Design of Neck Protection Guards for Cricket Helmets

T. Y. Pang[a] and P. Dabnichki
School of Engineering, RMIT University, Bundoora Campus East, Bundoora VIC 3083, Australia

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Abstract: Cricket helmet safeguards have come under scrutiny due to the lack of protection at the basal skull and neck region, which resulted in the fatal injury of one Australian cricketer in 2014. Current cricket helmet design has a number of shortcomings, the major one being the lack of a neck guard. This paper introduces a novel neck protection guard that provides protection to a cricket helmet wearer's head and neck, without restricting head movements and obstructing the airflow, but achieving a minimal weight. Adopting an engineering design approach, the concept was generated using computer aided design software. The design was performed through several iterative processes to achieve an optimal solution. A prototype was then created using rapid prototyping technology and tested experimentally to meet the objectives and design constraints. The experimental results showed that the novel neck protection guard reduced by more than 50% the head acceleration values in the drop test in accordance to Australian Standard AS/NZS 4499.1-3:1997 protective headgear for cricket. Further experimental and computer simulation analysis are recommended to select suitable materials for the neck guards with satisfactory levels of protection and impact-attenuation capabilities for users.

1 INTRODUCTION

Cricket helmets were introduced into the sport to protect the head and face of batsman when a bowler intentionally aimed the ball at head height. The ball can reach speeds of up to 160 km/h (Mohotti *et al.* 2018). The helmets are engineered to disperse the kinetic energy of the ball on impact over a wider surface area to minimize the pressure and to prevent the likelihood of skull fracture or fatal head injury (Subic *et al.* 2014). Most helmets today are generally made of two components: a stiff shell to spread the impact force, and a soft liner to absorb the impact energy (Ranson *et al.* 2013). These two components are generally a fiberglass or ABS (Acrylonitrile butadiene styrene) shell and a low-density polyethylene. A faceguard is an additional component that attaches to the cricket helmet to protect the head and face from impact injuries (Subic *et al.* 2005). While every manufacturer develops their own design, all have to comply with the Australian Standard AS/NZS 4499.1-3 (Australian/New Zealand Standard 1997). Still, there are areas for the current helmet to be improved in order to provide further protection for head and facial injuries (Ranson *et al.* 2013). Stretch (2000) conducted an experiment on six different helmets with different features and materials at three different locations. Of 18 impact sites, only 14 met the safety standards of head deceleration below 300g when the ball impacting at the helmeted head at a speed of 160 km/h—a speed that a professional bowler is capable of achieving. This suggests that the design parameters are not the same across manufacturers and, hence, performance varies.

An earlier study by Ranson *et al.* (2013) noted limitations with the current cricket helmet designs where the neck and basal skull as the occiput regions are not protected. In this study, 17% of injuries occurred at the back of the skull and 6% occurred at the neck where there was no contact with the helmet, as shown in Table 1. A report published on injuries in cricket by Walker *et al.* (2010) stated that head injuries account for 23% of all cricketing injuries. Of these injuries, 35% were fractures, 18% were contusions, 12% were sport related concussions and 11% were open-wound injuries. Similarly, a recent study by Panagodage Perera *et al.* (2019) reported a

[a] https://orcid.org/0000-0002-4766-3042

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high incidence of head injuries among female cricket players who required hospital admissions.

Table 1: The number of injuries associated with each impact (Ranson et al., 2013).

Area of impact	Injuries	% Injuries
Faceguard	9	26
Peak and faceguard	9	26
Back of shell	6	17
Temple-protector	5	14
Through peak-faceguard gap	4	11
Occiput/neck (no helmet contact)	2	6
Total	35	100

The lack of neck and basal skull protection offered by current cricket helmets raised serious concerns, especially during the 2014 Australian One-Day International cricket event. Phillip Hughes, an Australian cricketer sustained fatal injuries after a ball hit his neck caused a haemorrhage. Hughes was wearing an older helmet designed by Masuri®, where the neck and basal skull were exposed and the blunt force caused a vertebral artery dissection leading to subarachnoid haemorrhage (Coverdale 2014).

