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Impact Injuries in Baseball

Prevalence, Aetiology and the Role of Equipment Performance

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Contents

Abstract

Baseball has one of the highest impact injury rates of all sports. These injuries are primarily attributed to impact by a ball after it has been hit, pitched or thrown. This paper will review the incidence and causal factors for impact injuries in baseball. Attention is given to the design and material properties of bats, in light of evidence suggesting balls hit into the infield from metal bats can reach velocities potentially lethal to defensive players. The distribution of bat mass along the long axis of the implement appears a major factor in the greater performance potential of metal bats over wooden bats of equal length and mass. The dynamic behaviour of baseballs has also been implicated in the severity of head and chest injuries experienced by players. Balls of greatly reduced stiffness have been introduced for junior play, but debate still remains over their performance and impact characteristics. The behaviour of the ball during high-speed impact with the bat has been the subject of relatively limited research, and the effect of manipulating baseball material properties to decrease batted-ball velocity is unclear. The value of batting helmets is evident in the observed reduction of head injuries in baseball, but the use of protective vests to decrease the incidence and severity of cardio-thoracic trauma appears to be contraindicated.

It was very unfortunate… I hit the ball extremely hard and he had no chance to get out of the way.

– Chicago White Sox hitter Frank Thomas after hospitalising Cleveland pitcher Steve Woodard on April 4, 2001.

Baseball (and softball) cause more injuries requiring emergency room attention in the US than any other sport.[1,2] The majority of catastrophic injuries and fatalities in the game involve ball impact to the player's head or chest. Reduction in the incidence and severity of impact-related injuries requires understanding of the biomechanical mechanisms underlying trauma. Rigorous quantification of equipment performance is also necessary to establish risk and tolerance criteria. This article provides a review of the current body of research on the effects of impact loading and efficacy of protective equipment in baseball. Prevention strategies to increase a player's time for evasive action are also discussed, with particular emphasis on the rebound characteristics of bats and balls.

1. Incidence and Morbidity of Impact Injuries in Baseball

In the US, 19 million people participate in organised baseball every year, including 5 million children aged under 14 years,[3] 400 000 high-school players and 20 000 collegiate athletes.[4,5] The US Consumer Protection and Safety Commission documented more than 2.6 million injuries presenting at US emergency rooms as a result of participation in baseball or softball between 1983 and 1989.[3] Mueller et al.[2] identified 29 038 injuries in Little League baseball from compensated insurance claims in 1987–96. The extent of non-hospitalisation injuries and those occurring to players in recreational play is unknown.

Softball and baseball are responsible for the highest rate of sporting fatalities in 5- to 14-year-old children in the US,[4] with 88 deaths recorded between 1973–95.[6] However, the prevalence of catastrophic injury and death among high-school and collegiate baseball participants is much lower. For the period 1983–2001, the National Center for Catastrophic Sports Injury Research recorded 38 direct catastrophic injuries (including eight fatalities) among approximately 7.6 million high-school baseball players. This equates to a fatal direct injury rate of 0.1 per 100 000 participants, compared with 0.46 for lacrosse and 0.18 for track-and-field athletics, two other major high-school spring sports in the US. Non-fatal and serious injury rates were also low (0.2). Eight direct catastrophic injuries were recorded for 400 000 collegiate players, including three fatalities, a fatal injury rate of 0.71 per 100 000 participants.[5]

Ball-player impacts account for 52–62% of baseball-related injuries.[2,7] Of these injuries, 68% occur to defensive (fielding) players.[6,7] Most catastrophic injuries in baseball involve ball impact to the head or chest. The US Consumer Protection and Safety Commission reported 14 fatalities in children from impact by a baseball to the head or chest between April 1994 and April 1995.[8] Of the 88 deaths reported in 1973–95, 77% were ascribed to impact from the batted, pitched or thrown ball. Thirty involved impact to the head and 38 to the chest. Thirteen deaths resulted from the player being struck by the bat.[6]

Approximately one-third of injuries in Little League baseball involve impact to batters by the pitched ball (20%) or to fielders by the thrown ball (13%). Impact by the batted ball accounts for 20% of injuries in Little League baseball, including 50% of injuries to infielders and 77% to outfielders,[2] and about 3% of injuries in collegiate baseball.[9] As the closest infielder to the hitter, the pitcher is at greatest risk of being struck by the batted ball. The incidence of pitchers being struck in the head and chest are approximately equal,[10] and these injuries were responsible for eight of 23 baseball fatalities documented between 1973 and 1983.[10] The risk may be increased in junior and collegiate leagues when hitters use metal bats as higher ball exit velocity (BEV) has been measured from these bats than from traditional wooden bats.[11-13]

