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Helmet protection against basilar skull fracture

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Abstract

In Australia, it is compulsory for all motorcyclists, pillion passengers and side-car passengers to wear helmets certified to AS/NZS 1698. Most riders prefer to wear full-face helmets, which appear to offer better facial protection during a crash. Some researchers have noted a greater prevalence of fractures to the base of the skull in full-face helmeted riders. The aim of this study was to improve the understanding of basilar skull fracture (BSF) causation in motorcycle crashes, to assess the capability of current helmets in reducing the risk of this injury and to assist in future standards setting.

A review of available field data on the incidence and causation of BSF to motorcyclists was completed and the findings compared with crashes collected in the CASR Head Injury Database. This database contains in-depth investigations of 174 mainly fatal motorcycle accident cases collected in South Australia between 1983 and 1994. It includes autopsy data, including an investigation of neck injury, the helmet and a detailed crash report. The CASR data was found to be representative of fatal crash studies in the literature and to consist of high severity crashes. In 70% of the cases full face helmets were worn. BSF was seen in 59% of these cases. Almost 50% of the severe impacts to the head were in the facial region and 42% of these impacts were to the chin bar. The prevalence of BSF was found to be mainly due to the migration of the skull fracture to the base of the skull due to the severity of the impact to the face (and other regions of the head).

Only two motorcycle helmet standards currently include chin bar tests: Snell M2005 and UN ECE 22.05. The tests have significant differences in their requirements and do not specifically address the issue of basilar skull fracture. The test requirements were assessed using a typical current Australian full face helmet. The results are discussed in terms of the protective requirements demonstrated in the field accident data and an understanding of current biomechanical injury tolerance. The study shows that the protection offered by the Australian motorcycle helmet needs to be extended to cover the facial area, with the aim of reducing facial fractures. The conflicting criteria required of a test method, to protect from facial fracture and brain injury, whilst not causing neck injury are also discussed, and the needs for further work are outlined.

Notes

(1) ATSB reports are disseminated in the interest of information exchange.
(2) The views expressed are those of the author(s) and do not necessarily represent those of the Australian Government or the ATSB.

CONTENTS

EXECUTIVE SUMMARY

Background

Since the 1960s, it has been compulsory for all motorcyclists, pillion passengers and side-car passengers in Australia to wear helmets certified to the Australian Standard AS/NZS 1698. In a 2001 survey of over 1200 motorcyclists in NSW (de Rome, Stanford & Wood, 2002), all riders indicated that they usually wore helmets. The majority (87%) of riders preferred full-face helmets.

In a 1988 review of crash performance of Australian market motorcycle helmets, Dowdell et al. (1988) examined 200 crash-involved helmets and found that the chin bar of the full-face helmet was the region with the highest average number of impacts. Almost 50% of the severe impacts were to the front of the helmet and 40% of these impacts resulted in basilar skull fractures (BSF). A recommendation was made that specifications be developed for a test aimed at reducing the effect of frontal impacts to the face by improving the energy absorption of helmets in this area.

Two current motorcycle helmet standards include chin bar tests: Snell M2005 and UN ECE 22.05. For the Snell test, a mass is dropped onto the chin bar of the helmet and a limit is set on the deformation allowed of 60 mm. For the ECE 22.05 test, the helmet mounted on a rigid headform with a chin is dropped onto a flat steel anvil. The acceleration measured at the centre of gravity of the headform is limited to 275 G.

These two chin bar tests have significant differences in their impact on helmet design and do not specifically address the issue of basilar skull fracture. The focus of the Snell test appears to be on movement of the chin bar towards the face and facial injury, while the ECE test focuses on the extension of the protective area of the head to the chin bar, based on prevention of brain injury rather than skull fracture.

Aims of the study

The aim of this study is to improve the understanding of BSF causation in motorcycle crashes and support the continuing development of the Australian motorcycle helmet standard AS/NZS 1698.

The only existing Australian database of motorcycle crashes that includes the crash-involved helmets, is a group of 172 motorcyclist fatality cases in the Adelaide metropolitan area collected over the period 1983 to 1991 by the Road Accident Research Unit (RARU), now the Centre for Automotive Safety Research, (CASR) of the University of Adelaide. The dataset includes extensive crash-related information collected at the scene, with an examination of the site, the crash-involved helmet, and detailed autopsy results.

The approach taken for the study was to review the various areas of BSF causation in motorcyclists. The incidence of BSF to helmeted motorcyclists in crashes was reviewed with special reference to the CASR data. This review was combined with the available knowledge of impact biomechanics related to mechanisms of BSF injury causation, and was then used to reflect on the available helmet test methods to formulate recommendations for the Australian Helmet Standards Committee.