Subsequently Masuri, developed a new StemGuard design. The StemGuard is made from thermoplastics and dense foam arranged in a honeycomb (Masuri 2015). It is an additional product with a clip attachment to their Vision Series helmets. Its design provided an ergonomic and practical option to protect the neck and basal skull region (Masuri 2015). The StemGuard is currently used by world class cricketers. Little information has been released on how the StemGuard was tested and how much energy it can absorb. The StemGuard is shown in Figure 1.

Figure 1: Masuri's StemGuard (Source: Masuri 2015).

An Irish cricketer, John Mooney, has invented an adjustable grill that extends to the back of the helmet, to provide additional protection to the neck (Figure 2). He based the design on the medieval armour that providing protection to the users around the throat and neck regions. The grill was made out of steel, but has yet been fully tested to confirm its safety performance (Brettig 2015).

Figure 2: Adjustable grill neck protector (Source: Brettig 2015).

The aim of this project is to design and optimise a neck protection guard (NPG) for a cricket helmet that provides protection to the basal skull and neck regions. Based on the knowledge gained from the Masuri's StemGuard concept, we aim to: (i) create a NPG design for a cricket helmet to ensure that the basal skull and neck region are protected; (ii) simulate impact tests using the finite element analysis to investigate the performance the NPG; and (iii) produce a prototype of the proposed design and conduct experiments for validation.

2 METHODOLOGY

To achieve these aims, an engineering design process was adopted. The computer aided design (CAD) software, CATIA, was used to create a 3D design of the proposed NPG. Finite Element Analysis (FEA) was used to perform virtual impact tests. A 3D model representation of the NPG with realistic material properties, boundaries and loading conditions was devised for impact simulation. FEA was performed to determine whether the initial design fulfilled the impact performance and to reduce physical testing.

2.1 Concept Designs

Several concepts were proposed at the initial stage of the design process, with consideration of a range of design criteria and objective functions. The objective functions for the design were: (i) the ability to protect the neck region from impact injury; (ii) the proposed NPG must be lightweight and flexible, yet rigid enough to maintain its shape; (iii) it must have adequate ventilation that will not prevent heat dissipation from the covered region; and (iv) the proposed design should not restrict any head and neck movement and so be detrimental to the player's performance. A collection of the initial conceptual designs is shown in Figure 3.

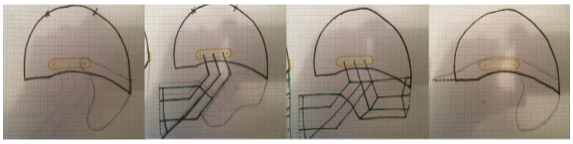


Figure 3: Conceptual sketches of the neck protection guard.

The design idea of the NPG was to provide sufficient protection towards the neck and basal skull region and could be easily attached to the faceguard.

2.2 Impact Energy and Force

When designing the NPG, it was expected the device will withstand the impact force in the real sports environment. Since the impact force at the basal skull region is unknown, we used the Momentum Conservation and Newton's Law to determine the impact energy and impact force.

Professional bowlers are able to throw the cricket ball at speeds reaching 160km/h, which is equivalent to ~44m/s. If we used this speed as an impact velocity, we were able to determine the kinetic energy, shown in the formula below:

$$K_e = \frac{1}{2}mv^2 \quad (1)$$

The mass of the cricket ball varies with different manufacturers. Using the Australian Standard AS/NZS 4499.1-3:1997, the mass of cricket balls vary from 156g to 163g.

When a force is moving the cricket ball in a linear direction, the work is equal to the force multiplied by the distance:

$$Work = F \times d \quad (2)$$

If the acceleration is constant when cricket ball is slowing down, we can utilise the equations of motion to calculate it corresponding velocities:

$$v^2 = u^2 + 2ad \quad (3)$$

where u is the initial velocity, v is the final velocity, a is the acceleration of the cricket ball and d is the displacement.

Based on the Newton's second law, we are able to solve for the acceleration:

$$F = m \times a \quad (4)$$

$$a = \frac{F}{m} \quad (5)$$

Substituting eq. (5) into (3), we get

$$v^2 = u^2 + 2 \times \frac{F}{m} \times d \quad (6)$$

Re-arranging eq. (6) to solve for F

$$(v^2 - u^2) \times m = 2 \times F \times d \quad (7)$$

$$\frac{1}{2}m(v^2 - u^2) = F \times d \quad (8)$$

From eq. (8) we are able to see that the work done on an object is equal to the change in kinetic energy.