2. Equipment Performance

The aetiology of impact injuries in baseball is multifactorial, with equipment design, playing technique, and the size and strength of players all contributing factors. This section outlines the likelihood and severity of impact injury in baseball as related to the properties of bats and balls used by the players. The speed with which a ball can be hit toward a defensive player is a product of the material behaviour of both bat and ball,[12,13] and likewise, the extent of injury caused to a player hit by the ball is a function of the ball mass, stiffness and viscoelastic properties.[14-19]

2.1 Baseball Bats

The rate of deaths from chest impact in baseball increased from 2.1 per year in 1973–80 to 3.3 in 1986–90.[20] While this may reflect increased participation, higher BEV from increasingly lightweight and high-performance metal bats may also be a contributing factor. Wooden bats have been used in baseball since the nineteenth century and are still exclusively used by professional players. More durable aluminium alloy bats were introduced into baseball in 1972, and are now in world-wide use in most college and youth baseball leagues.

Seventy-five percent of ball-related injuries (49% of all injuries) to Little League baseball pitchers[2] are due to impact from the batted ball. The prevalence of such injuries in high-school and collegiate play is not known, although in 1998, 375 National Collegiate Athletic Association (NCAA) Division I collegiate pitchers were struck by the batted ball, with 11% requiring medical treatment.[9] The risk of impact injury to pitchers may be greater when hitters use metal bats. BEV for balls hit with metal bats has been demonstrated as higher than that from wooden bats.[11-13] Bryant et al.,[11] quantified mean BEV from wooden bats at 39.4 m/sec, and 41.1 m/sec from metal bats (n = 6 collegiate hitters). No details were given as to bat length, mass or moment of inertia. Substantially higher mean values were obtained by Greenwald et al.[12] (n = 19 high-school, collegiate and minor league players). Five metal and two wooden bats of varying length and mass were employed, and mean BEV from the top 10% of hits from wooden bats was measured at 43.8 m/sec, while that from metal bats was 45.8 m/sec, with a range of 44.8–47.3 m/sec across the five models. Mean BEV for 17 high-school, collegiate and professional Australian hitters using metal bats was quantified by Nicholls et al.[13] at 44.0 m/sec, with a mean for wooden bats of 40.8 m/sec. This study was the only one that restricted wooden and metal bats to those of identical length and mass, enabling direct comparisons in bat performance.

In an unpublished thesis, Cassidy and Burton estimated 400ms is required for a pitcher to complete a protective movement such as lifting the hand to the face. This corresponds to a ‘safe’ velocity of about 42 m/sec. Although individual variation in a pitcher’s follow-through technique was not accounted for in this study, BEV values reported in the literature suggest a high potential for impact injuries from balls hit by metal bats. Skull fracture has been shown to occur at impact speeds of 26 m/sec in cadaver heads,[16] highlighting the potentially catastrophic nature of injuries faced by pitchers.

The source of difference in BEV between wooden and metal bats has been previously proposed to depend on bat material and vibrational properties.[21,22] However, during a high-speed impact at the bat centre of percussion or at a vibrational node, where no vibrational response is generated in the bat and maximum energy is retained by the ball,[11,22] the baseball is in contact with the bat surface for just 1–2ms[1,12,22] and the flexure and vibrational properties of the bat materials exert little effect on the energy returned to it. Therefore, the linear velocity of the bat at impact is of major importance to the momentum transferred to the ball.[12,13] The velocity with which a bat can be swung is dependent on the bat design, particularly the distribution of mass along the long axis of the implement (moment of inertia [I]). For hitting implements, I is most commonly reported about an axis perpendicular to the proximal (grip) end of the bat.[13] As aluminium is four times as dense as wood, metal bats are fashioned as hollow shells to remain comparable in mass. Wooden bats are solid and the bat weight is distributed through the implement, with a narrower but relatively heavier barrel. Mass distribution has a quadratic effect on resistance to angular acceleration: the relative extra weight in the barrel of a wooden bat increases the torque required to accelerate the bat, and the corresponding reduction in linear bat velocity results in lower BEV.[12,13]

2.2 Baseballs

The material properties of the baseball are important in two instances with respect to injury. First, ball response to high-speed loading affects the dynamics of the bat-ball interaction, and thereby both BEV and time available for evasive action. Secondly, in the event of the player being hit, the material properties of the ball also determine the severity of the injury.

