A Numerical Model for Risk of Ball-Impact Injury to Baseball Pitchers

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ABSTRACT

NICHOLLS, R. L., K. MILLER, and B. C. ELLIOTT. A Numerical Model for Risk of Ball-Impact Injury to Baseball Pitchers. *Med. Sci. Sports Exerc.*, Vol. 37, No. 1, pp. 30–38, 2005. **Introduction:** Metal baseball bats produce higher ball exit velocity (BEV) than wood bats, increasing the risk of impact injuries to infield players. In this paper, maximum BEV from a wood and a metal bat were determined using the finite element method. **Methods:** Three-dimensional (3-D) bat kinematics at the instant of impact were determined from high-speed videography ($N = 17$ high-performance batters). A linear viscoelastic constitutive model was developed for stiffer and softer types of baseballs. The risk of impact injury was determined using available movement time data for adult pitchers; the data indicate that 0.400 s is required to evade a batted ball. **Results:** The highest BEV (61.5 m·s^{-1}) was obtained from the metal bat and the stiffer ball model, equating to 0.282 s of available movement time. For five impacts along the long axis of each bat, the "best case scenario" resulted from the wood bat and the softer ball (46.0 m·s^{-1}, 0.377 s). **Conclusions:** The performance difference between the bats was attributed to the preimpact linear velocity of the bat impact point and to differences in orientation on the horizontal plane. Reducing the swing moment of the baseball bat, and the shear and relaxation modulii of the baseball, increased the available movement time. **Key Words:** BASEBALL EQUIPMENT, DESIGN MODIFICATION, FINITE ELEMENT METHOD, IMPACT HAZARD ANALYSIS

The financial cost and morbidity from sports injuries are major public health concerns. Baseball, one of the most popular team sports in the world, is generally considered to entail low risk of injury due to the noncontact nature of the game. However, baseball (and softball) has recently been shown to cause more injuries requiring medical attention than any other sport in the United States (5,32), with more than 2.6 million incidents reported in 1983–1989 (28). Of the 88 fatalities recorded between 1973 and 1995, 76% resulted from impact by the batted, pitched, or thrown ball (5). The pitcher is the closest infielder to the hitter and is therefore at greatest risk of being struck by the batted ball, with 23 deaths recorded between 1973 and 1983 (28).

Reduction in the incidence and severity of such impact injuries not only requires understanding of the biomechanical mechanisms underlying trauma but also rigorous quantification of equipment performance to establish the risk of such an injury occurring. Marshall et al. (16) showed, in a review of 6,744,240 junior player seasons, that modification to the material properties of baseballs can result in reduced incidence and severity of impact injuries. However, the contribution of bat type and bat design to the incidence of players being struck by the ball was not discussed. Wooden bats have been used in baseball since the game originated in the early 19th century. Professional players still exclusively use these bats. More durable metal bats were introduced into baseball in 1972 and are now in worldwide use in most amateur, college, and youth baseball leagues. Metal bats outperform wood bats when performance is measured by ball exit velocity (BEV) (12), which has provoked further scrutiny of metal bat performance (e.g., (10)). However, ball-impact injuries are also reported in professional baseball (7,32), indicating the problem is not confined to leagues using metal bats.

During a high-speed impact, the baseball is in contact with the bat for as little as 1 ms (4), a period less than the typical vibrational response time of a wood or metal bat (21). Factors beside bat material properties therefore affect BEV from each bat type. Experimental studies by Fleisig et al. (10) and Greenwald et al. (12) have shown bat mass distribution, which differs considerably in metal and wood bats of equal mass and length affects the preimpact linear velocity of the bat and, by inference, the momentum that can be imparted to the baseball. Bat orientation at impact, which also affects the exchange of energy between bat and ball, has never been quantified but could reasonably be expected to differ in bats of different mass distribution.

Although much attention has been devoted to bat performance, the contribution of the material characteristics of the baseball to BEV remains unknown. Baseball stiffness (14,16,28) and mass (9,15) have been identified as impor-

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tant to the magnitude and severity of impact injury, but the behavior of the ball during interaction with the bat is yet to be quantified.

Despite the concerns expressed over the potential for balls hit at high velocity to cause injury to infield players, restrictions on bat performance are not evident at most levels of the game. Metal bats used in collegiate (National Collegiate Athletic Association (NCAA)) baseball in the United States are currently subject to a maximal BEV restriction of 43.1 $m \cdot s^{-1}$ when tested using robotic hitting machines which swing the bat in a horizontal plane at 29.3 $m \cdot s^{-1}$ against a ball projected at the same velocity (2). Such devices, designed for simplicity and repeatability, may not truly reflect the performance capabilities of a bat when swung by a hitter. In this paper, finite element analysis (FEA) was used to approximate the maximum BEV generated from wood and metal baseball bats when swung by high-performance players. FEA has previously been used to quantify baseball bat performance (17,25,26). However, these models did not account for important factors in the dynamics of impact such as the moment of inertia of the bat, preimpact linear velocity of the bat impact point, and three-dimensional (3-D) orientation of the implement. The purpose of this study was to use a model of bat–ball impact based on experimental data for bat kinematics and ball time-dependent behavior to quantify the maximum risk of a pitcher being struck by a baseball from each bat type.

