcher requires approximately 0.4 s to complete a protective motion in response to a batted ball (Cassidy & Burton, 1989), which corresponds to a BEV of approximately 41 m s^{-1}. Mean BEV values previously obtained from wood bats range between 39.6 and 44.2 m s^{-1} (Bryant, Burkett, Chen, Krahenbuhl, & Lu, 1977; Elliott, 1979). Greenwald, Penna, and Crisco (2001) quantified mean BEV from metal bats swung by semi-professional and college hitters at 47.6 m s^{-1}, with even high-school players achieving exit speeds above 44 m s^{-1}, which translates to 100 mph.

The difference in performance of wood vs. metal bats has been attributed to the elastic and vibrational behavior of the bat materials (Ashley, 1990; Brody, 1986; Noble & Eck, 1985). However, the ball impact period of approximately 1 ms is much shorter than the period of oscillation of a bat held in the hands, and it is well known that impacts occurring at the bat vibrational nodes result in zero reaction force at the hitters' hands and little or no vibration being excited in the bat structure (Adair, 1997; Cross, 2001). Hence, factors beyond the behavior of bat material may contribute to the production of BEV. These may include bat linear velocity and bat "impact mass" (Adair, 1997; Fleisig, Zheng, Stodden, & Andrews, 2002). This study proposed that the manner in which the bat is swung, and hence its orientation and velocity at impact with the ball, play an important role in determining BEV.

The selection of wood or metal materials in bat construction promote differences in design which affect the manner in which the bat is swung. The varying densities of the materials particularly affect the distribution of mass along the long axis of the bat. Aluminium alloys are four times as dense as wood, meaning that a metal bat must be shaped as a thin-walled hollow tube to maintain the same weight as a solid ash bat, whose mass is distributed throughout the entire implement. If a bat is made up of N small elements of mass m_i at a distance x_i ($i = 1...N$) along the bat from the hand, the three moments of importance to the swing are represented by the relation

$$M_j = \Sigma m_i x_i^j$$

j = 0, 1, or 2

x is the distance from the hand to the bat center of mass (Brody, 2000).

The zero moment (M_0), $\Sigma m_i x_i^0$, corresponds to the total mass of the bat, and is unaffected by the dispersal of mass among the N elements. However, both M_1 and M_2 depend on the spatial distribution of mass. M_1 ($\Sigma m_i x_i^1$) is proportional to the torque required to keep the bat barrel above the level of the hands during the swing. A greater first moment (end-heavy), as would be expected in a wood bat, may affect the position of the bat barrel with respect to the hitter's hands at impact, and thus the ability to drive the ball directly toward the pitcher. This bat orientation has not been previously quantified.

The rotary nature of the baseball swing indicates the importance of bat angular acceleration in developing linear velocity of the bat impact point. A change in mass distribution has a quadratic effect on resistance to angular acceleration (i.e., bat swing moment, M_2, $\Sigma m_i x_i^2$) about an axis perpendicular to the handle in the plane of the bat. Decreased resistance to angular acceleration permits delay in the onset of the swing, giving the hitter greater opportunity to detect the flight and velocity of the incoming ball (Thurston, 1999). A thin-walled metal bat has a relatively lighter barrel than its solid wood counterpart and would be expected to have a lower swing moment, with the corresponding gain in linear bat velocity resulting in an increase in BEV (Brody, 1979, 1997; Cross, 2001; Elliott, 1982; Mitchell, Jones, & King, 2000; Sprigings & Neal, 2001). The horizontal orientation of the bat at impact may also be affected by the greater barrel velocity. A more direct impact between bat and ball will also contribute to an increased BEV as less energy is lost to friction, heat, and sound (Hay, 1973).

The purpose of this study was to examine the effect of bat moment of inertia on bat linear velocity, as one variable among those that contribute to BEV. This variable was chosen because it has been formally identified by the NCAA as a potential control mechanism in bat design to reduce BEV to safer levels for infielders (Dick, 1999). High-speed videography was used to determine the effect of bat inertial characteristics on BEV. Bat linear velocity and orientation at 0.005 s prior to impact were also used as indicators of bat performance.

