The Development of a Test Methodology for the Determination of Cricket Batting Helmet Performance when Subjected to Ballistic Impacts

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Abstract The study presented in this paper was conducted in support of the development of a proposed revision to a cricket helmet certification test standard. Helmets were impacted between the peak and faceguard by 'projecting' balls at them at velocities up to 80 mph. The velocity at which the balls penetrated between the peak and the faceguard (or grille) for the various permissible peak-grille gap settings for each helmet was recorded. The study progressed to compare these penetration velocities against the equivalent found when 'game-aligned' alternate (drop) test methodologies were used.

The results demonstrate that the penetration velocities are considerably lower than those that might be observed in play. As peak-grille gap settings were reduced, penetration velocities increased as expected but, significantly, balls were able to penetrate despite gap settings, on occasion being considerably smaller than the ball diameter. The penetration velocity was also found, as expected, to vary with the stiffness of the ball with increased ball stiffness leading to reduced penetration velocities. When comparing penetration velocities against those found using the alternate methodologies, significant differences were found, suggesting that such methodologies cannot be used to reliably evaluate the performance of helmets to ball impacts occurring in this particular region.

Keywords cricket, helmet, impact, injury prevention, penetration testing

I. INTRODUCTION

Since the introduction of protective headwear in cricket in the 1970s to combat an increasing level of cranial and facial injuries, its design has changed considerably to account for the level of protection required by players, the increased level of use and the performance demands during use [1-2]. Modern cricket helmets were first introduced in the 1980s and were often used without faceguards. The use of a faceguard increased during the 1990s and 2000s with a continuing number of serious facial injuries being sustained despite the more frequent use of helmets [2].

As shown in Figure 1, modern cricket helmets consist of three main parts: 1) the shell, 2) the liner and 3) the faceguard (or grille). The shell and liner work together to distribute the impact force over a large area and attenuate impact energy [3], whereas faceguards are designed to prevent ball contact with the face. Traditionally, helmets are most commonly constructed with a fibreglass or Acrylonitrile Butadiene Styrene shell, a low-density polyethylene liner [4] and steel or titanium faceguards. More recently alternative materials (e.g. carbon-fibre reinforced polymer for shells and air bags for liners) have been observed in some designs. Despite the advances in materials technology and helmet designs, however, head and face injuries during cricket batting are not uncommon.

Walker *et al.* [5] reported that head injury in cricket accounted for 23% of all cricketing injuries for both recreational and professional players over a 6 year period, of which 12% were concussions, 35% were fractures, 11% open wound injuries and 18% contusions. The work continued to show that open wound injuries and fractures were most commonly localised in regions that were protected by the faceguard. Similar injury rates were found in the study by Stretch *et al.* [6] and in the review by Finch *et al.* [7]. The ability of the ball to breach the peak-grille gap, impact the face and cause injury was identified by McIntosh *et al.* [8] as an important area of design improvement but few studies other than that of Walker *et al*. [9] exist that have confirmed this area as a particular shortcoming with current designs. This absence was addressed by Ranson *et al*. [10] who, using game-recorded video, identified that injuries were most prevalent when impact occurred with either the

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faceguard or, more commonly, the gap between the peak and the faceguard thereby identifying a particular inadequacy with current helmet designs.