Incidence of head and neck injury in helmeted motorcyclists

A review of the literature revealed the following regarding head and neck injury in helmeted motorcyclists:

- Improvements to helmets in the last decade had reduced the proportion of head injuries suffered by motorcyclists from 40% to 18% (Richter et al. 2001).
- Helmets were found to provide protection from all types and locations of head injury suffered by motorcyclists (Richter et al. 2001; Sarkar et al. 1995).
- Helmets were not associated with increased neck injury suffered by motorcyclists (Richter et al. 2001; Sarkar et al. 1995; Johnson et al. 1995; Thom & Hurt 1993).
- Helmets were found to provide protection from craniofacial injury suffered in motorcycle crashes (Johnson et al. 1995).
- There was no correlation of neck injury with helmet weight (Richter et al. 2001; Johnson et al. 1995; Konrad et al. 1996).
- Only 40% of the head impacts were found to fall within the test area of the standard. The majority of the remaining impacts were to the face and chin (Richter et al. 2001; Dowdell et al. 1988).
- There was no added benefit or harm in wearing a full-face helmet relative to an open-face helmet, in terms of cervical spinal cord injury (O’Connor et al. 2002).
- Injuries occurring remote from the point of impact were often the result of impacts against the anterior part of the head of the motorcyclist, especially against the face (Krantz 1985).
- Helmets may promote disruption of the junction of the head and neck, where no sign of impact against the head could be detected (Krantz 1985).
- Facial fractures in motorcyclists may protect the head and neck in facial impacts (Cooter & David 1990).

Incidence of BSF in helmeted motorcyclists

A review of the literature revealed the following regarding basilar skull fractures in helmeted motorcyclists:

- There may be a greater prevalence of some types of fractures to the base of the skull in full-face helmeted riders (Bly 1994; Cooter 1988).
- Severe impacts to the head, cervical axial loading and hypermotion of the neck are all likely to lead to BSF with or without a helmet (Thom & Hurt 1993).
- A correlation has been demonstrated between BSF and helmet weight (when >1.6kg) (Konrad et al. 1996).
- Fractures of the base of the skull and injuries to the brain stem were somewhat more common in non-helmeted riders (Sarkar et al. 1994).

Biomechanics of BSF

BSF is any fracture, which originates at or propagates to the bones in the base of the skull. Such injuries are often severe (complete ring fractures are mostly fatal) and have been shown in laboratory tests to occur due to various mechanisms including impacts to the mandible or face, lateral impacts, impacts to the cranial vault, or due to inertial loading by the head. Ring fractures may result from vertically directed contact forces applied either inferiorly to the crown (compressive forces) or from superiorly directed forces applied to the occiput or the mandible.

In a padded impact to the crown of the head, the neck is the region most susceptible to injury. BSF due to crown impact has been shown to require a high velocity, low duration, high energy impact. While direct impacts to the mandible have been shown only to produce fractures of the mandible, BSFs were observed when the impact is combined with tensile loading at the foramen magnum.

The fracture strengths of the facial bones, except for the mandible in certain directions of impact, are less than for the skull and the neck in shear. In a facial impact the head and neck may be protected to some extent by the failure of the facial bones. The stiffness of the zygoma and maxilla are much less than for the skull base, frontal bone and temporo-parietal regions. This adds further support for the hypothesis that in a facial impact, the head and neck may be protected to some extent by the failure of the facial bones.

Analysis of the CASR database

Investigation of the CASR database gave similar findings to the literature on the incidence and type of BSF in fatal motorcycle crashes. The helmets in this sample were from fatal motorcycle crashes and hence were from the severe end of the crash spectrum.

The database contains in-depth investigations of 174 mainly fatal motorcycle accident cases collected in the Adelaide metropolitan area between 1983 and 1994. In this group, 71% of helmeted head impacts resulted in skull or facial fracture, compared with 54% of unhelmeted head impacts. It was found that open-face helmets did not protect the wearer from skull fracture in any case. BSF was seen in 59% of cases in which full-face helmets were worn, and 83% in which open-face helmets were used.

A subset of thirty cases was selected for detailed analysis. Details of the cases are available in Appendix I. These were cases in which:

- A head impact was involved;
- The helmet was on at the time of impact;
- The helmeted rider suffered fracturing to the base of the skull;
- The helmet was available for inspection.

The group included 23 full-face helmets and 7 open-face helmets. In 21 (70%) of these cases, BSF was the primary injury resulting in death.

Eighteen cases (60%) in the study received impacts to the facial area, which is outside the protective area in the helmet standards. Nine of the 21 impacts were to the chin bar region of the full-face helmet. Of the 18 facial impact cases, nine sustained some neck injury of which only 5 were significant (AIS ≥ 2). Eleven cases in the study involved only impacts to the facial region of the helmet. Of these, 10 resulted in significant brain injury (AIS ≥ 3).

The study showed that the protective area offered by the Australian motorcycle helmet needs to be increased to cover the facial area. It also showed that the protection offered in this area needs to be capable of providing the same level of protection as the rest of the helmet.

Current helmet chin bar test methods

Comparison tests of the two test methods revealed significant differences in their demands on helmet design.

The Snell test method limits the movement of the chin bar towards the face to less than 60 mm. The aim of the standard is therefore to set a minimum allowable stiffness for the chin bar. It does not attempt to address the complications regarding the chin bar hitting the chin during the head impact.

When tested according to the Snell M2005 chin bar test, the absence of a headform in the helmet allows it to bow significantly in the lateral direction. Hence the measured stiffness of the chin bar is not necessarily related to its stiffness when on the head of the wearer.

Further, the ultimate deflection of the chin bar of the helmet during an impact in reality is limited by the chin of the wearer. For the chin to become involved in the impact, the head must rotate within the helmet. The amount of rotation is dependent on the geometry of the retention system and helmet liner, the tautness of adjustment, and the position of the chin within the helmet. There is no headform or retention system involved in the Snell test.