Baseballs are made from a cork or rubber core wound in grey and white wools, covered in two hourglass-shaped pieces of cowhide. Regulation baseballs have a circumference of 22.8–23.5cm and a mass of 155–163g. The sole performance indicator used to establish regulations on baseballs is the coefficient of restitution (COR), which is determined by firing the baseballs at 26.8 m/sec (60 miles/hour) against a flat wall, and is reported as the ratio of outbound to inbound velocity. Baseballs are required to have a COR of 0.543–0.555 (NCAA, 2000 regulations).

2.2.1 Baseball Properties and Ball Exit Velocity

Reduction in the velocity of balls hit into the infield is required to reduce both the incidence and severity of impact injuries to defensive players. During impact with the bat, the baseball is compressed to 22% of its original diameter in less than 1ms,[23] using finite element analysis (figure 1). Most previous investigations of ball material behaviour during compression have been limited to mechanical compression tests to 10% of original ball diameter,[14-17,24] in which range ball behaviour is presumed linear elastic. Nicholls et al.[23] showed baseball behaviour is non-linear (hyperelastic) during unconfined compression to up to 25% of ball diameter (figure 2). Similarly, the data of Hendee et al.[17] show the dynamic behaviour (COR) of the baseball is strongly velocity-dependent, or viscoelastic, with COR decreasing with increasing impact velocity. This may explain why COR has previously

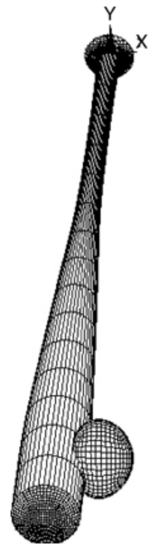

Fig. 1. Finite element analysis enables detailed investigation of transient high-speed events such as the impact of a baseball with a bat, which occurs over a period often less than 1ms. Nicholls et al.[23] used this method to investigate the deformation and recovery patterns of different types of baseballs with wood and metal bats. X denotes the horizontal axis (directed into the infield), Y is vertical and Z is the cross-product of the two (directed out of the page).

shown no relationship to ball stiffness or mass,[14,17] but is, as shown by Nicholls et al.,[23] a function of the time-dependent properties of the soft polymers used in ball construction.

3. Head and Chest Injuries

The biomechanical response during ball-player impact is affected by the ball velocity, mass and material properties, and the properties of the target. Both baseball stiffness[3,9,14,16,25] and mass[1,14] have been identified as important to the magnitude and severity of head and chest injury.

3.1 Head, Ocular and Dental Injuries

Head injuries are commonly classified as either damage to the soft tissues or scalp, bony fracture or brain contusion.[18] 170 000 head injuries occur in baseball each year,[26] constituting 86% of impact injuries in Little League baseball.[2] Eighty percent of head and facial injuries are experienced by fielding players,[7] probably due to the use of helmets by