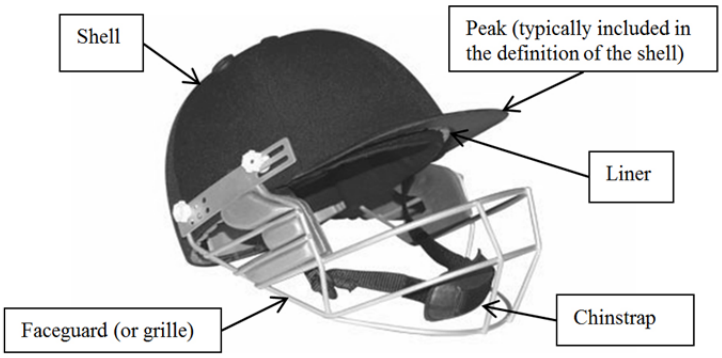

Fig. 1. “Modern” cricket helmet anatomy

The inclusion of a specific procedure within the current helmet test standards [11-12] to determine whether or not the ball can pass between the peak and the faceguard would surely invoke a design revision. Currently these test standards focus only on the impact attenuation performance of the shell and of the faceguard, using the instrumented headform peak acceleration as an indicator of whether or not the helmet is suitable for use. Walker [9] and Ranson [10] both found that injuries in the regions protected by the faceguard were, most commonly, fractures, lacerations and contusions, all of which were caused by ball or faceguard impacts to the face. It can therefore be argued that head acceleration should not be the only measure of interest when concerned with the protection offered by cricket helmets, particularly when concerned with impacts between the peak and the faceguard or on the faceguard alone.

Despite the potential severity of injury that may be sustained if the ball breaches between the peak and the faceguard, little work has been conducted to evaluate the performance of helmets specifically concerning this region. Instead, experimental work has been limited to impacts on the shells [3,6] and theoretical work to impacts occurring on the faceguards [4]. Additionally, the ability to replicate a typical gameplay ball-helmet impact, i.e. with the at-speed ball freely impacting the helmet, in laboratory conditions is often unachievable or at best impractical or unpredictable. Generally, therefore, alternative methodologies, either such as those presented by Stretch [6] and defined in the Australian/New Zealand Standard [12] in which a falling mass impacts the helmet, or that defined in the British Standard [11], in which the helmet/instrumented headform fall onto a ball-shaped anvil, are used with the impact velocities tuned in order to arrive at an impact energy equivalent to that which would result from the ballistic impact.

The purpose of this study, therefore, was to determine the performance of a range of currently available cricket helmets when subjected to ballistic impacts between the helmet peak and faceguard. ‘Game-aligned’ testing methodologies were employed with a view to proposing a test protocol for future inclusion in the British Standard. In addition, the study aims to identify whether or not the use of drop test methodologies provide a suitable alternative to projectile equivalents, allowing them to be used interchangeably when concerned with impacts within this specific region.

II. METHODS

Three helmet-impacting methods were used in this study: 1) a projectile test, 2) an anvil drop test and 3) a helmet drop test. Anvil drop and helmet drop tests are currently used in the Australian/New Zealand and British Standard impact attenuation tests, respectively, to determine whether or not current helmets provide sufficient protection to players.

Helmet Selection and Configuration

Four readily available cricket batting helmets (H1-H4), shown in Figure 2, were selected for use in this study. The helmets selected were a fair representation of the helmets that are currently used in game play, varying in design (materials/geometry) and construction (manufacture). The range of gap sizes between the faceguard and peak of the helmet selected for testing were dependent upon the permissible settings on the various helmets. Four sizes were tested for helmet H1 (73.8, 60.6, 55.6 & 40.6 mm), six for helmet H2 (59.1, 57.9, 50.9, 49.3, 48.8 & 41.1 mm), five for helmet H3 (71.0, 63.8, 58.6, 54.8 & 45.8 mm) and only one for helmet H4 (56.8 mm).

Fig. 2. Four cricket batting helmets used in this study

Throughout all tests, faceguards were correctly fitted to helmets, using the predefined settings and the screws provided by manufacturers. The helmet position was adjusted such that the peak of the helmet was parallel with the direction of travel and in order that the ball/anvil would come into contact with the peak and the faceguard (near-) simultaneously. The position of the faceguard, relative to the direction of travel, was dependent upon the positioning of the peak of the helmet.

A single frontal impact location between the peak of the helmet and faceguard was used during the tests. Each helmet was tested at its widest gap setting first, for all impactors, until penetration had occurred, after which the gap setting was reduced to the next increment smaller and the test repeated. A single trial was used during tests to minimise the damage potential to helmets but trials were repeated if: a) the impactor became ‘wedged’ between the peak and faceguard or, b) a simultaneous impact between the peak and the faceguard was not observed. Trials were also repeated in projectile tests if a ±2 mph (0.9 m/s) condition was not adhered to. Trials were completely terminated if a helmet or faceguard had become visibly and irreversibly damaged. Impacts throughout all studies were recorded using a Photron Fastcam SA1 high-speed video camera, capturing at 8000 frames-per-second (1/frame rate shutter speed). Video capture was used to determine impact location and ensure helmet position was consistent between trials. Two Arri Pocket Par 400 lights were used to provide sufficient lighting for video capture.

