Mechanisms of head and neck injuries sustained by helmeted motorcyclists in NSW, Australia.

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ABSTRACT

The wearing of a standard-approved motorcycle helmet has been the most significant step in reducing fatal and serious injury among motorcyclists worldwide. Mandatory helmet use for motorcyclists is now in place in many parts of the world. Nevertheless, some researchers have observed a high percentage and duration of hospitalisations in helmet-protected motorcyclists with the long-term outcome considerably influenced by head injury severity. The objective of this study was to investigate head and neck injuries sustained by helmeted motorcyclists in real world crashes and define the circumstances which result in injury.

Data were collected by in-depth crash investigations of motorcyclist crashes in NSW, Australia. The crash investigations included inspections of the accident scene, the crash involved motorcycle and the helmet. Where possible, detailed helmet examination including helmet disassembly was performed to identify all crash related damage. The type of damage, damage location and damage severity on the helmets were recorded. The major head and neck injury types sustained by these helmeted riders were analysed for crash and helmet damage related factors which influenced the incidence of injury.

Due to the recruitment procedures used, participants in this study were biased towards lower severity head injuries. A head injury was sustained in 23.9% of cases but serious (AIS 3+) head injury was sustained in only 2.3%. There was neck injury in 9.1% of cases but no serious (AIS 3+) neck injuries. The main head and neck injury types by frequency were superficial injury (13.6%), "diffuse" type brain injury (13.6%), facial/dental fracture (4.5%) and cervical spine fracture (4.5%).

Helmet damage was observed in the majority of cases (86.4%) suggesting successful injury prevention in many instances. A high proportion of observed impact damage was to the front of the helmet (78.5% of cases), particularly the chin bar and visor of full-face helmets. Impact damage associated with a predominantly tangential force onto the head was more common than radially directed force damage.

Superficial head injury and facial/dental fractures was significantly more common (p < 0.01) in riders who were wearing open face helmets, where the face and chin are exposed to direct impact, compared to full face protected riders. There were significantly more cervical spine fractures in cases with damage indicative of a radially directed force (p = 0.036) than where damage indicated a tangentially applied force. The circumstances resulting in "diffuse" brain injuries could not be clearly defined by the data in this study due to the small number of riders with this injury.

The results highlight potential areas for improving the head and neck protection offered to motorcyclists including extending the required region of coverage, particularly to the face, and through mitigating the effect of tangential

impacts on the helmet. Given the high frequency of diffuse intracranial injury even in lower severity head injury cases, assessment of helmet effectiveness should use performance criteria reflecting the mechanisms of this type of injury.

INTRODUCTION

The effectiveness of motorcycle helmets in reducing fatal and serious injury among motorcyclists is well known [1–3]. Mandatory helmet use is now required by motorcyclists in many countries including Australia and throughout Europe. Nevertheless, a high percentage and duration of hospitalisations have been observed even in helmet protected motorcyclists [5] and injuries to the head are still the most common cause of death in fatally injured helmeted motorcyclists [6].

Current motorcycle helmet designs are largely shaped by helmet performance standards which are in force in most countries. Standards define how a helmet must perform in an impact consisting of dropping an instrumented rigid headform, fitted with the test helmet, onto a rigid anvil. The helmet is assessed based on the linear acceleration experienced by the headform centre of gravity. This test and helmet assessment criteria were originally developed in the late 1960's [7] using some of the earliest and most widely used biomechanical head injury tolerance data, the Wayne State University Concussion Tolerance Curve [8], which despite its name, was originally based on the level of linear acceleration producing a linear skull fracture in an adult. The simplified loading conditions of the impact attenuation tests were chosen to ensure the test results were repeatable and reproducible, both necessary and appropriate for ensuring the consistent performance of a mass produced product such as helmets. However the drop test may not reflect what occurs to the head of a motorcyclist in a real crash. Furthermore the response criteria measured during these tests cannot assess the potential for all types of head and neck injury.

