Dynamics of Neck Injury and Options for Injury Risk Mitigation for Batsmen Playing Fast Short-pitched Bowling

Franz Konstantin Fuss1, René ED Ferdinands2

Abstract

Introduction: In late 2014, batsman Phillip Hughes was hit in the neck by a bouncer and died 2 days later. The purpose of this study is to evaluate the options for cricket ball shock absorption at the neck and whether the current solutions are feasible.

Materials and methods: The impact speed and the kinetic energy of the ball were photogrammetrically calculated from the match video. A library of impact absorber materials providing data on the optimal shock absorption point was used to select the best material for shock absorption based on an acceptable thickness and a maximum deceleration of 250 g according to the British Standard (BS).

Result: The impact velocity on Hughes’ neck was 30 m/s, and the energy absorbed was 70 J. Using this energy and the mass of a cricket ball, no suitable material was found, either because of the unacceptable thickness (>0.7 m) or the deceleration (>1000 g). Using the data required by the BS (15 J and 5 kg), several solutions were feasible, with a thickness of 14–28 mm and a deceleration of 40–60 g.

Conclusion: When testing energy absorbers, it is not only the impact energy that is important but also the speed or mass. Testing an absorber at 70 J and a mass of 0.156 kg gives a different result than at 70 J and a mass of 5 kg. Reducing the impact energy to 15 J only makes it worse. The test conditions of crash cushions shall be based on the worst realistic case. If not, the designed shock absorbers are suboptimal at best.

Keywords: Bouncers, Cricket biomechanics, Cricket injuries, Phillip Hughes, Protective equipment, Shock absorber design.

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Introduction

On 25th November 2014, batsman Phillip Hughes was struck in the neck by a bouncer while playing a match in the Sheffield Shield competition between South Australia and New South Wales at the Sydney Cricket Ground. The impact of the ball caused a traumatic dissection of the vertebral artery with subsequent subarachnoid bleeding, making the batsman’s death inevitable.1–3

On 10th October 2016, an inquest into Hughes’ death began. Both authors of this study were asked to provide expert opinions for the investigation.4,5 The outcome of the Coronial Inquest into Hughes’ death in October 2016 was that “no one was to blame for the tragic outcome,” and “a minuscule misjudgment” caused Hughes to miss the ball.6

Owing to Hughes’ injury, the helmet manufacturer Masuri designed a shock absorber called the ‘stem guard’ that attaches to a cricket helmet and protects the neck behind the ear. Developed in partnership with Loughborough University,7 the new product was tested to the British Standard (BS) 1 year after Hughes’ death.7

This study aims to determine the actual impact speed of the ball and the energy released on the batsman’s neck, explore the options for shock absorption at the neck, as well as assess whether protection measures have been incorporated in the current helmet design.

Methods

Video Analysis from Photogrammetry, Including Estimation of Impact Velocity and Energy

The following method was also used for the first author’s expert report of this work for the coronal inquest into Phillip Hughes’ fatal injury.4 The video of the Sheffield Shield match between New South Wales and South Australia at the Sydney Cricket Ground on 25th November 2014 was provided by the New South Wales Police Force. The video was recorded at a frame rate of 25 frames per second.

The position of the cricket ball (black dots in Fig. 1), as well as the reference markers, were identified on each frame. The reference markers were a white object on the turf observed in front of the wicketkeeper’s hands (reference point represented by red dots in Fig. 1) and the return creases (black lines in Fig. 1). Subsequently, the frames of the video were superimposed using the reference markers, and the pitch (Fig. 1C) was reconstructed from the oblique angle of the video camera, showing the position of the ball in each individual image.