The linear momentum of an object is the product of its mass and velocity:

$$L = m \times v \quad (9)$$

From eq. (4)

$$F = m \times a = m\frac{\partial \mathrm{v}}{\partial \mathrm{t}} \quad (10)$$

and hence

$$F = \dot{L} \quad (11)$$

which states that the total force acting on an object is equal to the time rate of change of its linear momentum. Imagine that the force acting on the cricket ball between t_1 and t_2, eq. (11) can then be integrated in time to obtain:

$$I = \int_{t_1}^{t_2} F(t)dt \quad (12)$$

$$I = \int_{t_1}^{t_2} F(t)dt = \Delta \boldsymbol{L} = m\Delta v = (mv)_2 - (mv)_1 \quad (13)$$

This is called the linear impulse on an object and is assumed to be constant throughout the duration.

According to Russell (2011), the force exerted on the ball during impact is not constant, but follows a sine-squared time history, as shown in Figure 4.

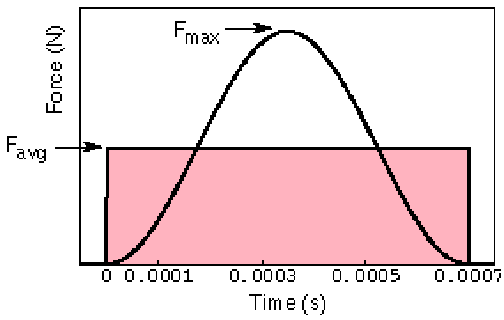


Figure 4: Example of a Force-Time function of a collision (Russell 2011).

Impulse forces vary with respect to time, when the average force, F_{ave}, may obtain by integrating the force over the contact time period. Making an assumption that the impulse is given, then:

$$F(t) = F_{max}\sin^2\left(\frac{\pi}{t_f}t\right) \tag{14}$$

From Figure 4, we can see that there is a maximum force during impact that is larger, but for a shorter time span. The area beneath the assumed impulse response is equal to the impulse determined from the change of linear momentum. Thus,

$$I = \int_{t_1}^{t_2} F(t)dt = \int_0^{t_f} F_{max}\sin^2\left(\frac{\pi}{t_f}t\right) \tag{15}$$

2.3 Finite Element Analysis

2.3.1 Static Structural Analysis

In order to evaluate the structural performance of the concept design, the honeycomb and lattice model was subjected to static load based on the estimated impact force. An isotropic plastic material with a Young's modulus of 2.2GPa, a Poisson's ratio of 0.38 and with no yield stress was selected.

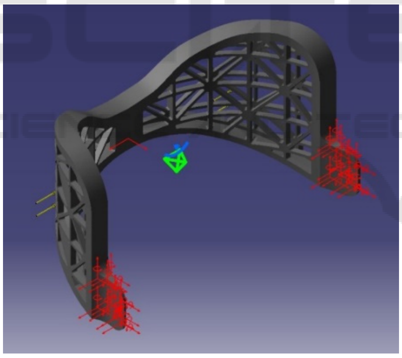


Figure 5: Lattice concept under static loading conditions.

The calculated maximum impact force of 31kN was applied on the outer surface of the NPG. The tabs that connected to the helmet were restrained in all translations (x, y, z) and rotational about y and z axis (Figure 5).

2.3.2 Dynamic Impact Simulation

Figure 6 shows the FEA set-up of the basic cricket helmet with the stem-guard attached, placed on a small size headform. The geometric model of the helmet was created by using a commercially available cricket helmet (Premiere98) with 55-58cm circumference. The FEA was performed using e ABAQUS® to identify the areas on the surfaces that are in contact, and to obtain the contact generated pressures.

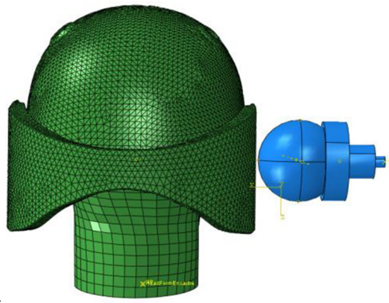


Figure 6: Finite element analysis setup for the impact analysis.