METHODS

Baseball bat models. The 3-D models of a wood and a metal baseball bat were developed using ANSYS/LS-DYNA 6.1 FEA software (LSTC, Livermore, CA.). Bat geometry was obtained using calipers at 168 intervals along the bat length from one aluminum alloy bat (Easton BE-811) and one white ash wood bat (Easton Redline Pro Stix 271) of identical length and mass (Table 1). The wood bat was modeled as a homogeneous rigid solid meshed with 9800 eight-node SOLID-164 hexahedral elements (Fig. 1). The metal bat was represented by a rigid hollow tube meshed with 12974 SOLID-164 elements to accommodate changes in wall thickness along its length (3.3–6.1 mm). The assumption of rigidity was appropriate as bat deformation is negligible compared with its overall motion, the collision duration was much shorter than the time taken for an impulse to be reflected from the hitter's hands, and using rigid bodies also reduced the computation time for an explicit analysis (6). Bat moment of inertia values were obtained using the pendulum technique and the parallel axis theorem

TABLE 1. Physical characteristics of baseball bats used to develop 3-D models in this study.

		Wood Bat		Metal Bat	
		Experimental	LSDYNA	Experimental	LSDYNA
Mass	kg (oz)	0.840 (29.6)	0.872	0.805 (28.4)	
Length	m (inches)	0.835 (32.8)	0.835	0.834 (32.9)	
Density	$kg \cdot m^{-3}$	600	600	2400	2400
Young's modulus	Pa	1.22E+10	1.22E+10	7.00E+10	7.00E+10
Poisson's ratio		0.371	0.371	0.300	0.300
Center of mass (CM)	m (%) Length	0.529 (63)	0.526	0.479 (57)	0.479
Diameter at widest point (barrel)	m	0.064	0.064	0.070	0.070
Wall thickness	mm				
Handle		n/a		34	
Throat		n/a		22	
Barrel		n/a		33	
Moments of inertia about bat knob					
Ixx	$kg \cdot m^{-2}$		0.356		0.336
Iyy (swing moment)	$kg \cdot m^{-2}$	0.329	0.309	0.269	0.254
Izz (polar moment)	$kg \cdot m^{-2}$	0.032	0.114	0.057	8.83E−02 –
Ixy	$kg \cdot m^{-2}$		−5.05E−02		1.35E+00
Iyz	$kg \cdot m^{-2}$		0.145		0.128
Izx	$kg \cdot m^{-2}$		9.32E−02		2.32E−02
Moments of inertia about CM					
Ixx	$kg \cdot m^{-2}$		4.33E−02		6.83E−02
Iyy	$kg \cdot m^{-2}$		3.76E−02		5.18E−02
Izz	$kg \cdot m^{-2}$		1.40E−02		1.82E−02
Ixy	$kg \cdot m^{-2}$		−4.89E−03		−1.21E−03
Iyz	$kg \cdot m^{-2}$		1.42E−02		1.14E−02
Izx	$kg \cdot m^{-2}$		9.05E−03		2.02E+03
Principal moments of inertia					
Ixx	$kg \cdot m^{-2}$		4.62E−02		6.84E−02
Iyy	$kg \cdot m^{-2}$		4.41E−02		5.53E−02
Izz	$kg \cdot m^{-2}$		4.59E−03		1.46E+02

Included are LSDYNA's estimates of bat mass and inertial properties from the 3-D models. Also given are experimental values for 3-D bat orientation angles, where horizontal orientation is the relative alignment of the bat to the global z-axis, and vertical orientation is expressed relative to the global y-axis. The LSDYNA working plane was rotated from its default x-y alignment to reflect the position of each bat, prior to entry of bat x, y, z coordinates in the modelling process. Linear and angular velocity loads applied to each bat were obtained using high-speed videography from seventeen elite baseball batters. Linear velocity loads were entered as time-varying array parameters applied to nodal components for each end of the bat. Angular velocities were applied about an axis 10 cm distal to the bat knob.

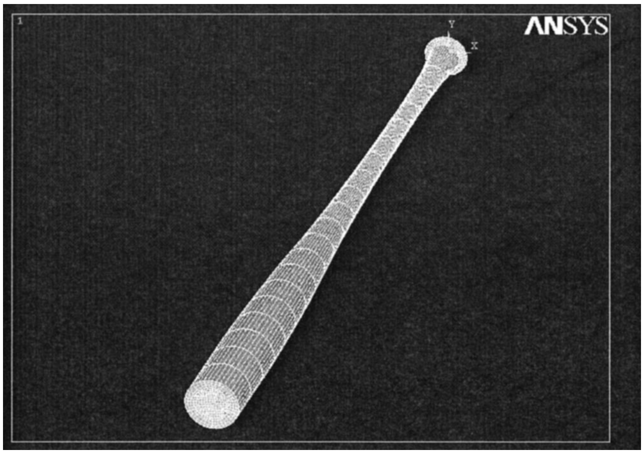

FIGURE 1—Baseball bat meshed with SOLID164 explicit hexahedral elements.

(31). These moments, and the inertial properties calculated by the software, are given in Table 1.

Bat position in 3-D space with respect to vertical and horizontal planes was input using kinematic data obtained from 17 high-performance batters (18) (Table 2). The mean position of the bat barrel below the hitters' hands at the instant before impact was very similar for metal and wood bats ($-27.8 \pm 7.5°$ and $-30.3 \pm 5.9°$, respectively, where 0° indicates the bat is horizontal). For the horizontal position of the bat, the metal bat was almost perpendicular to the path of the incoming ball ($-18.5 \pm 9.1°$; 0° indicates a perfectly "square" impact). The tip of the wood bat was located about 13° behind the position achieved by the metal bat.

In FEA of hitting implement behavior in sport, the acceleration histories, implement strains, and mode shapes have all been shown to be affected by the boundary condition imposed at the distal end of the implement (24,30). Smith (26) and Mustone and Sherwood (17) used a pinned condition to replicate the setup of a rotary hitting machine in FEA of baseball bat behavior. In our study, both ends of the bat were free to translate and rotate. The typical bat–ball impact duration of 1 ms is much shorter than the time taken for the vibration to be reflected from the batter's hands (21); hence, BEV cannot be affected by how the handle is secured.