Based on the trajectory of the ball, the three impacts were identified (Fig. 1C), namely the impact on the pitch (bounce) after the release, the impact on the batsman’s neck, and the impact on the pitch after bouncing off the batsman’s neck. The three impact points were then photogrammetrically projected onto the pitch in

1Chair of Biomechanics, Faculty of Engineering Science, University of Bayreuth, Bavaria, Germany
2Discipline of Exercise and Sports Science, Sydney School of Health Sciences, Faculty of Medicine & Health, University of Sydney, New South Wales, Australia

Corresponding Author: Franz Konstantin Fuss, Chair of Biomechanics, Faculty of Engineering Science, University of Bayreuth, Bayreuth, Bavaria, Germany, Phone: +49 921 78516101, e-mail: franzkonstantin.fuss@uni-bayreuth.de


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The kinetic energy $E$ of the incident ball was

$$ E = m \frac{v^2}{2} = 0.156 \cdot \frac{29.85^2}{2} = 69.5 \text{ J} \quad (4) $$

Where $m$ is the mass of the ball (0.156 kg), and $v$ is the incident speed from equation 3.

The linear momentum $p$ of the ball at impact was

$$ p = vm = 0.156 \cdot 29.85 = 4.66 \text{ kg} \cdot \text{m/s} \quad (5) $$

The impulse $S$ equals the change of the momentum, $\Delta p$ (which in turn is the integral of force over time).

$$ S = \Delta p = m \Delta v = 0.156 \cdot (29.85 - 1.95) = 4.35 \text{ kg} \cdot \text{m/s} \quad (6) $$

Since the impact of the ball on the neck occurred within one frame, the maximum contact time could theoretically be 0.04 s, which is not likely. To estimate a more realistic shorter contact time, the course of the impact force $F$ was simulated with a sinusoidal impulse (half cycle) of 4.35 kg m/s at different contact times. The deceleration of the ball, $-a$, was calculated from

$$ -a = \frac{F}{m} \quad (7) $$
Neck Injury in Cricket and Protection Thereof

The decreasing velocity during impact was calculated by integrating deceleration over time (with initial and final velocities of 29.85 m/s and 1.95 m/s, respectively). The displacement of the ball during impact was determined by integrating the velocity over time and by selecting a realistic displacement.

**Impact Absorption Mechanics and Shock Absorber Design Principles**

The method of impact absorption used in this study is based on the ratio $R$ of energy per unit volume to stress. From the stress $\sigma$ – strain $\epsilon$ data (Fig. 2) of a compressed shock absorber, the energy per unit volume (W) is calculated from the following equation.

$$ W = \int \sigma d\epsilon $$

(8)

$R$ is determined from

$$ R = \frac{W}{\sigma} $$

(9)

From the $R$ vs $\epsilon$ plot, the maximum $R_{\text{max}}$ is the optimum point of shock absorption, that is, maximum energy $W$ absorbed relative to the experienced stress $\sigma$. The optimal parameters associated with $R_{\text{max}}$ are $\sigma_{\text{opt}}$, $W_{\text{opt}}$, and $\epsilon_{\text{opt}}$, which are critical to designing an optimal shock absorber. At $\epsilon$-values smaller than $\epsilon_{\text{opt}}$, $R$ is smaller than $R_{\text{max}}$, and both $W$ and $\sigma$ are also smaller. At $\epsilon$-values greater than $\epsilon_{\text{opt}}$, $R$ is also smaller than $R_{\text{max}}$, since $W$ does not continue to increase, but $\sigma$ increases sharply, creating a critical situation as the severity of injuries increases drastically due to extremely high stress.

The design constraints are the space $d$ available for the implementation of a shock absorber and the recommended maximum deceleration, $-a_{\text{max}}$, according to established standards, rules, or regulations. For “stem guards” (neck protection in cricket), Masuri10,11 refers to the BS 7928:2013 + A1:2019,12 which prescribes the optimal parameters associated with the experienced stress $\sigma$, shock absorption, that is, maximum energy $W$, strain and stress, respectively at $R_{\text{max}}$.