The cricket ball was modelled as a solid hyper-visco plastic homogeneous part. The helmet and the NPG were modelled with ABS materials, and the headform was considered rigid. A general contact was defined between all the contacting surfaces.

2.4 Safety Performance Test

All the cricket helmets sold in Australia need to comply to the Australian Standard AS/NZS 4499.1-3:1997 protective headgear for cricket. The Australian Standard AS/NZS 4499.1-3:1997 states that a cricket ball with a circumference between 224mm and 229mm and a mass of 156g to 163g must be dropped from a 2m height to impact a bare headform. The impacted headform must have a mean deceleration between 400g and 500g (AS/NZS 2512.3.2). When a cricket helmet is placed on the headform, the difference between the maximum deceleration on the helmet and the mean deceleration of the bare headform, must be at least 25% at the temple, forehead, rear test area.

$$\text{Percent different} = \frac{\underset{\text{(bare headform)}}{\text{Mean decelearation}} - \underset{\text{(test site)}}{\text{Maximum decelearation}}}{\underset{\text{(bare headform)}}{\text{Mean decelearation}}} \times 100\% \tag{16}$$

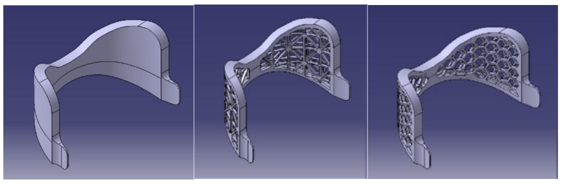
The detail of the test set up can be found in Pang *et al.* (2013).

3 RESULTS

The result of the engineering design approach, the FEA and the experimental results were used to determine the effectiveness of the novel NPG design.

3.1 Concept Designs

The 3D model was initially designed a solid piece with a variable cross-section following the curve of the helmet, shown by the line cutting across the surface (Figure 7a).



(a) Initial Concept (b) Lattice, (c) Honeycomb

Figure 7: 3D design of the neck protector guard.

Starting with the initial design concept of two thin walled surfaces, the initial model was a solid piece with a variable cross-section following the curve of the helmet. The NPG utilised the existing faceguard attachment point of the helmet. The concept design underwent several iterations to fulfil the design objective of overall weight reduction through using a lattice pattern (Figure 7b) and also a honeycomb pattern (Figure 7c). The overall weight reduction by implementing the lattice and honeycomb patterns was 46.6% and 44.3%, respectively.

The 'Human Posture Analysis' in CATIA software was used to determine the ergonomic aspects of the NPG. Figure 8 shows a fifty percentile American male wearing a cricket helmet with the proposed NPG. We analysed whether the NPG design may restrict any head and neck movements, and to ensure there was enough space for the neck when tilted backwards.

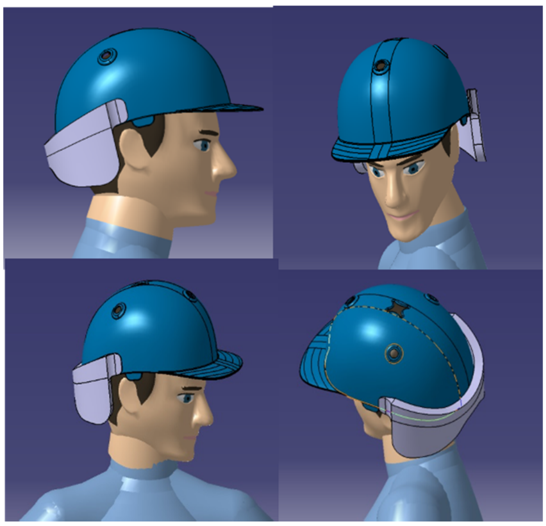


Figure 8: Ergonomic analysis of the neck protector guard.