Notations

BEV	ball exit velocity	($m\ s^{-1}$)
m	mass	(kg)
r	radius of rotation	(m)
t	time	(s)
v	linear velocity	($m\ s^{-1}$)
ω	angular velocity	($rad\ s^{-1}$)

Methods

One metal (Easton BE-811) and one wooden commercially available bat (Easton Redline Pro Stix 271), which are used in high school and college baseball, were selected for analysis. Bats were selected to be virtually identical in length and mass. The metal bat was constructed from an alloy of heat-treated aluminium, zinc, and magnesium. The wood bat was made of solid white ash. Bat swing moments were obtained using the pendulum technique described in Elliott and Ackland (1982), and the parallel axis theorem (Winter, 1990). These were verified using a three-dimensional (3-D) model of each bat constructed in AutoCAD 14 (Autodesk, San Rafael, CA) from measurements taken at 168 intervals along the length of the bat. This method was also used to obtain bat polar moments about the long axis of the bat. The location of the bat center of mass (CM) indicates the wood bat had a greater proportion of its mass located in the distal (barrel) end than did the metal bat (Table 1).

Table 1 Specifications of Bats Used in This Study

	Wood bat	Metal bat
Mass	0.840 kg (29.6 oz)	0.805 kg (28.4 oz)
Length	0.835 m (32.8 in.)	0.834 m (32.9 in.)
Center of mass (% bat length)	0.573 m (69%)	0.529 m (63%)
Diameter at widest point	0.064 m	0.07 m
Volume	0.320 m^3	0.318 m^3
Wall thickness	n/a	34 mm (handle)
		22 mm (throat)
		33 mm (barrel)
Polar moment	0.032 $kg{\cdot}m^2$	0.057 $kg{\cdot}m^2$
Swing moment about bat knob	0.329 $kg{\cdot}m^2$	0.269 $kg{\cdot}m^2$

Note: Bat specs expressed in both metric and empirical units, as is customary in baseball. Bat center of mass is measured from knob. Bat swing moment is expressed about the most proximal portion of bat (knob). Polar moment of each bat is expressed about the long axis of bat. Wall thickness of metal bat was obtained after sectioning the shell.

Informed consent was obtained from 17 hitters (10 right-handed, 7 left-handed) from an Australian summer baseball league. A minimum batting average of .300 from the previous season was required for selection. The mean batting average of the group was 0.336 ± 0.04. Participants were age 22.8 ± 4.6 years, with a mean height of 1.8 ± 0.7 m and average mass of 83.1 ± 8.6 kg.

All participants attended a familiarization session at the indoor hitting facility prior to filming, in which practice with each bat was undertaken in a net-mesh batting tunnel measuring 3 m × 4 m × 26 m. During data collection, experienced pitchers pitched baseballs to each batter from a distance of 10.7 m. The average pitch velocity was 23.2 ± 2.4 m s^{-1}.

Each participant hit with both wood and metal bats, presented randomly. Batters were instructed to swing at pitches only in the midsection of the strike zone, and they continued batting until five "line drives," directed toward centerfield, were recorded for each bat.

High-speed video data were collected using two electronically-synchronized 200-Hz cameras with a shutter speed of 1/1000 s. Cameras were positioned with their optical axes aligned to approximately 60°. Direct linear transformation (Abdel-Aziz & Karara, 1971) was used to obtain 3-D coordinates for the motion of the bat and ball in time increments of 0.005 s. A standard calibration frame provided 24 control points with known spatial coordinates in a volume of 2.5 × 2.0 × 1.5 m, which enclosed the total area of the swing and initial ball exit trajectory. In the global coordinate system, the positive x-axis was directed toward the pitcher (parallel to the turf floor), positive-y was specified as vertical, and positive-z as the cross-product of the x- and y-axes.

The middle of the ball and six points on the bat were manually digitized using Peak Motus 2000 software (Peak Performance Technologies, Englewood, CO), with a mean volume percentage error of 0.3% for manual digitizing and average mean square error of 0.0095 m. Repeatability of data was assessed by redigitizing three randomly selected trials for hitters using wood and metal bats, after 2 weeks. Bat tip linear velocity and bat orientations varied by less than 1%.

Three trials were digitized for each participant, selected on the basis of the ball being hit as a line drive predominantly in the positive X direction, using feedback from each hitter, and visual inspection of the ball flight path from each camera angle. The bat was digitized from the first movement of the hitter's hands in the negative Y direction, until one frame (0.005 s) prior to ball impact, to avoid discontinuity effects attributable to the momentum of the ball impacting the bat (Winter, 1990). The postimpact motion of the ball was digitized as a separate trial, beginning from the frame of bat/ball impact and concluding 10 frames later. Data were smoothed using a quintic spline function.