The European (ECE 22.05) chin bar test extends the protective area of the helmet to include the chin bar, but demands a lower drop energy requirement than the rest of the helmet. Also, the same 275 G limit for the resultant acceleration at the headform centre of gravity is used, which is aimed at preventing brain injury rather than skull fracture.

With a single pivot retention system, as typically fitted to a motorcycle helmet, there is a significant amount of rotation permitted between the head and helmet. Chin bar testing in the ECE 22.05 test configuration revealed some forward rotation of the headform within the helmet during impact.

While the Snell test does not assess the padding in the chin bar area of a helmet, the European test does. The ECE 22.05 test includes an ISO headform retained in place by the retention system, but the chin on the ISO headform is rigid metal. As has been shown by Hopper et al. (1994), the magnitude of the load placed on the mandible during a crash may be a critical factor in the BSF injury mechanism.

Testing of a typical full-face helmet model available in the Australian market demonstrated that the measured stiffness of the chin bar (80 N/mm) was of the same magnitude as measured for the facial bones (80-230 N/mm, Allsop et al. 1988), but significantly less stiff than the mandible (721 N/mm, Hooper et al. 1994). The stiffness and fracture tolerance of the mandible makes it the most capable of the various regions of the face to withstand impact forces, especially when clenched.

The ECE 22.05 test requirement equates to a minimum allowable deformation of about 20 mm for the chin bar test. The maximum allowable force on the chin bar in ECE 22.05, for a headform acceleration of 275 G, is approximately 17.5 kN. In our testing, the force on the chin bar from the measured headform resultant acceleration of 57.5 G was about 3.7 kN. By comparison, for injury to be unlikely, the maximum level of shear loading to the neck of a 50th -percentile male was suggested as 3.1 kN (Mertz et al. 2003). There appears to be a significant mismatch between the test requirement for the chin bar in the ECE 22.05 regulation and the likelihood of injury to the face and neck.

Recommendations

There is evidently some scope for optimising the stiffness of the chin bar for improved protection to the facial region and neck, or at least in defining the correct test requirements to minimise injury. Optimisation of the chin bar requires the control of helmet-related responses to impact on the chin bar. The first step is to control the stiffness of the chin bar, to ensure that it absorbs the maximum amount of impact energy possible without transmitting excessive shear force to the neck. If we can control the shear forces in the neck in this way at the beginning of the impact event, then the neck moments will also be reduced later in the event. The second step is to ensure the inclusion of effective padding material that will come into play when the deformation space between the chin and the chin bar is taken up. The available biomechanical data appears to be sufficient to allow better definition of these helmet stiffness and impact response requirements.

The most relevant helmet chin bar test engages the format applied in the ECE 22.05 helmet standard. This requirement in effect extends the helmet coverage to the facial region. The protection offered is currently at a lesser level than for the remaining protective area on the skull vault, and the test criteria is defined in terms of likelihood of brain injury, which is not appropriate. Further work is required to select the optimum stiffness for the chin bar and the chin bar padding to maximise the protection to the face and base of skull, whilst avoiding potential neck injury.

Several lines of further research offer themselves as approaches to refining the requirements for chin bar testing:

1. Assessment of Current Helmet Chin Bar Characteristics: A sample of current full-face helmets should be tested to the Snell and ECE 22.05 test methods to ensure the helmet characteristics assumed in this report, based on a single sample, are typical of the helmets on the market.

2. Investigation of Helmet Chin Bar Characteristics and Injury: Biomechanical testing of a range of current full-face motorcycle helmets will give better understanding of the helmet performance during crashes. The testing would not be based on the currently available test methodologies, but would assess the trade off between chin bar stiffness and injury due to impacts to the facial region. With the use of a THOR dummy as the test subject, test impacts could be designed to simulate related categories of crashes as suggested in the International Standard ISO 13232. Based on the data generated in testing, the adequacy of the available testing regimes could be assessed and refined as necessary.

3. Verification of Helmet Chin Bar Characteristics and Injury by Simulation: To extend the use of testing outlined above, it would be beneficial to use the injury risk/benefit methodology developed by Van Auken et al. 2003, which is based on ISO 13232. In this methodology a validated dummy model would be used to simulate a matrix of motorcycle crash types with known injuries. This matrix has been based on representative motorcycle crash data (n=501) from Los Angeles and Hannover, with a further series of fatal motorcycle vs car accident cases (n=67) from the University of Southern California (USC). The motorcycle and helmeted rider simulation is based on the MATD riding a GPZ 500 motorcycle and has previously been validated by crash testing. This technique has sufficient accuracy to use in conjunction with the test program above to explore the characteristics of the helmet chin bar and the causation of injury.

ACKNOWLEDGEMENTS

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ABBREVIATIONS

AIS

Abbreviated Injury Scale - A consensus derived, anatomically based system that classifies individual injuries by body region on a 6-point ordinal severity scale each of the body regions. AIS-1 injuries are minor and usually include superficial injuries to the skin such as abrasions, contusions, lacerations, avulsions and superficial penetration. AIS-2 injuries are moderate and include deeper skin disruptions, joint dislocations and closed fractures. AIS-3 injuries are serious and include skin disruptions with major blood loss, arterial lacerations, organ disruptions, and open/ displaced/ comminuted fractures. AIS-4+ injuries are severe to fatal (AIS-6) and in the case of head injury, include complex basilar skull fractures and brain injury to massive crush injuries. The system was developed by the Association for the Advancement of Automotive Medicine (AAAM 1990).