Baseball model. Although a baseball is typically made up of multiple layers (a central cork or rubber core, wool packing, and a stitched leather cover), in this study, the baseball was represented as a homogeneous solid sphere of radius 36 mm, meshed with 2000 SOLID-164 hexahedral elements. This is in keeping with previous models such as that of Shenoy et al. (25), who obtained reliable BEV data for baseballs hit by a robotic hitting machine, using a homogeneous model. A linear viscoelastic material model was used to account for the time-dependent response of the ball to impact:

$$G(t) = G_\infty + (G_0 - G_\infty)e^{-\beta t} \quad [1]$$

Quasistatic uniaxial compression experiments to 50% of ball diameter were conducted on seven models of baseballs to obtain force-displacement data. FEA was used to fit a value for G_∞ (relaxed shear modulus) to the experimental data (Fig. 2). The value for G_0 (instantaneous modulus) was obtained through simulation of impacts at five velocities ranging from 13.2 to 40.2 $m \cdot s^{-1}$, comparing the ratio of inbound to outbound velocity (coefficient of restitution, COR) with the experimental results of Crisco et al. (9). The value of the decay constant β was set to 0.0007 s (the approximate duration of bat–ball impact). To investigate the effect of variation in the time-dependent properties of the baseball on BEV, a set of constants was developed for the stiffest and most compressible baseball models (herein designated as A and B) (Table 2) (19).

Explicit finite element analysis of bat–ball impact. To account for the large deformations and nonlinear response during bat–ball impact, explicit FEA procedures were used (33). The inbound ball was given an initial velocity of 40.2 $m \cdot s^{-1}$ (90 mph), which is typical of pitch speeds in collegiate and professional baseball. LSDYNA's general surface-to-surface contact algorithm was assigned because it is suitable for arbitrarily shaped contact areas with large amounts of relative sliding (6). The friction coefficient (μ_c) of 0.2 was determined from the relative velocity of the surfaces in contact. To determine maximum BEV, the analysis was restricted to impacts where the ball contacted the point of greatest momentum transfer on the bat. Although the tip of the bat has the greatest linear velocity during the swing as it is furthest from the axis of rotation, an antinode or point of maximum vibration exists here, and impact at the bat tip results in significant losses to bat deformation. Maximum BEV has been shown to occur in a region in the barrel close to the nodes of the lowest frequency bending vibrations (21). In this analysis, five impact locations were trialed for each bat: 570, 610, 630, 650, and 670 mm distal to the bat knob. Maximum BEV for the wood bat was obtained for impact 650 mm from the knob and at 670 mm for the metal bat (20).

Aerodynamics and risk analysis for impact injury to the pitcher. The effect of the flight characteristics of the baseball on the time available for a pitcher to avoid a batted ball was calculated using aerodynamic analysis based on differential equations that have been derived for the ball motion (11):

$$m\left(\frac{dv_x}{dt}\right) = -D_x \quad [2]$$

$$m\left(\frac{dv_y}{dt}\right) = -mg + L_x \quad [3]$$

m represents the ball mass (kg) and g = 9.8 $m \cdot s^{-2}$. L_x and

TABLE 2. Linear viscoelastic material constants for baseball Model A and Model B.

		Model A	Model B
Density	$kg \cdot m^{-3}$	7.42	7.42
Long-term shear modulus (G_∞)	Pa	3.81E+02	9.34E+01
Instantaneous shear modulus (G_0)	Pa	4.34E+04	2.89E+04
β	s	0.0007	0.0007

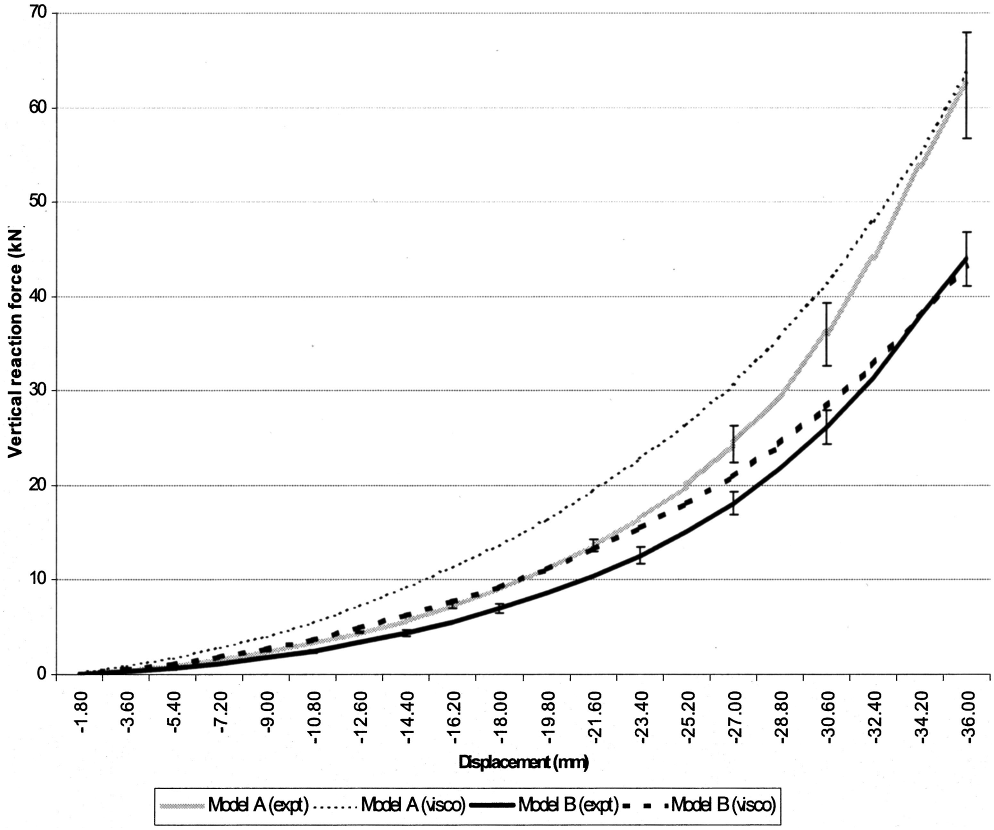

FIGURE 2—Force–compression curves for two models of baseballs. The experimental data are shown as solid lines, and the fit obtained using a linear viscoelastic material model given as dashed lines.