The aim of the present study was to investigate the types of head and neck injury sustained by helmeted motorcyclists in real crashes and common loading conditions to the helmet that result in injury to the rider. Hence indicating areas of helmet protection where further research effort can be applied to reduce the frequency and severity of head and neck injuries to helmeted riders in crashes.

METHODS

The data used for this study were collected by Neuroscience Research Australia as part of an in-depth case-control study of motorcycle crashes. 91 cases of injured motorcyclists over the age of 14, admitted to a NSW hospital, were recruited by research nurses. The participant then completed a face-to-face interview, self-reporting various details regarding the crash. The crash related injuries were recorded from the medical records of the patient. The crash involved motorcycle and the crash scene were inspected noting all evidence of the incident. The clothing and helmet worn by the rider at the time of the crash were also inspected. Where authorised by the study participant the clothing and helmet were collected for subsequent analysis. A subset of these cases has been previously presented assessing the effectiveness of the motorcycle protective clothing worn by the rider [9].

To address the aims of the current study, three of the cases were excluded from the analysis because there was either no helmet worn in the crash or the helmet was ejected sometime during the crash sequence. Helmets that were retained from the study participants were disassembled and any internal or external evidence of crash related damage was also recorded.

The data were analysed using the Statistical Package for Social Sciences, version 21. Pearson's Chi-square tests and Fisher Exact tests were used to analyse any differences in the proportion of injured riders with respect to variables of crash characteristics, helmet characteristics, helmet damage and damage location. A p-value of < 0.05 was considered significant.

RESULTS

The 88 helmeted riders had an average age of 36.9 ± 15.6 years with a range of 16 to 80 years. 82 riders were male (93.2%) and six (6) were female (6.8%). The following sections outline the injuries sustained by these riders, the general crash characteristics and details regarding the helmets.

Incidence of Head and Neck Injury

Head injury was sustained in 21 of the 88 cases (23.9%), see Table1. but serious (AIS 3+) head injury was sustained in only 2 (2.3%). Based on the frequency and severity of the injuries, the major injury types sustained in this set of riders were superficial head injury, diffuse intracranial brain injury, facial/dental fractures and cervical spine fractures.

Superficial head injury was most common with the face sustaining the majority (80.8%) of these injuries. Of the 9 fractures to the head 1 (11.1%) involved the skull vault and the remaining 8 (88.9%) involved the facial bones or teeth. The intracranial injuries seen in this study were predominantly "diffuse" type brain injuries which included closed head injury/loss of consciousness, concussion or change in cranial pressure which was sustained by all 12 riders with intracranial injury. Neck injury was sustained in 8 cases (9.1%), see Table1., but there were no serious (AIS 3+) neck injuries. Cervical spine fractures occurred in 4 cases (5%) and minor injuries to the skin and soft tissues occurred in a further 4 cases (5%).

Table1.
Head and neck injury cases

Injury type		Number of cases (% of total cases)	Total no. of injuries	Frequency of injury severity (% of injuries)			
				AIS 1	AIS 2	AIS 3	AIS 4
Head injuries	Superficial	12 (14%)	26	26 (100%)	0	0	0
	Fracture	4 (5%)	9	2 (22%)	6 (67%)	1 (11%)	0
	Intracranial	12 (14%)	17	6 (35%)	7 (41%)	3 (18%)	1 (6%)
	All Head Injury	21 (24%)	52	38 (68%)	13 (23%)	4 (7%)	1 (2%)
Neck injuries	Superficial	2 (2%)	4	4 (100%)	0	0	0
	Fracture	4 (5%)	4	0	4 (100%)	0	0
	Soft Tissue	2 (2%)	2	2 (100%)	0	0	0
	All Neck Injury	8 (9%)	10	6 (60%)	4 (40%)	0	0

Crash Characteristics

The estimated speed prior to crashing was recorded for 91.2% of cases, with a median estimated pre-crash speed of 52.5 km/h and a mean of 52.3 ± 23.9 km/h.