Projectile, Anvil and Helmet Drop Methodologies

For the projectile test, a Fourway hydraulic air cannon was used to launch impactors at the helmets. Three types of impactor were used: 1) a standard ‘Tiflex’ cricket ball (dia. 72 mm, 163 gr), 2) a BOLA training ball (dia. 72 mm, 150 gr) and 3) a hockey ball (dia. 74 mm, 163 gr). Helmets were suspended using four bungees orthogonal to the direction of travel, as shown in Fig. 3, and impactors were launched at the helmets in 10 mph increments, with impact velocities ranging between 30 mph (13.4 m/s) and 80 mph (35.8 m/s). Given the design of the air cannon, 30 mph was the minimum velocity that could be achieved while maintaining a reasonably consistent impact location. Impact velocities were confirmed with a light gate located 60 mm prior to impact.

An Instron Dynatup 9250HV machine was used in order to carry out anvil drop tests with helmets being positioned upon a rigid cylindrical ‘tee’ as shown in Fig. 3. A spherical steel impactor (dia. 72 mm, 1.68 kg) was used in this test with the option to add mass to the carriage (total mass 9.78 kg inc. impactor). Drop heights were adjusted according to two different scenarios: 1) matching the impact *kinetic energy* of a cricket ball and 2) matching the impact *momentum* of a cricket ball, in each case for a ball travelling at 5 – 25 mph (2.2 – 11.2

m/s) in 5 mph increments and 30 – 80 mph (13.4 – 35.8 m/s) in 10 mph (4.5 m/s) increments. To arrive at impact *kinetic energies* that were consistent with a cricket ball travelling at a given velocity, an additional 18.87 kg was added to the system (with the drop height varied accordingly). To match the *momentum* a cricket ball would contain whilst travelling at certain velocities, no additional mass was used. All kinetic energy matching tests were completed first, followed by all momentum matching tests.