The trial producing the highest bat-tip linear velocity in the preimpact frame was selected for analysis for each hitter. The preimpact linear velocity components of the most distal aspect of the leading surface of the bat tip, the bat knob, and a point between the hitter's hands, were determined using a second-order central difference algorithm. BEV was quantified from the mean displacement of the ball between the first and fourth frames after impact in the x-direction. Resultant velocities from both the bat and hands were determined from the square-root of the sum of the squared component velocities.

A numerical technique detailed in Verstraete and Soutas-Little (1990) was used to derive the components of the angular velocity vector, from digitized 3-D position data. The technique was based on the method of least squares. The bat was deemed a rigid body, in which the magnitude of the relative position vector between any two points remains constant with time, and the velocity, $\vec{v}$, of any point *m* may be expressed relative to the velocity of any other point *n* as:

$$\vec{V}_{m/n} = \vec{\omega} \times \vec{r}_{m/n} \tag{1}$$

The six digitized points on the rigid bat were used for this method, unlike previous methods of calculating bat angular velocity which have required additional kinematic data from the upper limbs of the batters (e.g., Fleisig et al., 2002). These points were selected as bat tip (TIP), a series of three orthogonal markers mounted on the bat 30 cm from the knob (MAR 1, 2, 3), a point between the hitter's hands (HANDS), and bat knob (KNOB). The relative position vectors and the relative velocity vectors formed by each point with respect to HANDS were determined for the frame prior to impact. The equations relating the angular velocity of the bat to the relative linear velocities of the target points were written in the form of Equation 1:

$$\begin{aligned}
\vec{V}_{\mathrm{TIP/HANDS}} &= \vec{\omega} \times \vec{r}_{\mathrm{TIP/HANDS}} \\
\vec{V}_{\mathrm{MAR\,1/HANDS}} &= \vec{\omega} \times \vec{r}_{\mathrm{MAR\,1/HANDS}} \\
\vec{V}_{\mathrm{MAR\,2/HANDS}} &= \vec{\omega} \times \vec{r}_{\mathrm{MAR\,2/HANDS}} \\
\vec{V}_{\mathrm{MAR\,3/HANDS}} &= \vec{\omega} \times \vec{r}_{\mathrm{MAR\,3/HANDS}} \\
\vec{V}_{\mathrm{KNOB/HANDS}} &= \vec{\omega} \times \vec{r}_{\mathrm{KNOB/HANDS}}
\end{aligned} \tag{2}$$

For each vector equation, three scalar equations were written to solve for the components of ω. Thus, for the set of vector equations (Eq. 2), a total of 15 scalar equations was obtained. The solution for both metal and wood bats was obtained using a linear equations solution method written in Matlab 5.3 (Mathworks, Natick, MA).

Paired-sample one-tail t-tests were used to test for differences between the wood bat and metal bat for linear velocity of the tip of the bat at the instant prior to impact for each of the component velocities (X,Y, Z), and ball exit velocity. The Wilcoxon signed ranks test was used to examine differences between bat resultant velocities, due to the noncentral chi square nature of the data distribution. The Bonferroni correction was taken into consideration in selecting a significance level of $p < 0.01$ (Thomas & Nelson, 1996).

Results

The results indicated that baseball bat design, particularly bat swing moment of inertia, plays an important role in the production of BEV. Significant differences were evident in bat tip linear velocity and implement orientation 0.005 s prior to impact between the wood and metal bats. Mean BEV from hitters using the metal bat exceeded that from the wood bat by 2.6 m s^{-1} (Table 2), and exceeded the recommended safe limit of 41 m s^{-1}. In addition, a positive skew (k = 0.604) for BEV from the metal bat indicated this bat was likely to produce BEVs higher than 44.3 m s^{-1}.

Hitters in this study achieved significantly greater bat tip resultant linear velocity when swinging a metal bat (Table 2). The primary manifestation of the difference in swing speed between wood and metal bats was in the x-component of velocity, the component directed into the infield. This is the primary component of velocity in a line drive, which reflects danger to the pitcher of being struck by the ball. This result was also noted for the linear x-component velocity of the hands immediately prior to impact (Table 2).