ATD

Anthropomorphic Test Device (or Dummy): A human surrogate used in testing to simulate the motions and reactions of a body under force.

ATSB

Australian Transport Safety Bureau

Biofidelity

A measure of how well a model (or dummy) simulates the forces and motions of the human body.

Biomechanics

The application of the laws of physics and engineering concepts to study the forces acting on the body during motion and their effects.

BSF

Basilar skull fracture: fracture to the skull base, usually in the region of the foramen magnum.

CASR

Centre for Automotive Safety Research, University of Adelaide

Chin bar / chin guard

The portion of a full-face helmet which covers the mandible.

Chin strap

Straps usually attached to the temporal regions of the helmet, used to secure the helmet. Fasteners such as buckles, clips, or D-rings allow tight adjustment under the chin to prevent dislodgment during an accident.

FMVSS

Federal Motor Vehicle Safety Standards in the U.S. Code of Federal Regulations.

Full-face helmet

A motorcycle helmet with an extended area of coverage including a chin bar and usually a clear visor.

G

Gravitational acceleration constant (9.81 m/s^2)

Headform

A surrogate used to simulate the human head in testing.

HIC

Head Injury Criterion - A commonly used indicator of head injury based on the acceleration of the head resulting from an impact.

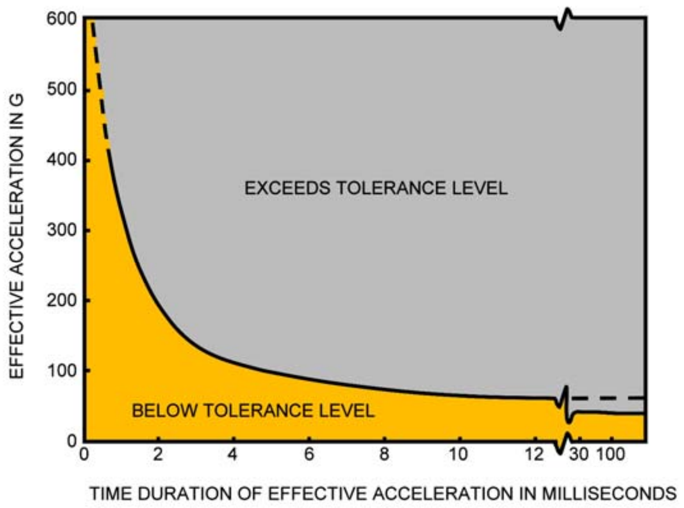
HIC is defined as:

$$HIC = \max\left[\frac{1}{(t_2 - t_1)}\int_{t_1}^{t_2} a(t)dt\right]^{2.5}(t_2 - t_1)$$

where: $a(t)$ = resultant acceleration of the head's centre of gravity during the $t_2 - t_1$ time interval (G)
$t_2 - t_1$ = time interval during the acceleration pulse in which $a(t)$ attains a maximum value (ms)

HIC is based on the Wayne State University Concussion Tolerance Curve (below) proposed by Lissner et al. (1960). This curve plots the effective acceleration of the head, which is an average anterior-posterior acceleration of the skull measured at the occipital bone, in impacts of the forehead with a rigid planar surface, against effective duration of the pulse (SAE 1980). The latter part of the curve with the asymptotic value of 42G is based on volunteer whole body data, which did not involve direct blows to the head. Patrick et al. (1965) recommended that this asymptotic value be raised to 80G. This revised level has been used as the basis of the U.S. Federal Motor Vehicle Safety Standards (FMVSS).

The Wayne State University Concussion Tolerance Curve, after SAE (1980).



Open-face helmet

A motorcycle helmet which covers only the skull vault and provides no facial protection. May have a visor.

Stobie pole

Utility poles constructed of two steel-I beams, held together by tie bolts and filled with concrete, used extensively in South Australia to carry electricity cables and telegraph wires.

UNECE / ECE

United Nations Economic Commission for Europe

1 INTRODUCTION

1.1 Background

In Australia, motorcycles represent only 3% of all registered vehicles on our roads, yet riders account for over 10% of all road user fatalities each year (ATSB, 2006). While measures to improve vehicle occupant safety have resulted in a decline in the overall road toll from 2,015 in 1995 to 1,634 in 2005, motorcyclist fatalities have remained relatively steady over the ten-year period, see Figure 1. In the fatality rate per 10,000 registered vehicles, there has been a significant decrease for all road users, while motorcycle fatalities show only a slight downward trend, Figure 2.