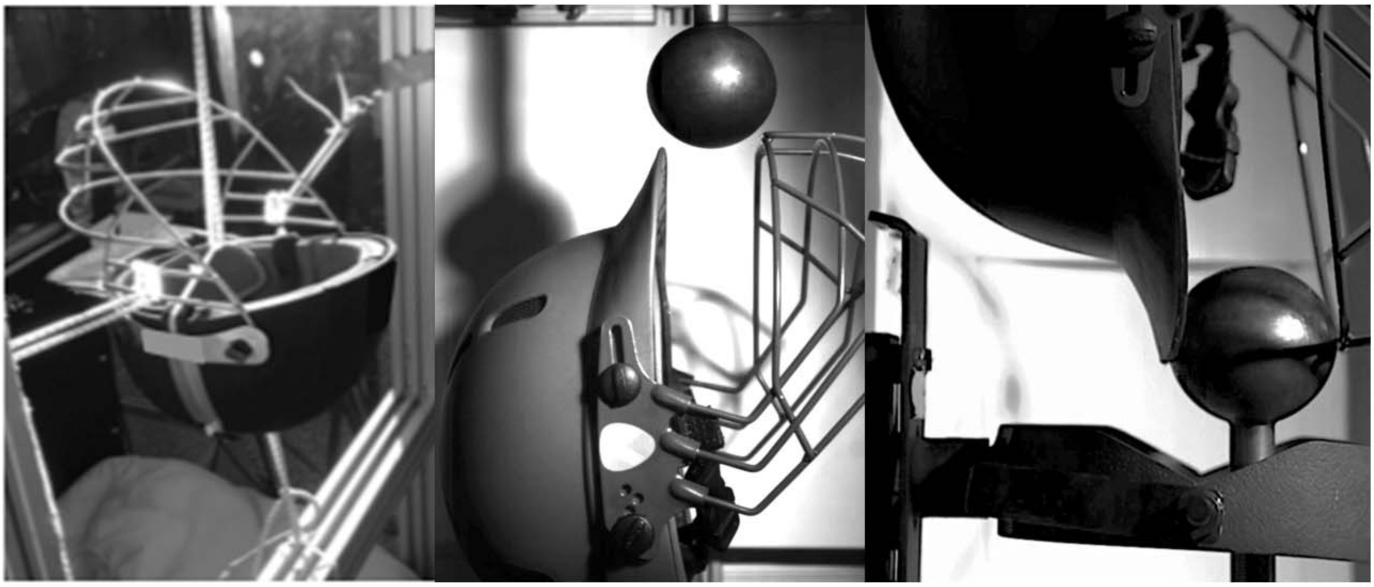

Fig. 3. Projectile, anvil drop and helmet drop test configurations

A bespoke rig, also shown in Figure 3, was used in order to conduct helmet drop trials. Helmets could be positioned on the falling carriage such that the impact could be achieved at almost any location. Helmets were free to separate from the carriage following impact. The same spherical steel impactor (dia. 72 mm, 1.68 kg) was used during this test but in this case as an anvil rigidly connected to the bespoke rig which was freestanding on a massive concrete floor. In this test configuration the difference between penetration speeds when a correctly fitted headform (bespoke facially featured, nominally homogenous Silastic 3481 of mass 5.8 kg) was or was not included inside the helmet. Drop heights were again adjusted to arrive at impact energies consistent to that of a cricket ball travelling at 5-80 mph as for the anvil drop tests. All tests were completed for helmets without the headform first and then repeated for helmets with the headform included.

III. RESULTS

By plotting the various penetration speeds against the tested gap sizes, a potential “safe” region could be defined where, in accordance with the findings of this study, a ball impacting the peak-grille would not penetrate and potentially cause injury to the wearer. An example of such a plot is shown in Figure 4 for the projectile test scenario; similar plots were constructed for the other two test scenarios. The coloured vertical lines in the plot indicate the range of the gap sizes permissible for the various helmets as set out in the previous *Helmet Selection and Configuration* sub-section. Helmet H1, for example, has a range of possible peak-grille gap sizes from 73.8 to 40.6 mm and was tested at all. Helmet H2, however, was not tested to the extent of its permissible gap setting range (59.1 to 45.8 mm) as visible damage occurred at the 49.3 mm gap setting and further trials were therefore terminated. Helmet H3, conversely, was tested at its entire range of gap settings (71.0 to 45.8 mm) but damage occurred at the 70 mph (31.3 m/s) impact velocity step and a green cross is therefore plotted at this point to indicate that the ball did not penetrate at this speed but that tests were terminated due to helmet damage. Shaded regions on the graph indicate the “safe” regions for the various helmets, thus providing a measure for the ‘safest’ helmet of those that were tested. Helmet H4 had only one permissible gap setting and a single point, therefore, only exists at the speed at which the ball penetrated between the peak and faceguard. Theoretically the helmet is ‘safe’ for all regions that extend vertically below this point but unsafe for those above. Helmet H1 demonstrates a penetration speed of 0 mph where the gap setting is 73 mm given that the diameter of a cricket ball is smaller than this particular gap size and the ball will therefore penetrate readily.

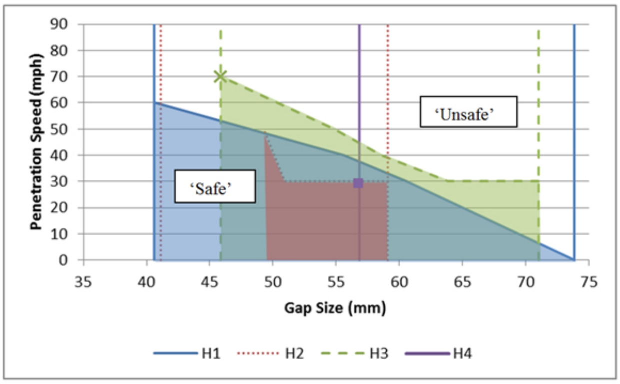

Fig. 4. Penetration speed vs. gap size for a cricket ball for the projectile test configuration

In addition to determining for what projectile velocities and for which peak-grille gap settings cricket ball penetration would occur, a further aim of the study was to determine whether an alternate, more consistently behaved impactor could be used instead of a cricket ball. Significant variations in impact velocity, trajectory and location are observed when launching a cricket ball with the air cannon used in this study, due in particular to the seam and its unpredictable interactions with the barrel. Should the projectile test be subsequently incorporated into a standard test there is, therefore, a desire to specify a more consistent impactor. The plots for the equivalent trials conducted with the hockey and BOLA balls are shown in Figure 5.