D_x are mutually perpendicular lift and drag forces, respectively:

$$L = \frac{1}{2}\rho C_L v^2 A \tag{4}$$

$$D = \frac{1}{2}\rho C_D v^2 A \tag{5}$$

The collision was assumed to take place at sea level and ambient temperature, hence ρ (air density) was specified as 1.29 $\text{kg}\cdot\text{m}^{-3}$. A is the cross-sectional area of the ball. The assumption of horizontal postimpact trajectory implies $v^2 \sim v_x^2$ (where v_x represents the component of ball velocity directed horizontally toward the pitcher, and v_y is considered vertical). C_D and C_L are dimensionless drag and lift coefficients.

Ball angular velocity (ω) in this case is selected as 40 $\text{rev}\cdot\text{s}^{-1}$ based on the typical spin rate of a pitched fastball (4) as no experimental data for the spin rate of batted balls are available. From tables established by Gerhart et al. (11), this value corresponds to $C_D \sim 0.35$ and $C_L \sim 0.070$. Although these tables were formulated from experimental data for smooth spheres, the data of Achenbach (3) indicated for Reynolds numbers corresponding to the BEV values in this study, these values are appropriate for baseballs. It is difficult to quantify the true C_D of a baseball as the procedure is undertaken using wind tunnels, and the values obtained depend on the tunnel width, the type of turbulence damping used, whether the ball is free to rotate, and ball orientation (3). Equation 2 is integrated for v_x:

$$\int_{v_{x0}}^{v_x} \frac{dv_x}{{v_x}^2} = \frac{-\rho C_D A}{2m}\int_0^t dt$$

Hence, the horizontal component of postimpact velocity evaluates to:

$$v_x = \frac{1}{\dfrac{1}{v_{x0}} + \dfrac{\rho C_D A t}{2m}} = \frac{v_{x0}}{1 + \beta t} \tag{6}$$

To find time of flight (t), equation 6 was substituted into $\frac{dx}{dt} = v_x$, and integrated:

$$\int_0^x dx = \int_0^t \frac{v_{x0}dt}{1 + \beta t}$$

where x = 0 at t = 0. From this expression, the time taken for the baseball to travel 16.46 m is derived as:

$$t = \frac{1}{\beta}\left[\exp\left(\frac{\rho C_D A x}{2m} - 1\right)\right] \tag{7}$$

Cassidy and Burton (8) estimated that a minimum of 400 ms is required for an adult pitcher to take evasive action against a ball hit directly at him, over a distance of approximately 16.50 m. Owings et al. (22) experimentally determined that 8-yr-old players were able to safely avoid baseballs hit at velocities below 26.8 $\text{m}\cdot\text{s}^{-1}$, and 16-yr-old players at $<$33.5 $\text{m}\cdot\text{s}^{-1}$. These results are used as the basis for risk analysis of the pitcher being struck by the batted ball in this study. Validation of the BEV values was difficult, as

TABLE 3. Results of bat–ball impact analysis for wood and metal bats impacted with two types of baseballs. Aerodynamic analysis was used to extrapolate BEV at 0.005 s postimpact to determine the time for the ball to travel 16.46 m.

		Wood Bat		Metal Bat	
		Model B	Model C	Model B	Model C
BEV(res) (0.005 s postimpact)	$m \cdot s^{-1}$	50.9	46.0	61.5	55.4
BEV(x)	$m \cdot s^{-1}$	42.0	35.1	59.1	52.8
BEV(y)	$m \cdot s^{-1}$	10.4	12.2	8.8	9.6
BEV(z)	$m \cdot s^{-1}$	26.8	27.1	14.7	13.8
Impact duration	s	0.0009	0.001	0.0009	0.0011
Peak reaction force (resultant)	kN	23.49	21.83	26.98	22.53
Time of peak resultant force	s	0.0006	0.0005	0.0005	0.0004
% impact time	%	66.7%	50.0%	55.6%	36.4%
Peak reaction force (horizontal − x)	kN	22.0	20.6	26.8	23.3
Time of peak x-force	s	0.0005	0.0004	0.0004	0.0005
% impact time	%	55.6%	40.0%	44.4%	45.5%
Peak reaction force (vertical − y)	kN	4.1	4.6	3.3	3.1
Time of peak y-force	s	0.0006	0.0006	0.0006	0.0007
% impact time	%	66.7%	60.0%	66.7%	63.6%
Peak reaction force (lateral − z)	kN	7.3	6.8	3.4	2.9
Time of peak z-force	s	0.0006	0.0004	0.0006	0.0006
% impact time	%	66.7%	40.0%	66.7%	54.5%
Maximum ball compression	m	0.0124	0.0135	0.0162	0.0172
Maximum compression	% diam	17.2%	18.8%	22.5%	23.9%
Time of max compression	%	44.4%	40.0%	55.6%	45.5%
Maximum ball lateral deformation	m	0.0049	0.0055	0.0064	0.0082
Maximum lateral deformation	% diam	6.8%	7.6%	8.9%	11.4%
Time of max lateral deformation	%	44.4%	40.0%	55.6%	45.5%
Impulse of impact	N·s	13.2	12.5	14.8	13.9

"the worst case scenario" cannot be easily replicated experimentally because it is relatively rare. Validation of the numerical model was undertaken by repeating the FEA to compare BEV from wooden and aluminum bats with the same initial conditions of bat linear and angular velocity and 3-D orientation.