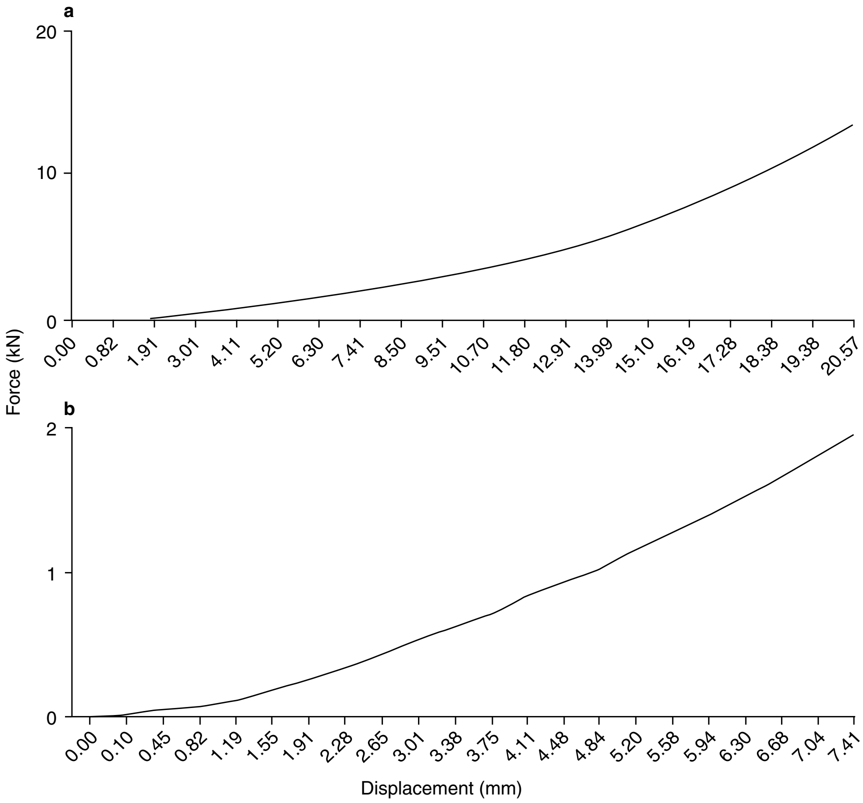

Fig. 2. The nonlinear force-displacement response of a baseball during compression to 25% of its original diameter is evident in (**a**). This large deformation is typical of compression reached during bat-ball impact. Previous studies of baseball material behaviour have been confined to compression to 10% of original diameter, in which force-displacement response is largely linear (**b**) [reproduced from Nicholls et al.,[23] with permission].

batters. The US Consumer Protection and Safety Commission proposed softer baseballs could prevent or reduce the severity of 47 900 head, neck and facial injuries per year.[27] Softer balls have cores that compress over a larger area and for a longer time, thereby increasing ball deformation and impact time, and reducing peak impact force. Increased peak force, highly localised impact, and shorter dwell time have been linked to higher stress transmitted to bone and increased severity of head injury.[3,14,15,17,18]

The biomechanics of head injury are complex and involve a combination of translational and rotational motion, structural vibration and inertial response transmitted through the cervical spine. A pressure gradient (compressive pressure near the impact site and tensile pressure at the opposite location), and shear strain maxima occur in the vicinity of the impact load, indicating additional potential for tearing or cavitation to the soft tissues within the skull.[18] Head injury risk is often quantified using the Head Injury Criterion (HIC), derived from measures of head acceleration. Decreasing the ball modulus has been shown to reduce impact force and peak head acceleration up to 72%,[3,14] and decrease the risk of head injury from 52% to 14%.[3] Heald and Pass[16] indicated injury risk (HIC) balls for lateral head impacts at 28.6 m/sec, was only 1% for ‘soft’ baseballs – those with a compression strength of 175 N/cm or less, compared with a professional standard baseball (700 N/cm or more).

Crisco et al.[14] demonstrated a theoretical relationship between ball mass and head injury, in which decreased ball mass reduced peak impact force and peak acceleration 41% at velocities to 40.2 m/sec. However, simplifications of material properties of head and baseballs (each of which were assumed linear elastic isotropic) and neglect of neck compliance, which contributes up to 29% of total force for forehead impacts,[3] may explain the large discrepancies between reported absolute values for peak head accelerations and those of experimental studies.[3,16]

Dental injuries constitute 10% of injuries to Little League baseball players, although this may be as high as 18% for outfielders.[2] The effect of ball mass, stiffness and viscoelastic behaviour on dental injury is unknown. Baseball is the leading cause of sports-related eye injuries in 5- to 14-year-old children in the US, accounting for 55% of baseball-related injuries treated in hospital emergency rooms.[27] Zagelbaum et al.[26] documented 24 eye injuries occurring to professional players in the infield or on the sidelines. These injuries included malar fractures, ocular tearing, corneal abrasion and subconjunctival haemorrhage. The eye is a viscoelastic tissue whose response to loading depends on the rate of force application, hence the use of softer baseballs may decrease the severity of both ocular soft tissue and associated bony structures. Impact at 24.6 m/sec with a traditional ball has been shown to cause ocular rupture, with almost total extrusion of the intraocular contents, whereas a modified ball caused only posterior translation of the eye at speeds up to 33.5 m/sec. While an extremely soft baseball (10% of professional stiffness) may actually intrude into the orbit, ocular impact force is reduced for most modified balls.[19]

3.2 Chest Injuries

More deaths in 5- to 14-year-old baseball players result from impact to the chest than to the head. The use of batting helmets has reduced the incidence and severity of head injuries.[2,3,6,27] However, protective devices for the thorax are not used by any players with the exception of the catcher. The US Consumer Protection and Safety Commission attributed 41% of the 51 deaths reported in 1973–85 to chest impact by the ball. Such injuries comprised 35% of 23 deaths among pitchers between 1973–83.[10]