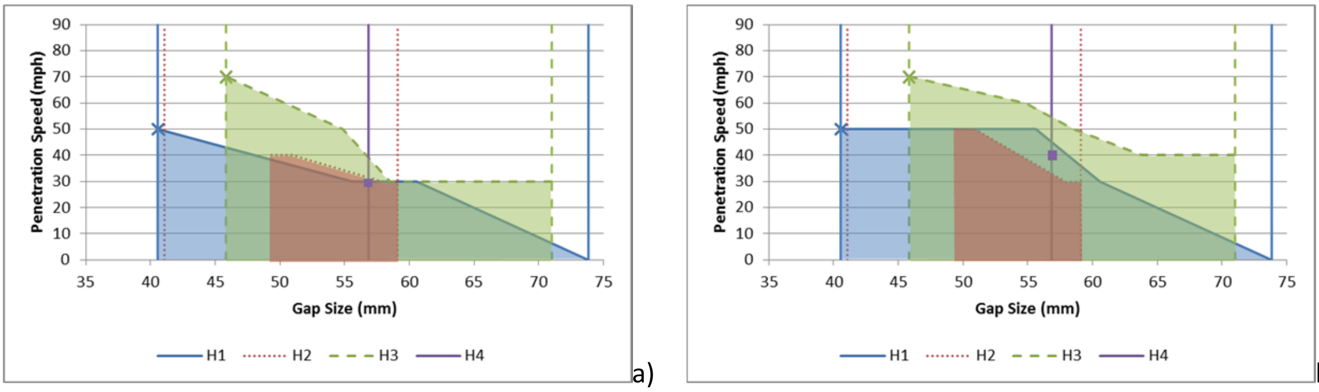

Fig. 5. Penetration speed vs. gap size for a a) hockey and b) BOLA ball for the projectile test configuration

(Nominal) penetration speeds from the drop tests are shown in TABLE 1. For comparative purposes, the penetration speeds in the equivalent projectile tests are also presented in the table. As can be seen, the anvil drop test generally results in ball penetration speeds that are either an underestimation (energy matching) or an overestimation (momentum matching) of those found in the projectile tests. The helmet drop tests also generally demonstrate an underestimation when the headform is included and an overestimation when it is not but, when plotting the data, it can be seen that the trends are similar to those from the projectile tests. It is hypothesized, therefore, that it may be possible to use the helmet drop test configuration as an alternative to the projectile test configuration with an appropriate "calibration factor".

IV. DISCUSSION

This preliminary investigation, aimed at the development of a test methodology for the determination of cricket batting helmet performance when subjected to ballistic impacts in the previously identified as vulnerable region between the peak and faceguard, clearly has a number of limitations. Firstly, the ideal scenario would be one in which a new helmet was used prior to each new impact since repeated heavy impacts clearly lead to a difference in performance since the structure of the helmet may become damaged when absorbing the impact energy. Indeed in some cases in this study, helmets suffered damage to the extent that further tests had to be terminated. As specified in the Standards and as recommended by manufacturers, helmets "any helmet that sustains a severe blow needs to be replaced even if damage is not apparent". Future