Since

$$ W = \frac{E}{V} = \frac{E}{dA} $$

(10)

Where $E$ is the energy from equation 4; and $V$, $d$, and $A$ are the volume, thickness (design space), and support area of the shock absorber, respectively; the optimal design thickness $d_{\text{opt}}$ of the shock absorber is calculated from the following equation.

$$ d_{\text{opt}} = \frac{E}{W_{\text{opt}}A} $$

(11)

The maximum deceleration, $-a_{\text{max}}$, is calculated from the following equation

$$ -a_{\text{max}} = \frac{A\sigma_{\text{opt}}}{m} = \frac{F_{\text{peak}}}{m} $$

(12)

Where $F_{\text{peak}}$ is the expected peak force at the shock absorber, not necessarily identical with $F_{\text{max}}$ in equation 7; and $m$ is the mass of the mobile rigid body whose energy has to be absorbed.

The parameters $\sigma_{\text{opt}}$ and $W_{\text{opt}}$ used to select the optimal shock absorber come from an extensive library of shock absorber materials and structures. The library included 220 foams with densities $\rho$ between 15 and 475 kg/m$^3$, including foams and absorbers such as Skydex, plastic castle, Poron, fabric spacers, cardboard absorbers, D3O, expanded polystyrene (EPS), Artilage, Berkeley, Solyte, and Speva.

Further input parameters for calculating $d_{\text{opt}}$ and $-a_{\text{max}}$ were: $E$ from equation 4; the shock absorber area $A$ to protect the neck (estimated at 0.02 m$^2$); and the mass of the cricket ball (0.156 kg). In addition to the energy $E$ of from equation 4, that is 70 J, the shock absorber design was also calculated for 15 J.1712

For each set of input parameters, the output parameters $d_{\text{opt}}$, $-a_{\text{max}}$, and $F_{\text{peak}}$ were correlated to understand the individual shock absorption dynamics.

**RESULTS**

**Video Analysis**

The incident speed of the ball on the batman’s neck has been estimated at around 30 m/s, which is 108 kph or 67 mph. The neck had to absorb approximately 70 J of impact energy.
Estimation of Impact Force and Deceleration

The simulated data of peak force, deceleration, and displacement of the ball’s center of mass (COM) as a function of contact time are shown in (Table 1). If the contact time lasts 0.04 seconds, the displacement of the COM is 640 mm. However, the human neck is about 120 mm in diameter. It is, therefore, reasonable to assume short contact times with small displacements, especially considering that the higher the impact velocity, the stiffer the viscoelastic soft tissue becomes.

Impact Absorber Design

Absorber Design when Using Phillip Hughes’ Impact Data

Based on the estimated dynamics data in the Phillip Hughes incident, the design solution for neck cushions was calculated using an impact energy of 70 J, an absorber area of 0.02 m (e.g., 100 × 200 mm), and a ball mass of 0.156 kg, under boundary conditions of peak acceleration (\(\ddot{a}_{\text{peak}}\)) of 250 g, a maximal impact force of 400 N, and a preferred optimal absorber thickness of \(<0.1\) m.

The optimal absorbers with the smallest thickness \(d_{\text{opt}}\) (at the optimum point of \(R_{\text{max}}\)) are shown in (Table 2). Clearly, the absorber thickness of 0.73–0.81 mm is not feasible.

Selecting an alternative foam with higher relative density and/or greater modulus of the base material, for example, EPS (standard bicycle helmet material; Table 2), the thus thinner absorber would be too stiff and would lead to excessive decelerations and impact forces when placed on a hard substrate. Since the absorber is designed to protect the neck, the soft tissues of the neck would absorb all of the energy before the absorber material participates in shock absorption. In such a case, increasing the area of the shock absorber would be the correct design strategy, but due to the small size of the neck, this strategy would be unsuccessful.

Absorber Design According to the Data of the BS

If the calculation were carried out according to the BS \(^{212}\) with an impact energy of 15 J, \(^{13}\) an impact mass of 5 kg \(^{13}\) (impact speed of 2.45 m/s \(=\) 8.82 kph, fall height 0.306 m), and an absorber surface of 0.02 m, with boundary conditions of peak acceleration (\(\ddot{a}_{\text{peak}}\)) of 250 g, then the thickness of the absorber (Active comfort, \(\rho = 30 \text{ kg/m}^3\)) would only be 73 mm, at a g-rating of 8.8 g and an impact force of 430 N. If only decelerations between 40 and 60 g are chosen (comparable to the average deceleration of the Masuri StemGuard of 53 g \(^{13}\)), then the absorber thickness would be between 14 mm and 28 mm (the actual thickness dependent on the type of absorber used, here specifically: XPF13-1647, ISF136, plastic castle T14, Poron 15500, D30 Aero, Artilage, Berkeley 77), at excessive impact forces ranging from 2005 to 2929 N, matching the forces resulting from the smallest contact time window in (Table 1).