Giacobbe et al.[15] proposed that thoracic injury may result if the internal soft tissues are excited into resonance by the impact. Excitation depends on the dynamic hardness of the ball (a measure of the frequency of the energy transferred to an impacted object).[15] If dynamic hardness is below the natural chest wall frequency, the majority of impact energy will be transferred into vibration of the internal organs. The dynamic hardness of standard baseballs was quantified as 400Hz, and that of modified balls as 78Hz. The natural frequency of the chest wall is 50–100Hz and the heart 20–30Hz, indicating the lower dynamic hardness of the modified ball may be undesirable since most of the impact energy can be passed beyond the chest wall. However, dynamic hardness was measured in that study at 2.2 m/sec and the data may not be representative of a high-speed impact.[15]

Commotio cordis (death from blunt thoracic trauma in the absence of cardiac abnormality) accounts for 2–4 deaths in baseball per annum.[1] Vincent and McPeak[20] documented 76 occurrences of commotio cordis in sport, of which 40 were baseball-related. Death was instantaneous in about half of the cases, while in the others there was a brief period of consciousness before collapse.[20] The rate of successful resuscitation is only 10%.[10] A primary feature of deaths from commotio cordis is the absence of clinically significant cardiac injury at autopsy.[8,10,20] The aetiology of commotio cordis has been proposed as a direct concussive effect from the abrupt deceleration of the heart as it strikes the sternum or spine.[1] The result may be functional disruption of electrical conduction leading to fatal arrhythmias such as atrial or ventricular fibrillation, T-wave depression or inversion, ventricular tachycardia or complete heart block. Link et al.[28] proposed the risk and type of arrhythmia depended upon when the impact occurred during the cardiac electrical cycle (figure 3). Impacts occurring 15–30ms before the T-wave peak (the time of great-

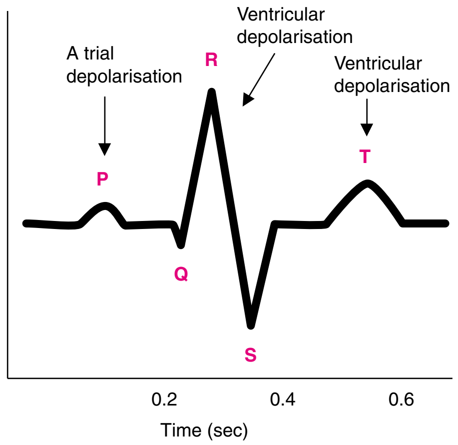

Fig. 3. Schematic of an electrocardiogram tracing showing the distinguishable deflection waves of the cardiac cycle.

est heterogeneity of repolarisation) produced immediate ventricular fibrillation in 90% of impacts in a swine model.

Van Amerongen et al.[8] contended children may be particularly vulnerable to thoracic injury because of the elasticity of their rib cage. In addition, the narrower antero-posterior diameter of the thorax provides less protection to the underlying organs, and slower reflexes and lower awareness of risk may contribute to the higher incidence of commotio cordis among youth players as reported by Van Amerongen et al.[8] and Vincent and McPeak.[20] However, Mueller et al.[2] indicated that only 1.4% of ball-related injuries in Little League baseball occurred to the chest, of which none were fatal.

The likelihood of commotio cordis was initially believed to be proportional to both the speed and force of the impact and the size of the contact area.[11] Link et al.[28] indicated that a relationship exists between baseball hardness and the likelihood of ventricular fibrillation in a swine model. At 13.2 m/sec – a relatively slow velocity in baseball terms, but reflective of the slow speeds at which commotio cordis has been documented to occur[1] – the softest baseballs produced ventricular fibrillation in only two of 26 impacts, compared with eight instances after 23 impacts with regulation baseballs. In a follow-up study, tests at 18 m/sec triggered ventricular fibrillation in less than 22% of instances compared with 69% with standard baseballs.[29] It was concluded that wider use of modified baseballs may reduce (but not eliminate) the risk of commotio cordis.

A theoretical lumped-element viscoelastic model of the chest in which both ball mass and modulus could be varied, showed peak impact force decreased by 80% when both variables were decreased.[14] The results of this analysis were not presented as functions of momentum, an important contributor to chest response.[30] Viano and Lau[31] proposed the viscous criterion as a predictor of commotio cordis. Viscous criterion is an index of the magnitude of chest wall deflection and the velocity of deformation, normalised for chest thickness; the higher the viscous criterion, the greater the energy absorbed by the tissue and the risk of injury.[20,31,32] Reduction in viscous criterion is achieved by reducing the velocity of deformation and/or extent of compression of the chest during impact. In a review of 88 700 impact injuries, Kyle et al.[27] reported that softer balls reduce the frequency and severity of chest injuries in youth baseball. Although softer balls may produce lower viscous criterions than regulation baseballs, results vary widely across ball models.