3.2 Impact Energy and Forces

3.2.1 Impact Energy

Using the maximum and minimum weights, we were able to determine the corresponding kinetic energy of the cricket ball using eq. (1) as demonstrated below:

$$K_e = \frac{1}{2}mv^2$$

$$K_{e-min} = \frac{1}{2} \times .156(kg) \times 44^2$$

$$= 151J$$

$$K_{e-max} = \frac{1}{2} \times .163(kg) \times 44^2$$

$$= 157.78J$$

3.2.2 Impact Force

In order to achieve a suitable design solution that could absorb the impact energy using eq. (8) with the final velocity, v, is 0 and (6) is simplified as follows

$$\frac{1}{2}m(v^2 - u^2) = F \times d$$

$$\frac{1}{2}m(0^2 - 44^2) = F \times d$$

$$F \times d = -968m \qquad (17)$$

As solved in Section 3.2.1, the kinetic energy was 157.78J. Substituting the maximum weight energy into eq. (17), we obtained:

$$F = \frac{157.78}{d} \qquad (18)$$

The average force, F_{ave}, was determined depending on the amount of deformation/ displacement of the impacted surface (Table 2), varying from a displacement of 20mm to 1mm.

Table 2: Range of Forces with respect to Displacement.

Kinetic Energy (J)	Displacement (mm)	F_{ave} (N)
157.78	20	7889
	15	10518.7
	10	15778
	5	31556
	1	157780

Using eq. (9) solving for impulse, we obtained:

$$L = .163(kg) \times 44$$

$$= 7.172 \frac{kgm}{s} \ (Ns)$$

The contact time with respect to average force is presented in Table 3.

Table 3: Contact time with respect to average force and impulse.

Kinetic Energy (J)	F_{ave} (N)	Impulse	Time (ms)
157.78	7889	7.172	0.909
	10518.7		0.682
	15778		0.455
	31556		0.227
	157780		0.0455

As stated in eq. (15), impulse forces vary with respect to time, and the peak force can be determined as:

$$7.172 = \int_0^{t_f} F_{max} \sin^2\left(\frac{\pi}{t_f} t\right)$$

Table 4 shows peak force calculated with the corresponding average force and contact time.

Table 4: Peak forces with respect to average force.

F_{ave} (N)	Time (ms)	Peak Force (kN)
7893.5	0.909	15.8
10524.67	0.682	21.0
15787	0.455	31.6
31574	0.227	63.1
157870	0.0455	315.6

The peak impact force to achieve a deformation of 10mm was used to determine the structural performance of the NPG under static load.

3.3 Finite Element Analysis

3.3.1 Static Load

Using generative structural analysis involving CATIA, we were able to determine and compare the local stresses and displacement of each design (Figure 9).

When comparing the lattice and honeycomb designs, the honeycomb design was slightly heavier than the lattice design. The honeycomb exhibited a greater displacement, slightly higher localized stresses, but lower global strain energy as shown in Table 5.

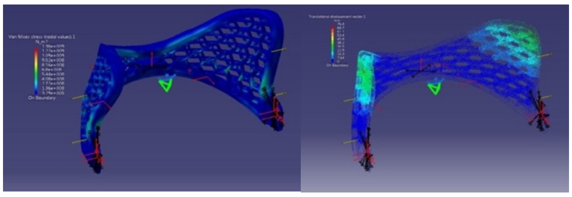


Figure 9: Stress distribution of honeycomb design under static loading conditions.

Table 5: Comparison of honeycomb and lattice designs in term of deformation, stress and strain from FEA.

	Displacement (mm)	Von Mises Stress (MPa)	Strain Energy
Lattice Structure	39.6	1150	160.194
Honeycomb Structure	48.8	1300	123.205

3.3.2 Dynamic Impact

Figure 10 shows the FEA of the cricket ball impacting the NPG. The stress when the ball was impacting the NPG was taken at the point of contact, and the kinetic energy of the ball on impact was dispersed over a wider surface area through the NPG. The deceleration results from the FEA simulations (Figure 11) were used to compare different NPG design solutions, and to drive further design modification for improvements.

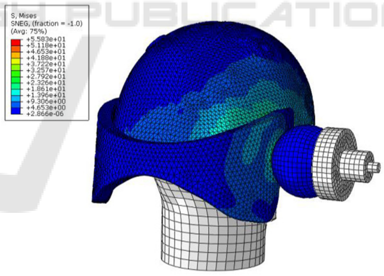


Figure 10: FEA simulation the cricket ball impacting the neck protection guard.