RESULTS

Results of the analysis are given in Table 3. The following abbreviations are used in description of results:

Metal bat impact with Model A baseball: M_A

Metal bat impact with Model B baseball: M_B

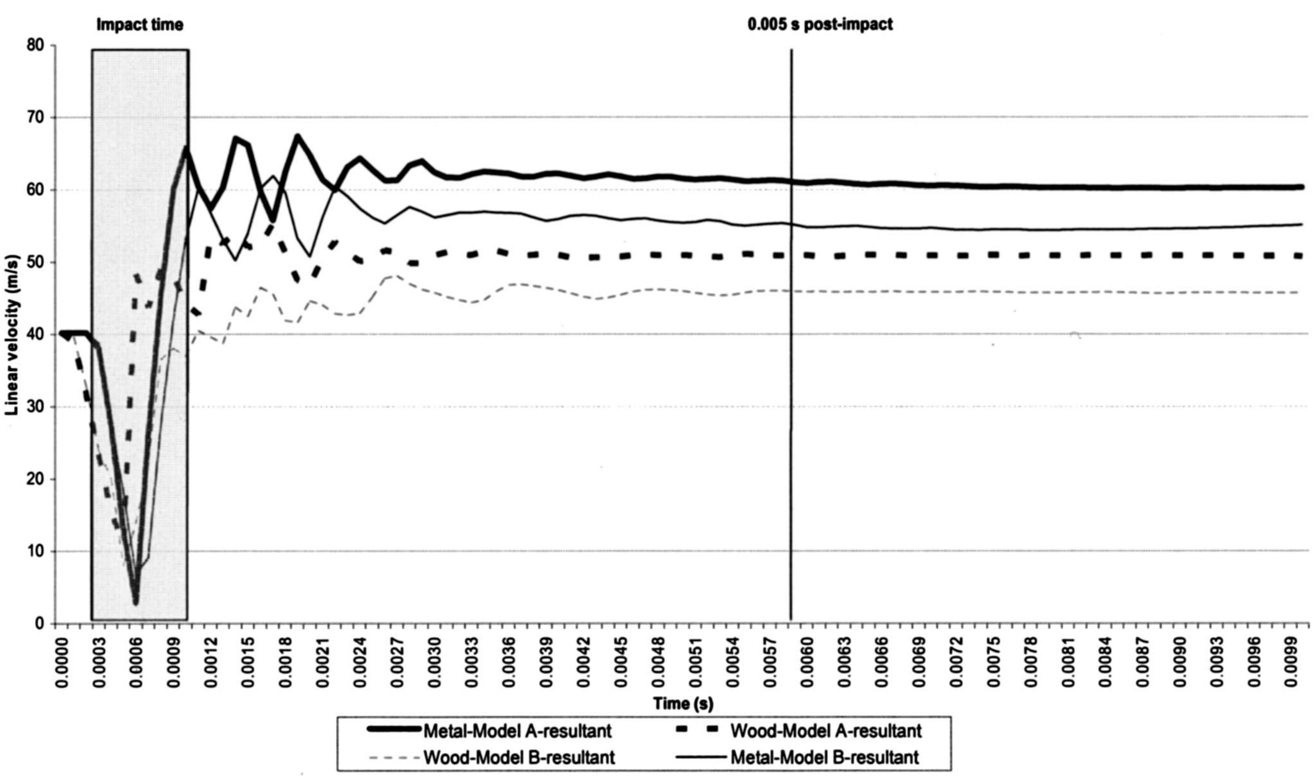

FIGURE 3—Resultant ball linear velocity ($m \cdot s^{-1}$) from wood and metal bats impacted with both Model A and Model B baseballs. BEV is measured 0.005 s postimpact.