In the majority of cases (75%), the crashed motorcyclist was involved in a collision with another vehicle. The predominant collision opponent was a passenger car (58%) followed by the roadway/kerb only (13.6%) and then poles/trees (6.8%).
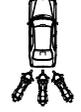
Table2. shows the distribution of crash configurations based on the classification used in the COST 327 study of European motorcycle in-depth crash investigations [1]. Type 7 crashes (at 29.5%) were most common, which included 22 cases of single vehicle loss of control crashes (25% of all cases). Circumstances where the front of the motorcycle collided with the rear (Type 5) or side (Types 3 and 4) of a passenger car were also common.

Helmet Type

The majority of riders (86.4%) wore a full face type motorcycle helmet which included a chin bar and the remainder wore an open face "jet" style helmet (13.6%).

There was a statistically higher proportion of open face helmeted riders who sustained superficial head injuries (p=0.009, FET) and facial/dental fractures (p=0.007, FET) compared to full face protected riders.

Table2.
Distribution of crash configurations

Collision Types	Description	Diagram	Number of Cases (% of cases)
Type 1	Side collision against the front of a four wheel vehicle		4 (4.5%)
Type 2	Head-on collision against the front of a four wheel vehicle		7 (8.0%)
Type 3	Head-on against the side of a four wheel vehicle		12 (13.6%)
Type 4	Oblique collision against the side of a four wheel vehicle		13 (14.8%)
Type 5	Head-on collision against the rear-end of a four wheel vehicle		14 (15.9%)
Type 6	Rear-end collision against the front of a four wheel vehicle		12 (13.6%)
Type 7	Collision against pedestrians, bicycles, non-moving objects		26 (29.5%)
Total			88

Helmet Damage Type

There was observed or reported damage to the helmet in 76 cases (86.4%), 10 helmets (11.4%) were undamaged and the condition was not known for 2 (2.2%). Scratches were most common, observed in 72 cases, followed by cracks to the shell (16) and observable liner damage (10).

The type of helmet damage was assessed in 69 cases as either associated with a tangentially directed force or radially directed force to the head. Tangentially directed force damage was more common (62.5%) than radially directed force damage (44.9%) and 24.6% of cases had areas of both types of damage.
Cases with radially directed impacts had a significantly higher incidence of cervical spine fracture than cases without normal impacts ($p = 0.036$, FET).

Helmet Damage Location

The location of the damage on 65 inspected helmets was mapped on a schematic of the helmet divided into zones based on the crown, front, sides and rear of the helmet at varying levels of elevation from the helmet rim. Figure1. shows that the majority of helmet damage was to the face, despite 11 open face helmets without a chin bar and 5 of these without a face shield (visor) that could not sustain damage in these areas. The remainder of the damage was concentrated in a band around the sides and the rear of the mid-level of the helmet with relatively infrequent damage to the crown. The proportion of cases sustaining damage to each area of the helmet is shown in Table3.
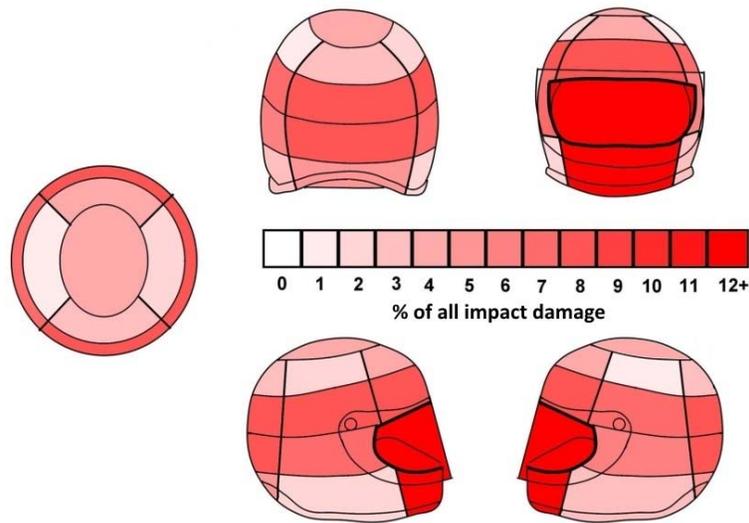
Figure1. Distribution of impact damage on the 65 inspected helmets.