Mean swing times (ST), the time from the first movement of the hitter's hands in the negative y-direction to the instant prior to ball contact, were significantly different for hitters using metal bats (0.139 ± 0.02 s) vs. those using wood bats (0.150 ± 0.01 s), $p = 0.01$. In spite of the relatively shorter swing time, the metal bat tip was located an average of approximately 13° ahead of the horizontal position achieved by the wood bat 0.005 s prior to impact (with this orientation, TRANS, described by an angle between the z-axis and a vector from the batter's hands to the bat tip, projected on the XZ plane) (Figure 1). The position of the barrel above or below the hitter's hands at impact (TILT, Figure 2) was not significantly different (Table 2).

Bat angular velocity about an axis between the batter's hands was calculated for a subsample of 9 hitters (Table 2). This subsample was selected from trials with the best image clarity of the bat markers, as the calculation method relied upon precision of marker identification for these markers, particularly in the frame prior to impact. This position of the instantaneous axis of rotation had previously been reported by Noble and Eck (1985). While Mitchell et al. (2000) suggested that the relationship between implement swing weight, linear velocity, and angular velocity was erratic and sensitive to player timing, the least-squares method of calculating angular velocity has yielded consistent values (Verstraete & Soutas-Little, 1990). The primary component of angular velocity related to BEV, ω_y, was approximately 40 rad/s for all hitters regardless of bat design.

Table 2 Dependent Variables for Hitters Using Wood and Metal Bats

	Wood bat	Metal bat	p
Ball exit velocity			
BEV (m s^{-1})	41.7 ± 1.9	44.3 ± 2.5	0.001*
BEV (mph)	93.9 ± 4.9	99.1 ± 6.1	
Bat linear velocity – distal end			
TIP X (m s^{-1})	35.2 ± 1.8	37.2 ± 1.8	0.002*
TIP Y (m s^{-1})	–1.7 ± 4.3	–0.7 ± 5.1	0.248
TIP Z (m s^{-1})	3.9 ± 6.0	4.8 ± 4.6	0.284
TIP R (m s^{-1})	36.4 ± 1.7	38.3 ± 1.8	0.001*
Bat linear velocity – proximal end			
HANDS X (m s^{-1})	3.9 ± 2.0	5.4 ± 1.6	0.01*
HANDS Y (m s^{-1})	1.1 ± 1.5	1.2 ± 1.1	0.486
HANDS Z (m s^{-1})	–0.2 ± 5.5	1.0 ± 5.8	0.230
HANDS R (m s^{-1})	6.9 ± 2.1	8.1 ± 1.9	0.051
Bat angular velocity			
ω_x (rad s^{-1})	4.6 ± 4.2	6.5 ± 4.0	n.a.
ω_y (rad s^{-1})	40.0 ± 9.9	40.4 ± 4.5	
Bat 3-D orientation			
TILT (deg)	117.8 ± 7.5	120.3 ± 5.9	0.125
TRANS (deg)	251.5 ± 10.4	264.3 ± 9.1	0.001*
Hitter swing time			
Swing time (s)	0.150 ± 0.01	0.139 ± 0.02	0.01*

Note: Velocities and angles expressed at 0.005 s prior to ball contact. Mean resultant linear vel. (m s^{-1}) reported as square root of summed squared component velocities. Bat angular vel. (rad s^{-1}) is expressed about an axis of rotation between the hitter's hands. Global coordinate system is rotated 180° about y-axis for left-handed hitters to maintain sign convention. Angle TILT = orientation of bat barrel above or below a horizontal plane: 90° means bat is perfectly horizontal. TRANS is measured counter-clockwise from global x-axis, and 270° means bat is parallel to global z-axis. Swing time = instant of first negative-y displacement of hitter's hands, until ball impact.