TABLE 1

COMPARISON OF PENETRATION SPEEDS FOR PROJECTILE, ANVIL AND HELMET DROP TESTS

Helmet	Gap Size (mm)	Penetration speeds (mph)						
		Projectile			Anvil Drop		Helmet Drop	
		Cricket	Hockey	BOLA	Momentum Equivalent	Energy Equivalent	No Headform	Headform
H1	73.8	0	0	0	0	0	0	0
	60.6	<30	<30	<30	<5	<5	40-50	<5
	55.6	30-40	<30	40-50	50-60	<5	80+	15-20
	40.6	50-60	50+	50+	80+	15-20	80+	40-50
H2	59.1	<30	<30	30-40	<5	<5	<5	<5
	57.9	<30	<30	30-40	<5	<5	<5	<5
	50.9	30-40	<30	40-50	40-50	<5	40-50	<5
	49.3	40-50	40-50	50-60	50-60	<5	40-50	<5
	48.8	-	-	-	50-60	<5	50-60	<5
	41.1	-	-	-	80+	10-15	60-70	5-10
H3	71.0	<30	<30	30-40	<5	<5	<5	<5
	63.8	<30	<30	30-40	<5	<5	10-15	<5
	58.6	30-40	<30	40-50	<5	<5	30-40	<5
	54.8	40-50	40-50	50-60	30-40	<5	50-60	<5
	45.8	70+	70+	70+	70-80	5-10	80+	10-15
H4	56.8	<30	<30	30-40	<5	<5	25-30	<5

studies should look at the repeatability and consistency of the performance of helmets for specific configurations using new helmets and determine whether the early findings presented in TABLE 1 are statistically significant.

A further limitation of the study, in particular with respect to the cricket ball impactor but also for the projectile test in general, is the (lack of) control over the impactor launch conditions. Variations in velocity and trajectory are observed which lead to non-simultaneous contact of the impactor on the peak and faceguard. Upon contacting either feature first, the impactor is deviated from its preferred trajectory toward the other feature and will subsequently impact that feature more heavily, reducing the likelihood of penetration and incurring a false negative result. During the study conducted here, such obvious problematic impacts were rejected and recaptured but the problem identified previously, i.e. that the structure of the helmet may have become damaged, is exacerbated.

A final challenge which extends across all test configurations and one which continues to lead to contention when specifying test protocols in Standards is the fact that, due to (sometimes only subtle) differences in the design of the helmets, alignment of the helmet with the impactor travel direction was not trivial nor obvious. Indeed, in some cases, helmets have peaks that protrude significantly further out in front of the faceguard than the norm making it more difficult to arrange for simultaneous contact of the impactor on the peak and grille (and, in doing so, give the ball the best chance of penetrating). Furthermore, in some cases peak-grille gap size varies significantly between the front of the helmet and towards the sides, clearly meaning that the likelihood of penetration is dependent upon where and in what direction impact occurs. It is important to explicitly state here that, the process of incorporating further test protocols within Standards for such protective equipment should be done so with the increased safety of the user in mind and ideally without stifling innovation in the development of the product.

V. CONCLUSIONS

The possibility of a cricket ball penetrating between the peak and the faceguard of a cricket helmet has resulted in the injuries sustained, while batting, to be predominantly located around the eye orbits, maxilla and nasal bones. Such injuries can be severe and, potentially, career threatening. Despite this, little work has been conducted to date to assess cricket helmet performance to ball impacts occurring in this region. The study presented in this paper was intended to address this deficiency in support of the development of a proposed revision to the cricket helmet certification test standard.

The development of a practical approach to test the performance of cricket helmets when subjected to ball impacts that occur between the peak and the faceguard of the helmet has shown that it is possible for a ball to penetrate even at relatively low velocities. Importantly, this indicates that current cricket helmets may require a design change to eliminate facial injuries from occurring in this region as a result of such penetration. Furthermore, the findings argue the case for the inclusion of an appropriate testing procedure for ball impacts occurring in this region, something that is not required by current helmet certification test standards.

In conclusion, this study has aimed to determine the applicability of drop tests as alternatives to projectile tests to determine the performance of cricket batting helmets when subjected to ballistic impacts between the peak and faceguard. Preliminary data processing has shown differences between helmet performances within the constraints of using the same helmet for various tests; future studies would limit the number of impacts per helmet to increase confidence and ascertain whether or not results are statistically significant. Furthermore, in the event that it is not possible to replicate helmet performance with either anvil or helmet drop tests, the study has also shown that alternative, more readily controlled impactors can be used in the projectile tests with equivalent results to those which would result when using cricket balls. Again, future work should focus on minimizing variability and determining whether these data are statistically significant.

VI. ACKNOWLEDGEMENT

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VII. REFERENCES

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