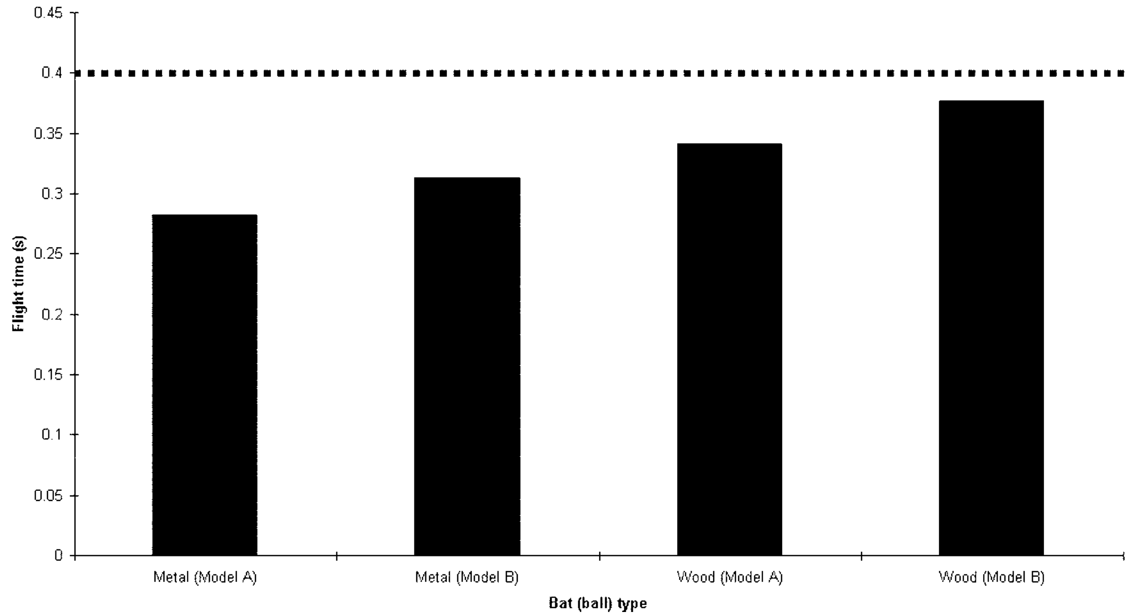

FIGURE 4—Time (s) taken by the ball to travel 16.46 m from the point of impact to the pitcher in the infield. The dashed line represents the data of Cassidy and Burton (8), who indicated 400 ms is required for a pitcher to complete a protective action against a ball hit directly at him.

Wood bat impact with Model A baseball: W_A

Wood bat impact with Model B baseball: W_B

The metal bat produced greater BEV (61.5 $m \cdot s^{-1}$ for the Model A ball, 55.4 $m \cdot s^{-1}$ for Model B) than the wood bat (50.9 $m \cdot s^{-1}$ and 46.0 $m \cdot s^{-1}$, respectively), regardless of the type of ball used (Fig. 3). For baseball Model A, BEV from the metal bat exceeded that from the wood bat by 10.6 $m \cdot s^{-1}$. A similar result was obtained for ball Model B between the two bats (9.5 $m \cdot s^{-1}$). When repeating the analysis with the same initial conditions for both bats, the metal bat produced a BEV of 45.4 $m \cdot s^{-1}$ compared with 50.9 $m \cdot s^{-1}$ for the wood bat, using the set of parameters defined for the wood bat by videographic analysis. When using the metal bat parameters, the wood bat produced a BEV of 61.2 $m \cdot s^{-1}$ compared with the metal bat 61.5 $m \cdot s^{-1}$ When impacted with the Model A baseball, peak resultant bat-ball reaction force in both wood (7%) and metal (19%) bats exceeded that observed with the Model B ball. The instant at which BEV should be quantified has not been defined in the literature. In this study, BEV was measured 0.005 s postimpact for a node at the geometric center of the ball. Extrapolation of BEV over 16.46 m indicated BEV from both types of bats and balls exceeds that corresponding to the 400-ms reaction time required by a pitcher to a avoid a batted ball (Fig. 4). M_A recorded the highest BEV, with 0.282 s available for evasive action. In the best case, W_B, 0.377 s was available for the pitcher to react to a ball hit directly at him.

The less oblique impact for metal bat impacts resulted in a higher proportion of postimpact ball velocity in the horizontal (v_x) component (Fig. 5). However, for the wood bat, a greater proportion of BEV was in the lateral (v_z) direction. Likewise, reaction force for metal bat impacts was dominated by the x-component, irrespective of ball type. For wood bat impacts, a large component of the reaction force consisted of lateral (F_Z) force (Fig. 6).

Peak ball deformation was measured from the relative displacements of a node on the leading and trailing surface of the baseball. An example of the pattern of ball deforma-

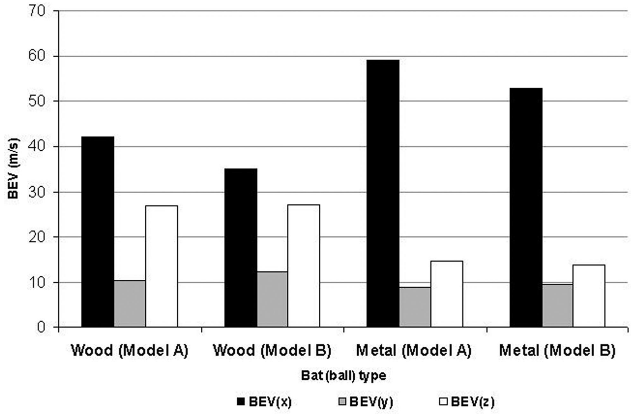

FIGURE 5—BEV from each bat type, showing each component of linear velocity (x, y, z) and the resultant velocity.

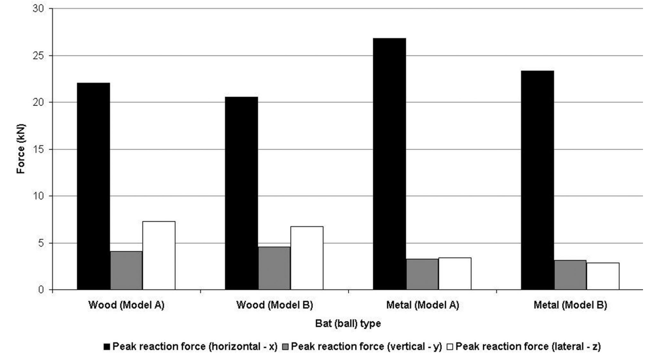

FIGURE 6—Peak reaction force from each bat type, showing each component of force (x, y, z) and the resultant force between bat and ball.