To be considered as an acceptable design solution, the deceleration recorded at the impact site on the NPG should not be less than 25% when compared with the cricket ball impacting on the bare headform as calculated from eq. (16).

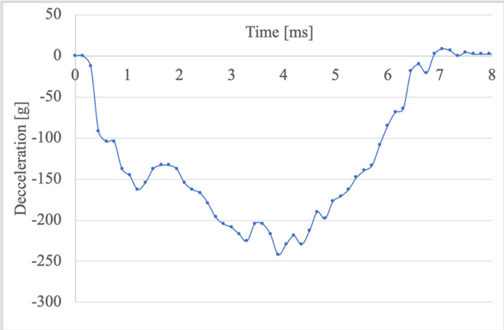


Figure 11: The deceleration of cricket ball impacting NPG.

3.4 Prototype

Figure 12 demonstrates the printed NPG protype using ABS plastic via fused deposition modelling (FDM) 3D printing technology. The first 3D printed prototype was attached to the helmet and its shape needed to be modified (the areas marked as red needed to be removed). The tabs that connect to the helmet were altered so that the curvature did not clash with the helmet and faceguard.

Figure 12: 3D printed neck protection guard.

After this modification, the final design was 3D printed to produce prototypes for a series of impact tests to determine the functionality and their impact performance.

3.5 2-wire Drop Test

The experimental drop test set up conformed to Australian Standard AS/NZS 2512.3.2 guidelines. A striker (i.e. cricket ball) of 1.56kg. with an accelerometer positioned within the fixture was used to measure the deceleration at impact sites. Figure 13 shows the impacted images, captured using a high-speed camera, of the cricket ball dropped from the 2m above the point of impact that resulted in 30J of kinetic energy, progressing from the initial impact until the kinetic energy was fully transferred and dissipated by the NPG.

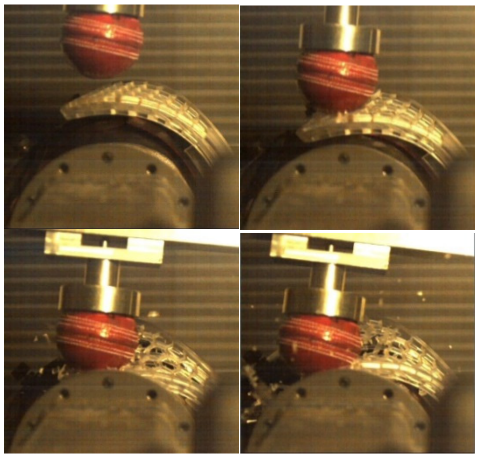


Figure 13: High speed camera images of the cricket ball impacting the 3D printed neck protection guard.

The peak accelerations of the bare headform without a helmet and with the helmet and NPG impacted with the 1.56kg striker are shown in Figure 14. The NPG reduced the peak acceleration, which could cause brain injuries, from more than 400g to approximately 150g. The mean decelerations as calculated via Equation (1) indicated that the lattice design and honeycomb designs managed to achieve a maximum reduction of 70% and 59.6%, respectively.

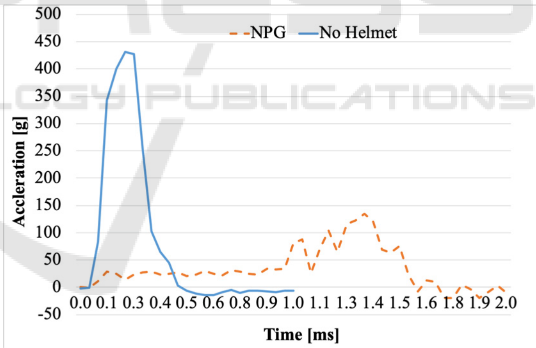


Figure 14: Peak acceleration from drop test when the striker impacting a bare headform and on the NPG.

4 DISCUSSION

4.1 NPG Design Development

Followed the initial concept from Masuri's StemGuard, a set of design criteria and objectives were selected to drive the design and development of the novel NPG. The novel NPG was intended to provide protection, absorb the impact force and promote rapid deceleration of the ball in the shortest possible distance. A cricketer needs to react and move quickly to duck, weave and play shots; hence, it is important that the new NPG added as little weight as possible that did not impede the user's performance by allowing fluid head movement on the field. A significant increase in mass would increase stress on the user's neck and shoulder muscles that control and move the head. Cricket is typically played in the hotter months. With an additional guard around the neck, the air flow might also be restricted, and significant thermoregulation issues could occur. Thus, the new NPG should promote good air flow to ensure the user remains comfortable and not overheat.