Discussion

Baseball hitting is an open-chain skill in which velocity of body segments progresses from the most proximal (the legs), to the most distal, the bat, which rotates freely through space and whose direction and motion determine the outcome of the swing (Putnam, 1993). In ascertaining the effect of bat design on BEV, it is important to determine the orientation and speed of this ultimate segment at impact. This research was the first to address the relationship of BEV to bat design

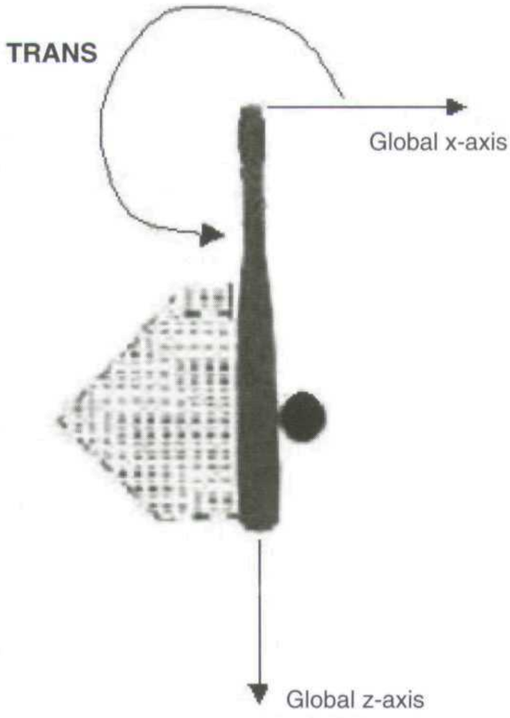

Figure 1 — Horizontal bat orientation (TRANS), viewed from above. An angle of 270° indicates the bat is parallel with the front of home plate and perpendicular to the global z-axis.

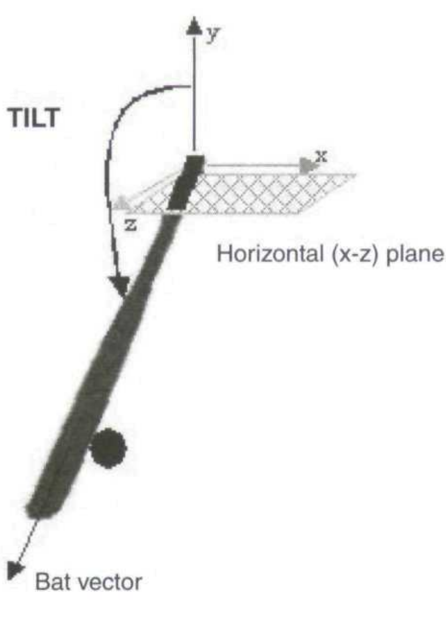

Figure 2 — TILT is measured as the included angle between the global y (vertical) axis and a vector corresponding with the long axis of the bat. This angle describes the orientation of the bat above or below a horizontal plane passing through the most proximal end of the implement, where 90° indicates the bat is parallel with this x-z plane.

by restricting test bats to those of identical length and similar mass but different swing and polar moments. The results clearly indicate that bat design, particularly bat weight distribution, is an important factor in BEV for the bats used in this research. A handle-weighted metal bat produced significantly greater linear velocity in the component of the swing directed toward the pitcher for an identical angular velocity and radius of rotation, and a significantly less oblique horizontal orientation just prior to impact (Table 2). This bat also produced a mean BEV that exceeded a velocity designated as sufficient for a pitcher to take evasive action (Cassidy & Burton, 1989).

Greater BEV from metal compared with wood bats has been reported as early as 1977, just 3 years after metal bats were introduced into college baseball (Bryant et al., 1977). Greenwald et al. (2001) most recently indicated significantly greater BEV for hitters using metal bats. The mean BEV reported in that research exceeded the results of the current research by approximately 3 m s^{-1}. However, the study by Greenwald et al., as with that of Fleisig et al. (2002), did not control for bat length and mass, so it is unclear whether the source of the BEV difference was due to bat weight distribution or to factors related to bat mass or length. The bat tip resultant linear velocity values obtained in this study were approximately 6 m s^{-1} greater than those reported by Hirano (1987) and by Welch, Banks, Cook, and Draovitch (1995), although those studies were restricted by small sample size and the use of a hitting tee, respectively.

Bat moment of inertia is one factor in an array of variables that may contribute to BEV, including, as indicated in this study, the linear velocity of the bat at impact (Fleisig et al., 2002), and the elasticity of the collision and material properties of bats and ball (Ashley, 1990; Brody, 1986; Bryant et al., 1977; Nathan, 2000; Noble, 1998; Noble & Eck, 1985). The purpose of this study was to examine the role of bat moment of inertia in producing BEV, as in 1999 the NCAA Baseball Rules Committee recommended that regulations be placed on weight distribution in metal bats so as to reduce the danger to pitchers (Dick, 1999). The results of this research support such a recommendation, which has not yet been enacted.