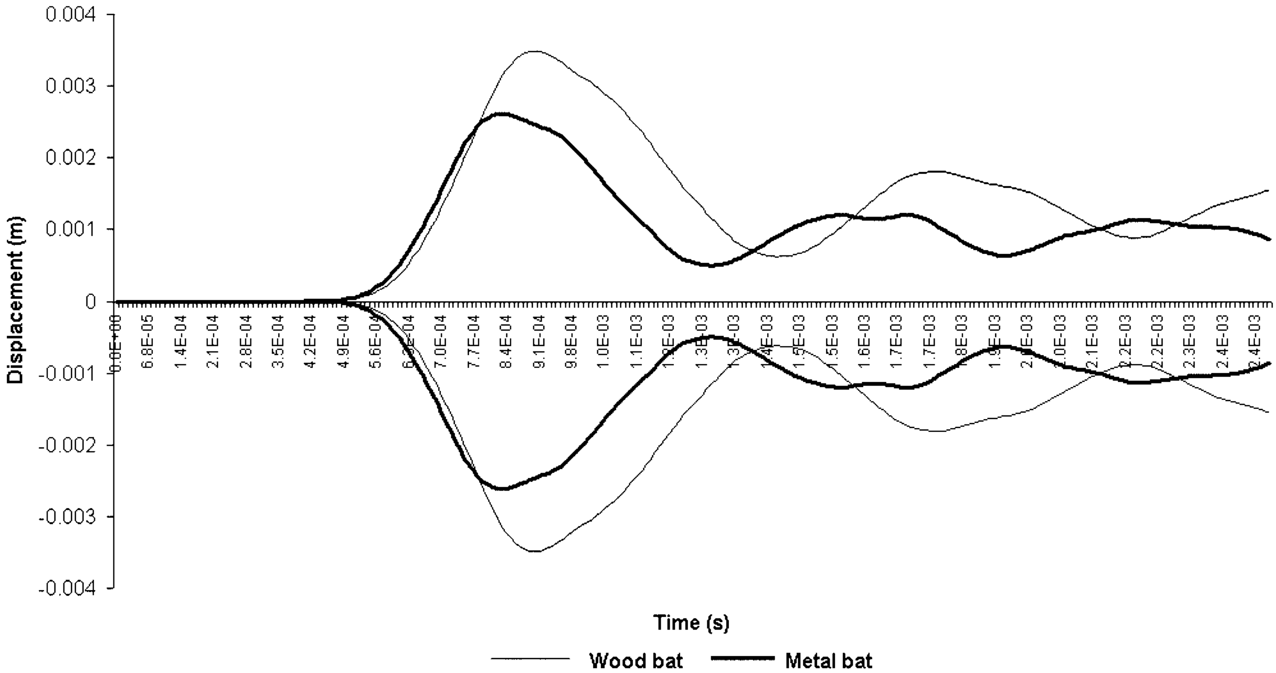

FIGURE 7—Variation of ball deformation in the x- (compressive) directions for metal and wood bats.

tion is shown in Figure 7. Peak deformation (Fig. 8) was greater for metal bat impacts, regardless of ball type. M_B demonstrated the greatest compression (23.9% of ball diameter), and W_A the lowest (17.2%). The Model B ball proved less stiff, with 23.9% and 18.8% compression for metal and wood bat impacts respectively, compared with 22.5% and 17.7% in the Model A ball. Peak deformation also occurred earlier in the impact period for this ball, as 40% for W_B compared with 55.6% for M_A. Impulse of impact was expressed as the integral of the impact force–time curve. The curve was fitted with a third order polynomial and the area bounded by the curve and x-axis estimated using the Trapezoidal Rule with 128 divisions. The impulse of impact was related to ball type, with greater impulse obtained for M_A and W_A than impacts with the Model B ball. The highest impulse was noted for M_A (14.8 N·s), and the lowest for W_B (12.5 N·s).

DISCUSSION

The incidence and severity of impact injuries in baseball is a substantial problem in sports medicine. Batted-ball injuries to pitchers from balls are well-documented phenomena in junior and collegiate baseball (5) and the professional game (7). Decreasing BEV may reduce the frequency and severity of such injuries. To develop meaningful performance regulations for bats and balls, the effect of equipment design on BEV must be rigorously quantified. This is the first study to evaluate the performance of wood and metal baseball bats in terms of the maximum risk of injury to the pitcher from balls hit by each bat directly toward him. Using a model driven by bat kinematics from high-performance hitters and experimentally determined ball time-dependent properties, it was shown both wood and metal bats can produce BEV that exceeds the reaction time of pitchers when compared with the data of Cassidy and Burton (8). Impact between the handle-weighted metal bat and the high stiffness ball (Model A) recorded the highest BEV (61.5 $m \cdot s^{-1}$), with 0.282 s available for evasive action (Fig. 4). For

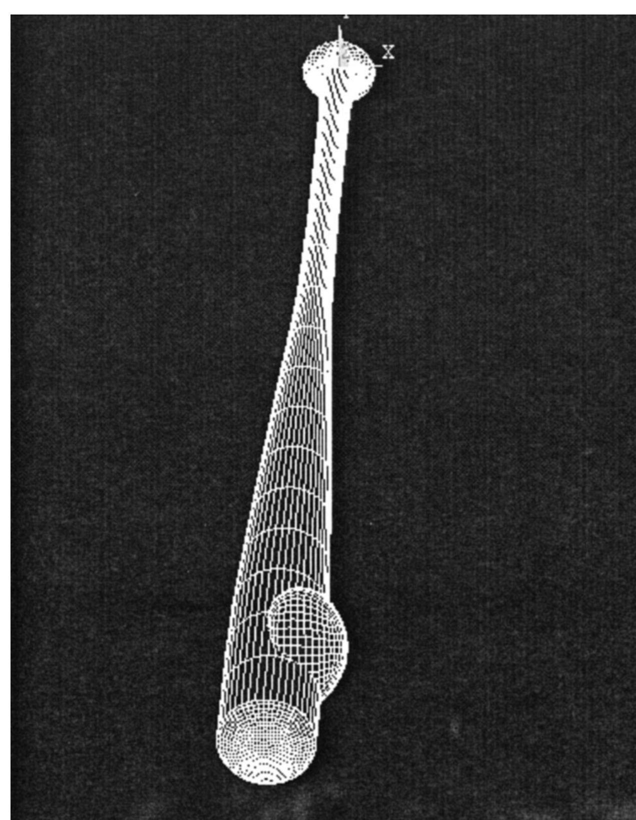

FIGURE 8—Deformed geometry for metal bat impact with Model A baseball, showing maximum ball deformation.