Table3.
Location of helmet damage for 65 inspected helmets

Location on helmet	Frequency of cases	Percentage of cases
Chin bar	34	63.0 (of full-face type helmets)
Visor/Facial	39	65.0 (of visor equipped helmets)
Frontal	19	29.2
Any frontal impact damage	51	78.5
Left	30	46.2
Right	32	49.2
Rear	40	61.5
Crown	8	12.3
Total helmets with recorded damage location	65	100.0

Devices attached to the Helmet Shell

11 (12.5%) of the crashed riders in this study had a Bluetooth headset attached to the exterior of the outer shell of the helmet. The devices allow the motorcyclist to communicate with other riders, make phone calls and listen to audio while riding and typically consist of a set of speakers and a microphone placed inside the helmet, and a small box of electronics mounted on the outside of the helmet, as shown in Figure 2. In one of these 11 cases, the helmet also had an attachment for a video camera device.

When an attachment to the external shell was present, 27.3% of riders sustained a diffuse type intracranial injury compared to only 7.4% of riders sustaining intracranial injury when there was no attachment. However, this difference was not statistically significant (p = 0.088, FET).

Figure2. Bluetooth device (left) and attachment point indicated by spots of glue (right).

DISCUSSION

In-depth crash investigations of the 88 helmeted motorcyclists attending an emergency room were used to identify the injuries being sustained by helmeted riders and to define the common and injurious loading conditions being applied to the helmet in real crashes. The collected cases demonstrate the effectiveness of motorcycle helmets in preventing injury as damage was present in over 85% of helmets while less than 25% of riders sustained a head or neck injury. However, the collected cases appear to be biased towards low severity head and neck injury as the proportion of serious (AIS 3+) head injury sustained by helmeted riders in this study (2.3%) is lower than that reported in European data [5] (9.7%) and in the Hurt data of crashes in the US [3] (17.9%). Exclusion of helmet ejected cases, which were classified as helmeted riders by both Richter et al. and Hurt et al., was not the reason for the difference with the two excluded cases in this study sustaining only AIS 1 superficial head injury. Nevertheless, the major injuries sustained by helmeted riders in these crashes in terms of frequency and severity were identified as intracranial injury, facial/dental fractures, superficial head injury and cervical spine fractures.

Superficial head injury (mostly comprising superficial facial injury) and facial and dental fractures were significantly more common when an open face helmet was worn compared to full-face helmet protection in this study. This result confirms the almost identical findings reported by Cannell et al. [10], although the relationship was not significant in their study, and is not surprising given the face of the rider is exposed to direct impact while wearing an open face helmet. Furthermore, inspection of the location of helmet damage demonstrates that the face region is the most commonly impacted region of the rider's head. Data reflecting a more severe group of fatal crashes is currently being investigated and will be able to determine whether this trend is also true for more seriously head injured riders.

Cervical spine fractures were sustained in only 4.5% of cases in this study. The cases indicated that cervical spine fracture tended to result from radially direct impacts to the helmet. This outcome relates to the clinical cadaver experiments performed by Hodgson and Thomas [11]. These researchers found that excessive strain on the cervical spine was produced in flat (radial) impacts to the crown and impacts inducing hyperextension on the neck. Hodgson and Thomas found that the effect of the helmet in preventing this type of injury was limited however considerable research effort has shown that the motorcycle helmet at least does not contribute to producing additional neck injury [12,13].