Figure 1 Australian road user fatalities, 1995-2005. Data Source: Australian Transport Safety Bureau (ATSB, 2006)

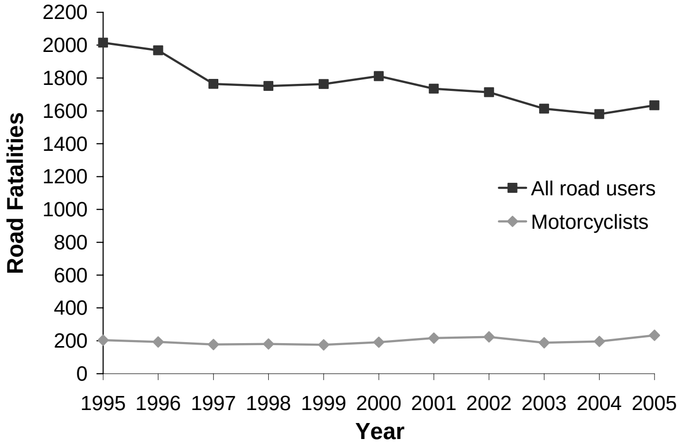
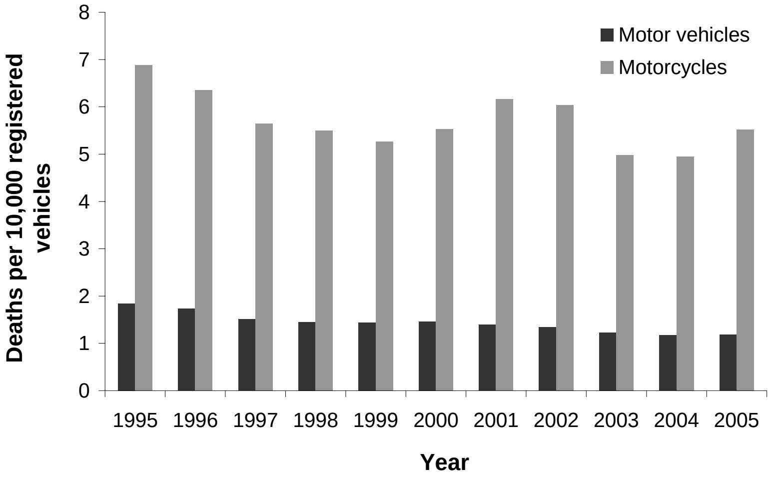


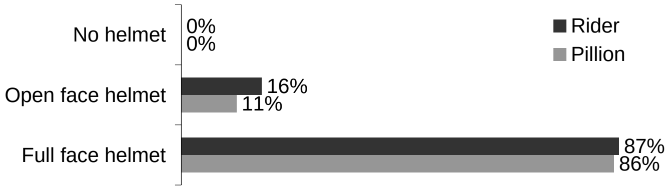
Figure 2 Comparison of death rates per 10,000 registered motor vehicles and motorcycles, 1995-2005. Data Source: Australian Transport Safety Bureau (ATSB, 2005).



Since the 1960s, it has been compulsory for all motorcyclists, pillion passengers and side-car passengers in Australia to wear helmets certified to AS/NZS 1698.

A 2001 survey of motorcyclists in NSW (de Rome, Stanford & Wood, 2002) found that all 796 rider respondents and their 417 pillion passengers indicated that they would usually wear helmets while riding. The majority of users preferred full-face helmets to the open-face variety, Figure 3.

Figure 3 Helmet use among motorcycle riders (n=796) and pillion passengers (n=417) in NSW, after de Rome, Stanford & Wood (2002).



Numerous helmet effectiveness studies have concluded that helmets greatly reduce the risk of head and neck injury, death and disability in motorcycle crashes (Rutledge et al. 1991; Sarkar et al. 1995; Kraus et al. 1994). Motorcycle helmets have been found to be very effective in preventing contact injuries such as lacerations and skull fracture, but less effective in preventing inertial injuries (Ryan 1992). There is much debate over which helmet type offers superior protection to motorcyclists in crashes.

Dowdell et al. (1988) completed the last comprehensive review of the performance of Australian market motorcycle helmets in crashes, in which 200 crash-involved helmets were studied in detail. The chin bar of the full-face helmet was the region with the highest average number of impacts. Almost 50% of the severe impacts were to the front of the helmet and 40% of these impacts resulted in basilar skull fractures (BSF). A recommendation was made that specifications be developed for a test aimed at reducing the effect of frontal impacts to the face by improving the energy absorption of helmets in this area.

Two current motorcycle helmet standards include chin bar tests: Snell M2005 and UN ECE 22.05.

- For the Snell test, a mass is dropped onto the chin bar of the helmet and a limit is set on the deformation allowed of 60 mm.
- For the ECE 22.05, on the other hand, the helmet mounted on a full rigid headform with a chin is dropped onto a flat steel anvil. The acceleration measured at the centre of gravity of the headform is limited to 275 G.

These two chin bar tests have significant differences in their impact on helmet design and do not specifically address the issue of basilar skull fracture. The focus of the Snell test appears to be on movement of the chin bar towards the face and facial injury and the ECE test on the extension of the protective area of the head to the chin bar, based on prevention of brain injury.

The only existing Australian database of motorcycle crashes, with the accident involved helmets included, is a group of 172 motorcyclist fatality cases in the Adelaide metropolitan area collected by the Road Accident Research Unit (RARU, now CASR) of the University of Adelaide over the period 1983 to 1991. The dataset includes extensive crash-related information collected at the scene with an examination of the site, collection of the helmet (in 61% of cases) and detailed autopsy results for 159 cases, which includes an external cervical spine examination. O’Connor et al. (2002) used the case information in this database when investigating the role of the helmet-type in cervical spinal cord injuries. This database also forms a necessary component of the study presented in this report.

1.2 SCOPE AND AIMS OF THE STUDY

The aim of this study is to improve the understanding of basilar skull fracture (BSF) causation in motorcycle crashes and support the continuing development of the Australian motorcycle helmet standard AS/NZS 1698.