impact from the wood bat with ball Model B, 0.377 s was available for the pitcher to react to a ball hit directly at him, which was still within the 0.400-s "danger window" for a pitcher to be struck by the ball (8). Reduction in the instantaneous shear (G_0) and relaxation (G_∞) modulii of the baseballs increased the time available for evasive action by the pitcher by approximately 10%.

The immediate implications for this research are in the risk and severity of injury faced by unprotected pitchers from balls hit directly toward them. Our results suggest in the worst case (M_A), the ball will have a velocity of 55.4 $m \cdot s^{-1}$ when it reaches the pitcher 16.46 m away. In the best case (W_B), the ball velocity at the pitcher will be 41.4 $m \cdot s^{-1}$. Although the biomechanics of impact injuries are beyond the scope of this paper, Heald and Pass (13) and Viano et al. (28) showed skull fracture in cadaver heads occurred at 26.2 $m \cdot s^{-1}$ for impacts with a professional standard baseball. Approximately half of the fatalities to baseball pitchers are caused by impact to the head (27). Pasternack et al. (23) indicated 86% of head and facial injuries in Little League players are caused by ball impact, of which 85% occur to defensive players. Chest impact by the ball comprised 35% of 23 deaths among pitchers between 1973 and 1983 (27). The rate of deaths from chest impact to nonprofessional baseball pitchers increased from 2.1 per year in 1973–1980 to 3.3 per year in 1986–1990 (29). While these figures may reflect increased participation, the use of increasingly high-performance metal bats and stiffer baseballs may also be a contributing factor. Link et al. (15) indicated, in a swine model, the likelihood of ventricular fibrillation was related to the timing of the blow within the cardiac cycle, not the velocity or force of the impact. The results of the present study highlight the danger faced by the unprotected pitcher. The BEV values obtained from this mathematical analysis are substantially higher than those suggested by Owings et al. (22) as the maximum which could be avoided by Little League players. Hence, increasing the available movement time by modification of equipment or playing rules is necessary to reduce the incidence of impact injuries to pitchers.

Pitcher fielding technique, and the size and strength of hitters, are two factors not considered in this study that may be related to the incidence of pitcher injuries. The relationship of the throwing and fielding technique used by pitchers compared with movement time needed to avoid being struck by the ball remains to be investigated. The power of modern professional hitters is demonstrated by Major League performances in the week of August 13, 2002, in which four players hit three home runs each in a game. Similarly, in collegiate baseball, the average number of home runs per game has doubled from 0.45 to 0.9 since 1972 (1). Reduction in ball-impact injuries requires a wide-ranging response and may include the use of safety equipment, separation of players by age, size, and skill level, and enforcement of existing rules regarding the distance between batters and fielders in practice and in games. This study was limited to assessment of the impact response of bats and balls, and the results are specific to the equipment models tested. However, the results have important consequences for the design and regulation of this equipment. The results obtained in this research indicate both bat design (moment of inertia) and ball behavior (shear and relaxation properties) influence BEV.

Metal bats were introduced into baseball in 1972 to address rising costs associated with broken wood bats. With 19 million participants each year in the United States (27), reversion to the exclusive use of wood bats is not an economically viable strategy to reduce the likelihood of ball-impact injuries to pitchers. Our findings lend support to the 1999 proposal by the NCAA Baseball Research Panel to instead regulate the swing moment of metal bats (10). Bat kinematics at impact have been shown to be a combination of translational and rotational motion (18). Resistance to this motion is affected both by bat mass and the distribution of that mass with respect to axis about which it is rotating. The results of this research indicate bat moment of inertia is an important factor in bat preimpact linear velocity and 3-D orientation and hence both resultant BEV and the distribution of the BEV among horizontal, lateral, and vertical components. Our results suggest handle-weighting of bats results in higher BEV. The higher moment of inertia of the wood bat resulted in lower preimpact linear velocity and a more oblique bat–ball impact. The energy lost to lateral motion was an important factor in the lower BEV recorded from this bat. The greater barrel lag at impact for the wood bat may point toward a potential design-control method for BEV. Similarly, metal bat swing moment may be controlled through modifications such as adjustments in barrel wall thickness and changes in handle diameter and knob weight.

Although it has been suggested having external automatic defibrillators and medical personnel present at youth games to treat impact injuries (29), prevention of such injuries may be more efficacious. The dynamic material behavior of the baseball is complex and was previously not well understood. The current study constitutes the first research to measure the elastic and time-dependent properties of baseballs under large-deformation conditions. The results of this analysis indicate variation in the time-dependent properties of the ball is a viable method for reducing BEV, which in turn may reduce the frequency and perhaps the severity of batted-ball injuries. The performance characteristics of softer balls have not previously been subject to rigorous study, and the results of the current study point to an avenue for improving the safety of infielders while retaining the intrinsic character of the game.

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Conflict of Interest: While acknowledging the support of the above-listed organizations who supplied two baseball bats and 70 baseballs for the purposes of this research, we hereby state we have no further or ongoing professional relationship with these companies or manufacturers from which they might derive benefit from the results of the present study. The results of the present study do not constitute endorsement of the product by the authors or ACSM.

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