As with the findings of Fleisig et al. (2002), the lesser swing moment of the metal bat produced no quantifiable difference in angular velocity about the swing axis of the bat (ω_y), under the assumption that hitters applied equal torque to the handle when swinging wood and metal bats. We propose that the differing x- and resultant linear velocities of the bat tip are the result of the effect of the swing moment at the player's hands. Thurston (1999) claimed a hitter's primary advantage in using a handle-weighted bat is the greater ability to develop angular acceleration, which permits a delay in the onset of the swing and allows more opportunity to detect the flight and velocity of the incoming ball. When using the metal bat, players in this study had notably shorter ST and significantly greater x- and resultant hand velocity, which in turn promoted greater bat tip velocity and the increased travel of the bat barrel to a position almost parallel with the global z-axis near impact. The ST values (metal bat: 0.139 ± 0.02 s; wood bat: 0.150 ± 0.01 s; $p = 0.01$) are similar to those reported by McIntyre and Pfautsch (1982), who indicated a mean time from the initial movement of the bat to ball contact of 0.125 to 0.142 s in college batters.

No previous research has reported player hand speed in relation to bat tip velocity. Similarly, there is no published data related to bat orientation at impact and subsequent BEV. The results of this study indicate that decreased obliquity of the metal bat/ball impact may have contributed to increased BEV. The mechanism for increased BEV was suggested to be a more direct application of force and reduced bat/ball frictional forces (Hay, 1973).

Cassidy and Burton (1989) indicated a BEV of approximately 41 m s^{-1} is the upper limit for a pitcher to avoid being struck by the batted ball. The mean BEV achieved by hitters in this study using metal bats exceeded this level by over 2 m s^{-1}. The finding that BEV from metal bats was as high as 54 m s^{-1} (121 mph) indicates a high potential for impact injury to the pitcher. Reverting to the exclusive use of wood bats is not an economically viable strategy for reducing the likelihood of such injuries, however, as a major reason for why metal bats were introduced into baseball was the high cost of broken wood bats and the increasing shortage of white ash wood for manufacturing bats.

Controls in bat design have been evident in baseball since 1876, and current NCAA regulations for metal bats have requirements for design features such as bat diameter and length-to-weight ratio. All bat models must also conform to a maximum BEV of 93 ± 1 mph when the bat is swung at 36 m s^{-1} (80 mph) by a robotic hitting machine. This limit, introduced in 2000, was established from tests conducted on solid ash bats. A mean BEV of 41.7 m s^{-1} (93.8 mph) from a wood bat in this study supports the use of wood bats as a gold standard to determine permissible bat performance in baseball.

It should be noted, however that, while specific to these bats and players, the results of this study clearly indicate that a "certified" metal bat swung by an experienced hitter may produce BEV exceeding that demonstrated by a robotic hitting machine, a result also reported by Greenwald et al. (2001). They showed that high school players consistently achieved a BEV exceeding 44 m s^{-1} (100 mph) with metal bats. Legendary hitters such as Ted Williams have previously indicated the value of contacting the ball with the bat directly over the home plate for maximum ball exit speed (Williams & Underwood, 1971) as ball energy loss to friction, heat, and spin is minimized (Hay, 1973). The greater lag of the bat 0.005 s prior to impact for the barrel-weighted wood bat in this study may point toward a potential design-control method for reducing BEV. Metal bat swing moment may be controlled through modifications such as adjustments in barrel wall thickness and changes in handle diameter and knob weight to both reduce the swing moment of inertia and the effective mass of the bat impact region

However, the issue of infielder safety in baseball may extend beyond bat design. The maximum ball exit velocity recorded from the wood bat in this study was 49.1 m s^{-1}, indicating that hitters using wood bats can also produce potentially dangerous line drives. These results suggest the issue of equipment design and safety in baseball is probably multifactorial. Further research is required into equipment behavior during high-speed impacts, particularly the elastic properties of the ball, and the dynamics of energy exchange between varying types of bats and the ball. The increasing size and strength of hitters, the variation in reaction time among pitchers according to individual pitching style, and the use of protective equipment by defensive players are additional variables in the risk analysis, and these must also be addressed.

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