When using an impact mass of 0.156 kg (cricket ball) at the same impact energy (15 J), then the absorber thickness and impact force would not change, but the deceleration would increase to 281 g due to the faster speed of the low-mass cricket ball and therefore exceed the recommended peak acceleration of 250 g. \(^{212}\)

Discussion

The incident speed of the ball that hit Phillip Hughes’ neck was calculated to be 107.4 kph, the average speed between the first two impacts (pitch and neck). The distance of 9.91 meters is the shortest distance between the two impact sites. However, the trajectory is slightly longer because it is curved due to gravity. A longer trajectory would result in higher speed; however, speed decreases during flight due to aerodynamic drag and gravitational acceleration. The impact speed at batman’s neck is therefore expected to be slightly <107 kph. Since the alignment and change in the ball seam as well as the post-bounce spin rate and, therefore, the aerodynamics, were unknown, we did not simulate the trajectory to estimate a more accurate incidence velocity.

Tunnicliff claimed that the ‘speed at which the ball struck Phillip Hughes’ was 90 mph.\(^{14}\) This speed is equivalent to 145 kph. This impact speed is unrealistic, as 145 kph is considered the speed of an elite international fast bowler at the time of release. During the period of ball impact on the pitch, the ball loses translational velocity due to loss of kinetic energy (i.e., from internal loss of energy from inner friction caused by the viscous behavior of the ball reflected in the coefficient of restitution; from external loss of energy from friction between ball and pitch; and from energy loss through energy transfer from translational to angular due to friction explaining why the ball acquires more topspin at the impact).

To prevent future injuries caused by impact, this study raises a number of problems in relation to designing appropriate neck protection.

- The calculated amount of energy absorbed is not sufficient to determine the design of the shock absorber. According to equation 4, the kinetic energy is half the product of mass and

| Table 1: Simulated data of peak force \(F_{\text{peak}}\), deceleration \(-\ddot{a}_{\text{max}}/g\), and displacement of the ball’s COM as a function of the contact time |
|---|---|---|---|
| Contact time (s) | \(F_{\text{peak}}\) (N) | \(-\ddot{a}_{\text{max}}/g\) (\(\cdot\)) | Displacement (mm) |
| 0.04 | 171 | 111 | 637 |
| 0.02 | 341 | 223 | 318 |
| 0.01 | 683 | 446 | 159 |
| 0.005 | 1365 | 892 | 80 |
| 0.0025 | 2730 | 1784 | 40 |

| Table 2: Results of the impact absorber design (unfeasible results in bold font) |
|---|---|---|---|---|
| Foam | Density \(\rho\) (kg/m\(^3\)) | Thickness \(d\) (m) | \(-\ddot{a}_{\text{peak}}/g\) (\(\cdot\)) | \(F_{\text{peak}}\) (N) |
| Ultimate comfort | 41 | 0.73 | 172 | 263 |
| Active comfort | 31 | 0.8 | 130 | 200 |
| Active comfort | 27 | 0.81 | 121 | 186 |
| EPS | 34–35 | 0.013–0.018 | 7020–9050 | 11k–14 k |