Diffuse intracranial injury was the most common and most severe head or neck injury sustained by the helmeted riders collected in this study but there were no clear circumstances that produced a significantly higher proportion of cases with this injury. The majority of these diffuse injuries were concussions and losses of consciousness. Such injuries have received considerable attention in sports such as American football. It is now understood that rotation of the head is the primary contributor to diffuse brain injury based on the pioneering experiments of Gennarelli et al. [14–16]. As a result, football helmets have undergone significant design improvements by using rotational head injury criteria specifically related to concussion. Assessment of motorcycle helmets to these criteria is ongoing[17–19] but it is important to note the concern that the stiffness of some helmets is such that they are ineffective in reducing brain injury risk at low impact speeds [20]. Given the severity and frequency of the diffuse brain injuries observed in real motorcycle crashes, there is a demonstrated need for helmet design to be assessed in a manner relevant to the known mechanism of this type of injury.

Examination of the crashed helmets in this study was performed to obtain data on the likely loading conditions experienced by the head and neck of riders in real crashes. In the distribution of impacts shown in Figure1., a high frequency of impacts occurred to the front and facial area of the helmets of crashed riders. This is in agreement with previous major crash investigation studies in Europe [5], the US [3] and Australia [21,22]. Despite this, the chin and facial region is outside the require region of protective coverage required by many motorcycle helmet standards, including the Australian Standard AS 1698 and the US regulation FMVSS 218. Further the distribution of impacts around the circumference of the crash damaged helmets, shown in Figure1., coincides with the edge of the region of protective coverage in AS/NZS 1698 and FMVSS 218. Previous Australian motorcycle crash studies recommended extending the area of impact protection to these areas to improve the protection of helmets in frontal and lateral impacts [21,22].

The specification of performance requirements for a helmet able to protect the rider in a frontal impact to the head is a complex task. This is due to the multiple types of injuries that can result from an impact to the face which include local focal injuries (face and skull fractures), remote focal injuries (basilar skull fracture) and head and neck motion induced injuries (brain and cervical spine injuries) [23]. Helmet design for facial impacts remains a critical area where further research could improve protection from injury for a motorcyclist.

The helmets in this study also predominantly showed damage indicating a tangentially directed force, or a rotation of the head. This has also been observed in real crash investigation studies by Otte et al. [24] and Hurt et al. [12]. Oblique impacts to the head have been the subject of ongoing research for two main reasons: First, current knowledge of head injury biomechanics recognizes the importance of head rotation in the production of brain injury; and second, most motorcycle helmet standards do not attempt to measure or produce this type of impact or rotation. A number of laboratory test methods [25,26] have demonstrated a reduction in angular head acceleration from current and new helmet designs but the relevance of these in real crash circumstances remains unknown.

The attachment of Bluetooth and video camera devices to the outside of the helmet shell is a relatively new issue. This tends to go against what is prescribed in motorcycle performance standards, such as in AS 1698 which requires a smooth outer helmet shell to minimize friction or snagging that may promote helmet rotation [27]. This study found a higher proportion of cases sustaining diffuse type intracranial injury when these devices were attached than when they were absent, although the difference was not significant. The fitment of such devices is becoming increasingly popular and accessible as they become cheaper and more reliable. The effect on head injury risk requires further investigation. At present there are no regulations in Australia regarding attaching these devices to helmets.

DIRECTIONS OF FUTURE RESEARCH

This crash investigation study has highlighted a number of areas where further research has the potential to improve the head and neck protection for helmeted motorcyclists in real crashes.
1. Diffuse type intracranial injury was the predominant injury type in terms of frequency and severity sustained by the riders in these crashes indicating the need to be able to assess the capability of the helmet to ameliorate the risk of this type of injury.
2. Impacts to the front and face of the helmet were common and injurious, particularly to open face helmeted riders. Given the existing lack of impact protection required in this area of the helmet by many current motorcycle helmet standards, there is a need to examine the optimal design of full facial protection for the lowest risk of injury to the face, the skull, the brain and the neck.
3. Tangential impacts to the helmet were the predominant damage type to the crashed riders in this study. Further assessment of these types of impacts in the laboratory is required to match a test methodology to the loads and injuries experienced by riders in real crashes.

ACKNOWLEDGEMENTS

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