4. Protective Devices

Batting helmets are now compulsory in baseball. Most batting helmets are open-faced and protect the majority of the supero-lateral skull but not the jaw or facial area. The US Consumer Protection and Safety Commission indicated helmets fitted with face shields may prevent or reduce severity of 3900 facial injuries to children each year,[27] but there is a lack of rigorous data to support such a claim.

Aside from the catcher, defensive players wear no special gear to protect against impact injury. The use of polycarbonate safety glasses for infielders have been encouraged by organisations including the American Academy of Pediatrics,[33] but not widely adopted due to a lack of supporting research. Most studies have focussed on the efficacy of equipment developed to reduce thoracic injury in fielders.[1,27,30,32] Increasing the effective mass of the chest using a padded vest may reduce the velocity of impact, viscous criterion and momentum transferred to the body.[32] Sternal acceleration was reduced by use of closed-cell foam vests for high-speed impacts in swine and dummy models,[30,32] but only minor reductions in the incidence of cardiac arrhythmia and viscous response were noted. In some vests, following impact with both standard and softer baseballs, peak force and momentum transferred to the chest were increased,[32] indicating debatable protective effect, which has forestalled the introduction of such products into the game.

5. Conclusion

The incidence and severity of impact injuries in baseball, particularly those to junior players, can be considered a substantial problem in sports medicine. However, the exact mechanisms of trauma, particularly in commotio cordis and role of stress and acceleration in head injury, remain unclear. The use of simplified models of ball and head[14] and the variety of experimental methods for chest impacts[1,28,30] may have contributed to varying conclusions to a highly complex problem, in which the involved biological tissues are acknowledged as inhomogeneous, anisotropic and nonlinear, and the material behaviour of playing equipment are similarly complex.

While it has been suggested having external automatic defibrillators and medical personnel present at youth games to treat impact injuries,[20] it is only by anticipating these injuries and trying to prevent them that they can be diminished in frequency and severity. Protective and modified equipment have been developed to protect players from the likelihood of, and severity of, impact injuries. Decreasing BEV is necessary to increase reaction time for defensive players and thereby reduce the incidence of batted-ball impact injuries. However, in order to develop effective standards for equipment, the effect of bat and ball design on BEV, and impact dynamics with the tissues of the body, must be further quantified.

There is debate over the performance characteristics of modified balls and the relative contribution of ball mass and stiffness to impact injury.[1,10,14-17,24,27] The reason for variance in impact severity amongst softer balls is unclear, although it has been shown modifying the time-dependent properties of ball material can reduce BEV.[23]

The behaviour of the ball during high-speed impact with the bat must also be quantified in order to regulate BEV to safe levels for infielders. The rebound characteristics of baseballs are currently only quantified at one velocity (60 miles/hour) before commercial sale, which is unrepresentative of bat-ball impact velocities and gives no information about the effect of rate of energy loss. The use of the finite element method has given more detailed information about the impact properties of the baseball (Nicholls et al., unpublished data).

Reduction in bat linear velocity (swing speed) reduces momentum transferred to the ball and thereby BEV, giving fielding players extra time for evasive action. The moment of inertia of metal bats has been identified as a critical factor in BEV.[11-13,24] Introduction of standards for non-wooden bats so the implement becomes “comparable to wood bats in weight variance” was first proposed by the NCAA in 1996[34] and supported by Fleisig et al.[24] However, optimal values will be difficult to identify as the effect of the size and strength of hitters is unknown, and the recommendations are yet to be adopted.

Impact tests using swine models[1,28,30,32] and test-dummies[1,3] indicate closed-cell foam chest protectors may not reduce, and indeed may increase, the peak force and momentum transferred to the chest. Test protocols with standardised boundary conditions, constraints and test velocities, are recommended to match ongoing improvement in the biofidelity of surrogate models, and increase the validity of further independent testing, evaluation and certification programmes. Current injury data are largely collected from emergency rooms[6,27] and insurance claims,[2] with no provision for non-hospitalisation injuries and those occurring in unorganised play. A large database of injury assessment reference values will also assist in continuing improvement in models of impact response.

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