The specific objectives are:

- To investigate BSF causation to helmeted riders in motorcycle crashes.
- To develop injury causation hypotheses of BSF to helmeted riders.
- To investigate the inclusion of a protective chin bar as a means of reducing the effects of frontal impacts to the face, by improving the energy absorption of helmets in this area.
- To use the crash data to evaluate the requirements of an effective chin bar test procedure, for inclusion in a motorcycle helmet standard to reduce the incidence of BSF.
- Similarly, to use the available biomechanical injury tolerance data to evaluate the requirements of an effective chin bar test procedure for inclusion in a motorcycle helmet standard.
- To support the new committee reviewing the AS/NZS 1698 Standard for Protective Helmets for Vehicle Users by supplying information as to the incidence, causation and test methodologies related to the specific injury mechanism of BSF in helmeted impacts.

The approach taken to achieve these objectives in this study was to review the various areas of BSF causation in motorcyclists, as outlined above. The incidence of BSF to helmeted motorcyclists in crashes was reviewed with special reference to the South Australian data collected by CASR. This review was combined with the available knowledge of the impact biomechanics related to mechanisms of BSF causation, and was then used to reflect on the available helmet test methods to formulate recommendations for the Helmet Committee.

The report takes the following format: Chapter 2 is a review of the literature related to the incidence of BSF in motorcycle crashes; in Chapter 3, the experimental biomechanics related to BSF and related injury is reviewed; the findings from a detailed review of the case information and examination of the helmets in the Head Injury Database at the Centre for Automotive Research (CASR), University of Adelaide are presented in Chapter 4; Chapter 5 summarises the test requirements related to BSF in current helmet test standards; in Chapter 6, the relationship of these current helmet test methods with the accident data and published biomechanical tolerance data and needs for further work are discussed ; and finally, Chapter 7 summarises the findings of this report.

2 METHOD

2.1 HEAD AND NECK INJURY IN MOTORCYCLE CRASHES

The following is a selection of the available literature on head and neck injury in motorcycle crashes.

Anderson and Kraus (1996) compared the risk of fatality among paired motorcycle drivers and passengers involved in a crash, to investigate the effectiveness of wearing a helmet. The data was obtained from the US Fatal Accident Reporting System 1976 – 1989. The researchers found the following:

- Helmet use was associated with a 35% lower risk of fatality overall;
- The effectiveness of helmet use improved from 14% in 1976 to 51% in 1989;
- The effect of helmet wearing was greater in the less severe accidents;
- The helmets mainly complied with the DOT requirements;
- The helmets were more effective in impacts with soft and non fixed objects than in crashes with motor vehicles and fixed objects;
- The helmets were more effective in side or rear collisions than in frontal impacts; and,
- The helmets were more effective in crashes with minor or moderate damage to the motorcycle rather than severe damage.

Sarkar et al. (1995) investigated 173 fatalities (155 drivers and 18 passengers) among motorcyclists in Los Angeles County. The findings were limited to 69 non-helmeted and 30 helmeted riders having equally severe injuries (MAIS ≥ 3) in anatomic regions other than the head or neck. This comparison was made to allow the pattern of head and neck injury with and without helmet use to be assessed independently of trauma in other body regions. The researchers found that facial fracture, skull vault fracture, or cervical spine injury (including fractures, dislocations, or cord injuries) were five to nine times more likely among non-helmeted riders than among helmeted riders. Cerebral injury and intracranial haemorrhage are more than twice as likely among non-helmeted riders as in the helmeted riders. Fractures of the base of the skull and injuries to the brain stem are somewhat more common in non-helmeted riders. In this study the wearing of a helmet was found to be protective with regard to all types of head and neck injuries. The hypotheses that injury may occur due to the increased mass of the helmet producing higher forces on the junction of the head and neck in a lateral blow to the head, and the increased size of the helmeted head increasing torque on the neck and skull base in the event of a tangential impact, were not found to be supported by the data.

Richter et al. (2001) presented the results of a European study of 218 accidents collected in Hanover, Munich and Glasgow from July 1996 to July 1998 as part of the COST 327 project. The study looked at head injury mechanisms in helmet-protected motorcyclists and included 226 riders with head/neck injuries. In the study there were:

- Eighty-four (84) fatalities, 74 of which suffered fatal head injuries. One-hundred and fifty riders suffered head injuries and 76 had helmet impacts but no head injury. There were 33 reported cases of BSF, 28 facial fractures, 19 skull vault fractures and 4 fractures or dislocations of the upper cervical spine.

- Most riders (80%) wore full-face helmets, of which 9% were dislodged.
- Of the 205 helmets inspected, there were 196 frontal impacts, including 115 chin bar impacts and 42 impacts to the visor. There were only 2 impacts to the crown of the helmet. 157 helmets had impacts to the rear and most helmets had lateral impacts (right 199, left 184).
- Head impact angle resulting in head lesions: 57% lateral (XY = ± 90º ± 15º), 23% frontal (XY = 0 ± 15º), 1% compression, 0.5% tension.
- The collision opponent was 57.7% car and 25.4% stationary object.