Having these clear design criteria, a base concept of two thin-walled surfaces was developed, a further design iteration was added to reduce the overall NPG weight, and the lattice pattern and honeycomb patterns were created (Figure 4). The patterns also allowed air to pass through and minimised the insulated heat for the users by permitting air to circulate around the neck region.

CAD software, ABAQUS and CATIA Human Posture Analysis, were used to investigate the proposed NPG designs in terms of their ergonomics and structural behaviour. The central bridge areas of the initial NPG design were widened laterally and narrowed in height to accommodate the neck tilt backward movements in the final design. By widening the bridge area, we ensured that the protector did not clash while still providing adequate protection to the neck region. An FEA simulation was used to verify that the NPG components could withstand the impact from the cricket ball at various impact speeds prior to the physical testing. From the FEA, we discovered that the initial designs were slightly flexible during the impact and, hence, additional rib structures were implemented to the lattice and honeycomb designs to improve the overall rigidity and maintain sufficient shape integrity during or after movement, particularly in the moments before a potentially catastrophic impact.

4.2 Impact Evaluation and Recommendations

The impact force of 31kN was used to conduct the structural analysis of the NPG design. As described by Fuss *et al.* (2007) an impact velocity at roughly 44 m/s will achieve a corresponding and peak force (kN), as shown in Figure 14.A cricket ball with a cork core and an impact velocity at roughly 44 m/s will achieve a corresponding maximum peak force of around 27 kN. It is worth noting that the peak force calculated in the present study was based on the assumption that the cricket ball is rigid, with no deformation, and the energy and momentum are linear. However, the peak force in Fuss et al. (2007) was based on a viscoelastic model, which accounted for the deformation of the cork centre and, hence, slightly lower than the estimated force for this study.

For the experimental testing, and as proof of concept, the prototype of the NPG was 3D printed using ABS material, which has a slightly lower impact strength. However, the results showed that the NPG provided a sufficient level of impact attenuation and protection to a wearer from head and neck injury.

We acknowledge that the ABS materials break easily when impacted by a cricket ball. This can cause more damage and injury to users from the remnant plastic after the impact.

Therefore, suitable material selection plays an important role in designing the NPG component. For the future applications, we recommend: (i) Polycarbonate (PC) as they are commercially available thermoplastic materials that are light weight, but yet have high impact strength and good energy absorption, and which are suitable in cold and hot weather as well as good in high humidity environments (Caswell *et al.* 2007); (ii) Kevlar® (DuPont), as they are lightweight advanced composite materials that provide high impact and blast-level protection, and which also play a significant role in future athletic gear (Caswell et al. 2007)—these are, however, slightly costly to manufacture and shape.

The NPG was only tested in laboratory conditions according to the AS/NZS 2512.3.2 guidelines. We acknowledge that a cricket ball of a mass of 156g to 163g dropped from a 2m height will only process a maximum velocity of 4.5 m/s. The drop speed was significantly slower than a fast bowler can achieved (~44 m/s) (Stretch 2000). Therefore, it is recommended that the NPG should be tested with a pitching machine, as described in Pang *et al.* (2013), for assessing the NPG protection performance.

5 CONCLUSIONS

The design and development of a novel NPG is presented in this paper. The design criteria in designing the NPG are to protect the neck and basal skull area, to achieve a light weight, to allow sufficient air flow and heat transfer in the protected region and, most importantly, to secure a safety performance that is able to dissipate impact energy thereby reducing the blow of a cricket ball and protecting a batsman from serious injury.

The engineering design process, an FEA for the impact of cricket ball on the NPG, and experimental tests results were presented. The initial conceptual NPG designs went through an iterative process to fulfil the design criteria and to identify improvements. The experimental results showed more than 50% reduction in impact deceleration with the new NPG. Future work should be directed towards a more comprehensive analysis, both numerically and experimentally, to select suitable materials for NPG with satisfactory level of protection and impact attenuation capabilities to users.

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