\(-\ddot{a}_{\text{peak}}\), maximum deceleration; EPS, expanded polystyrene; \(F_{\text{peak}}\), peak force; \(g\), gravitational acceleration (9.81 m/s\(^2\))
velocity squared of a moving body. Increasing the speed by reducing the mass for the same kinetic energy does not affect the thickness of the energy absorber or the magnitude of the impact force, but it does affect the deceleration of the moving body over the same thickness of the shock absorber. Accordingly, the faster the speed, the greater the deceleration (more “g”). In addition, it is important to note that the maximum permissible deceleration is only one of the two decisive design criteria of a shock absorber. According to equation 7, less mass is associated with more acceleration at the same level of force. The energy of a 156 g cricket ball flying at 107 kph is the same as that of a 2 g bullet fired at a speed of 950 kph. It is, therefore, not further surprising that a reasonable shock absorber could not be found for the input data relating to Phillip Hughes’s injury. Softer absorbers with less energy storage result in less deceleration (–a) and peak force but require greater absorber thickness. Conversely, stiffer absorbers with more energy storage result in increased and excessive deceleration (–a) and peak force but thinner absorbers. The trade-off between acceptable thickness d and deceleration (–a) does not provide acceptable solutions when using the input parameters of Phillip Hughes’ injury (“GAP” in Fig. 3). Increasing the mass to 10 kg for the same impact energy eliminates the gap in Figure 3 and produces overlapping solutions for thickness and deceleration.

- It is surprising that protective equipment designed to prevent fatal injuries is tested at impact energies lower than the actual energy causing those very incidents and at a mass far greater than that of a cricket ball. A guessimate of the impact speed (90 kph) was already published (albeit only in a daily newspaper) the day after Phillip Hughes was injured, and a more detailed impact velocity analysis has been available since the investigation. It appears that the impact energy has been simply taken from the standard for helmet testing before it was expanded to neck protection as a response to Phillip Hughes’ fatal injury. Therefore, it is not surprising that “In two 15 J tests, the (Masuri) StemGuard returned readings of 55.9 and 55.7 g,”

and in six 15 J tests data from 45.9 to 78.9 g (average 53.35 g) using 15 J impact energy and a mass of 5 kg dropped from a height of 0.3 m.

- It is unclear from where the recommendation for a maximum deceleration (–a_{max}) of 250 g originated. The BS recommends a maximal 250 g for head impacts to prevent severe traumatic brain injuries (contusion of the brain). Phillip Hughes’ fatal injury, however, was a dissection of the vertebral artery followed by intracranial subarachnoid hemorrhage. It is not known what magnitude of acceleration could cause such an injury. The British helmet standard recommends 250 g for helmet testing and appears to be staying at the same level when the standard was extended to include neck injuries. However, we must remember that fatal neck injuries in cricket are rare. Brukner et al. reported only two fatal neck injuries over the course of 152 years, both of which caused vertebral artery dissection followed by subarachnoid hemorrhage. This rarity contrasts sharply with head injuries suffered by cyclists, where, due to the lower impact velocity and greater mass of the head (= 5 kg), damping solutions are much easier to implement (e.g., standard bicycle helmets).

**CONCLUSION**

In cricket, it is difficult to find practical cushioning solutions for protective equipment to prevent severe neck injuries. While the size of the shock absorber (thickness, area) is a function of impact energy, the peak deceleration is a function of mass, and thus, via the impact energy, is also a function of impact velocity. The impact energy is a function of mass and velocity. Hence, the decisive factor in protector design is the impact speed: the faster the impact speed, the higher the deceleration required to stop the ball within a designated cushioning thickness. In addition, the smaller the mass and thus the faster the speed (projectile principle) at a given amount of impact energy, the further the practical measures are limited that can be taken to protect the neck region in cricket.
A shock absorber intended for neck protection should, at the very least, be tested at the correct speed and mass, not at an equivalent impact energy calculated on a higher mass and slower velocity that does not correspond to the match-play conditions in cricket. Furthermore, the impact energy required by the BS7928 is hardly representative, being only 15 J compared to the 70 J impact energy for Hughes’ injury.

Clinical Significance
In this study, we showed that shock-absorbing solutions with practical dimensions that do not inhibit the batter and with low decelerations are difficult to implement. However, in the aftermath of the Phillip Hughes incident, it is important that engineers and administrators come up with solutions to minimize such injuries. The only risk mitigation possible is to forego playing bouncers instead of using shock absorbers of questionable efficiency.

Orcid
Franz Konstantin Fuss https://orcid.org/0000-0001-9846-0985

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