The authors (Richter et al. 2001) concluded the following:

- That the improvements to helmets in the last decade had reduced the number of head injuries suffered from 40% to 18%.
- The helmets were found to provide protection from all types and locations of head injury and they were not associated with increased neck injury.
- There was no correlation of neck injury with helmet weight in this study.
- The helmets in the study mainly complied with ECE Regulation 22.4 which did not include the chin in the test area. Only 40% of the head impacts were found to fall within the test area of the standard. The majority of the remaining impacts were to the face and chin.
- The impacts were classified as direct, with a high percentage of fractures due to direct force transfer through the helmet, or indirect, with a high percentage of brain damage caused by acceleration or deceleration forces acting on the entire head and helmet.
- The area of the helmet found to be most susceptible to damage due to direct impact was the chin guard and the visor mounting points.

O'Connor et al. (2002) studied 172 motorcyclist fatalities in the Adelaide metropolitan area collected by the University of Adelaide Centre for Automotive Safety Research (CASR, formerly RARU) over the period 1983 to 1991. 11 of these cases were wearing an open-face helmet and 118 were wearing a full-face helmet. This study looked at an area related to this project, the role of the helmet-type in cervical spinal cord injuries. The data set used for the investigation included extensive crash-related information collected at the scene including examination of the site, collection of the helmet (in 61% of cases) and detailed autopsy results for 159 cases including external cervical spine examination. The study concluded that there was no added benefit or harm of the full-face helmet relative to the open-face helmet on cervical spinal cord injury. Similar results have been found by other researchers (see Lin et al. 2004, and Orsay et al. 1994).

Johnson et al. (1995) examined the location and patterns of craniofacial injuries among helmeted versus non-helmeted patients following motorcycle crashes. The incidence of craniofacial and spinal injury in 331 injured motorcyclists admitted to a Trauma Centre in a 4 year period were compared: 77 (23%) helmeted and 254 (77%) non-helmeted. The non-helmeted motorcyclists were three times more likely to have suffered facial fractures (5.2% vs. 16.1%) than those wearing helmets ($p < 0.01$). Skull fracture occurred in only one helmeted patient (1.2%), compared with 36 (12.3%) of non-helmeted patients ($p \leq 0.01$).

No cases of BSF were found in this series among helmeted patients. In non-helmeted patients, 9.4% of patients suffered BSF. When all skull fractures are included, non-helmeted patients had a tenfold increase, compared with those wearing a helmet. The incidence of spinal injury was not significantly different between the two groups. Failure to wear a helmet was found by the researchers to result in a significantly higher incidence of craniofacial injury among patients involved in motorcycle crashes, but did not affect spinal injury.

2.2 BSF IN MOTORCYCLE CRASHES

Fractures to the base of the skull are associated with high energy trauma such as in falls and traffic accidents. While full-face helmets are more likely to protect users from facial injury than open-face helmets, some investigators have noted a greater prevalence of fractures to the base of the skull in full-face helmeted riders (Bly 1994).

Pedder et al. (1979) report on a sample of ninety-three accidents involving 96 fatally injured persons involved in two-wheeled motor vehicle accidents. Forty-one cases in the sample approximated to the experimental motorcycle collision tests between an upright motorcycle and another vehicle. There was a high incidence of basal skull fractures with 35 out of the 57 casualties who received a skull fracture of some description, suffering fractures to the skull base. Brain damage rated as AIS 4 to 6 was reported for 75 casualties. In twenty (27%) of these cases the brain injuries occurred without any skull fracture. Of the remaining 55 cases, 13 involved brain injury with an overlying fracture and 12 were reported as exhibiting brain injury associated with a fracture in the base of the skull. Thirty cases were not reported in sufficient detail to allow these distinctions to be made. Nine casualties sustained an injury to the cervical spine in the region of the first three vertebrae. In 6 cases the neck injury probably occurred as a result of a direct blow to the user's head.

A consecutive series of 132 motorcycle and moped riders killed in 1977-1983 in southern Sweden were examined post mortem (Krantz 1985). Almost half of the fatal injuries of the head and neck occurred remote from the point of impact, including intracranial injuries without fractures, ring fractures of the base of the skull, disruption of the junction of the head and neck, and injuries of the cervical spine. Injuries occurring remote from the point of impact were often the result of impacts against the anterior part of the head, especially against the face. 16% of these remote injuries were ring fractures. Three kinds of ring fractures (n=21) were found and attributed to:

- Angular acceleration of the head: 9 cases due to impact to anterior part of head and 3 with no point of impact found.
- Torsion of the upper part of the head in relation to the base (n=2) resulting from oblique impact to the temporal or posterior part of the head.
- Displacement of the atlas and parts of the base of the skull around the foramen magnum into the skull.

All five riders who suffered disruption of the junction of the head and neck were helmeted, causing the researchers to suggest that a helmet may promote such injuries (Krantz et al. 1985). In some of these cases, no sign of impact against the head could be detected. The researchers hypothesised that the inertia of the head, enhanced by the mass of the helmet may have contributed to some of these injuries.

In 1988, Dowdell et al. (1988) completed the last comprehensive review of the performance of Australian market motorcycle helmets in crashes. In this study, 200 crash-involved helmets were studied in detail, with 72 of the crashes being fatal. 89% of cases involved the full-face helmet variety, and the chin bar of the full-face helmet was the region with the highest average number of impacts. Almost 50% of the severe impacts were to the front of the helmet and 40% of these impacts resulted in basilar skull fractures. There were 25 basilar skull fractures in the sample, only 2 of which were non-fatal. Four vault fractures were present and 3 of these were associated with impacts to the facial region of the full-face helmets. The basilar skull fractures were classified by the researchers as injuries caused by forces transmitted from impact sites remote from the injury. Frontal impacts to the chin region alone and to the forehead or to both were found to be capable of producing this injury. A recommendation from this study was that specifications be developed for a test aimed at reducing the effect of frontal impacts to the face by improving the energy absorption of helmets in this area. It is interesting to note that 35% of helmet impacts were outside the helmet test area, and this proportion was consistent between fatal and non-fatal cases.

The Dowdell et al study demonstrates some of the difficulties when fatal cases are used for motorcycle crash studies. A break down of injury severity to the head, neck, face and chest (Table 1) shows that the fatal cases had a much higher incidence of head and chest injuries, which were also more severe. Twice as many facial injuries were seen in the fatal cases than the non-fatal cases (17/72 and 15/128), however most of these were minor.

Table 1 Head, neck, facial and chest injury by severity in motorcycle crashes, Dowdell et al. 1988.

Body region	Cases with injuries	No. of injuries	AIS Injury Severity					
			6	5	4	3	2	1
Non-fatal cases (n=128)								
Head	58	61	0	0	0	5	46	10
Neck	25	25	0	0	1	1	2	21
Face	15	28	0	0	0	0	14	14
Chest	13	18	0	0	1	7	5	5
Fatal cases (n=72)								
Head	58	143	11	11	43	68	10	0
Neck	16	18	8	2	0	3	3	2
Face	17	25	0	0	0	1	8	16
Chest	62	139	12	17	53	37	18	2

Facial injuries fall within the first three levels of the Abbreviated Injury Scale (AIS) (AAAM 1990). The AIS scale rates injury severity by body region and not the response to injury. As examples, a simple facial fracture has a severity of AIS 1, where an open, displaced and comminuted fracture of the orbit will be AIS 3 and a LeFort III fracture with 20% blood loss AIS 4. This is the highest possible AIS score for a facial injury.

Cooter and David (1990) analysed the craniofacial injury patterns of a group of 24 fatally injured motorcyclists. These patterns were compared to a group of 50 patients hospitalised with craniofacial injury. The hospitalised group was found to have high scores of facial fracturing and low scores of cranial fracturing. In contrast, the fatally injured motorcyclists wearing full-face helmets had low scores for facial fractures and unsurvivable BSF. It was proposed that an impact to the face bar may load the chin strap and this would transmit the force to the mandibular condyles with sufficient load to cause fracturing of the skull base (Cooter et al. 1988). Helmet deformation patterns obtained from CT scans confirmed the load mechanism in these cases (Cooter 1990). This mechanism proposed by Cooter has been questioned by many other international experts, Thom and Hurt (1993) among them.

Konrad et al. (1996) retrospectively studied 122 fatally injured motorcyclists. The overall incidence of BSF was 9.2%. There was a positive correlation between the incidence of complete or partial ring fractures of the base of the skull and the weight of the involved helmet. There was a significant increase ($p = 0.012$) in incidences of this type of fracture when the helmet weighed more than 1,500 grams. Five helmets in the study weighed more than 1,600 grams; in this subgroup, only one patient's skull base was intact. The weight of the helmet had no effect on the incidence or severity of spinal injuries, but in 74 cases damage to the spinal column was seen. The researchers suggest that the trauma mechanism for the ring fractures was a sudden change in the rider's velocity during the collision with a second motor vehicle. In the group with basal fractures, the distance between the location of the collision and the end-point of the rider was less in comparison with the group with no such fractures but the difference was not statistically significant.

In the related area of motor vehicle crashes, one possible BSF injury mechanism has been illustrated by Bandstra and Carbone (2001). These researchers reported the findings of a post mortem examination of a driver involved in an oblique frontal collision (deltaV = 56 kph) who suffered an incomplete ring fracture to the base of the skull. The driver was out-of-position, slumped over the steering wheel, when the crash occurred. The investigators concluded that the force of the deploying airbag was directed to the mandibular region, causing distraction of the base of the skull from the cervical spine. The tensile strength of the atlanto-occipital ligaments caused the occipital portion of the skull to fail, producing the unusual ring-type fracture. This mechanism has also been found to occur in out-of-position frontal occupants due to airbag actuation (NHTSA 2000).

Thom & Hurt (1993) reanalysed the data from their earlier study of 304 fatal motorcycle accidents in Los Angeles between 1978 and 1981. The data included 60 helmeted riders, 21 of which had basilar skull fractures (35%) compared to 57.8% of unhelmeted riders. The authors found that BSF could not be precluded by helmet use. Severe impacts to the head, cervical axial loading and hyper motion of the neck were all likely to lead to BSF with or without a helmet.

2.3 SUMMARY

The findings of the review of literature concerning head and neck injury to helmeted motorcyclists in general and BSF in particular, can be summarised as follows:

For Head and Neck Injury:

- Improvements to helmets in the last decade have reduced the proportion of head injuries suffered by motorcyclists from 40% to 18% (Richter et al. 2001).
- Helmets were found to provide protection from all types and locations of head injury suffered by motorcyclists (Richter et al. 2001; Sarkar et al. 1995).
- Helmets were not associated with increased neck injury suffered by motorcyclists (Richter et al. 2001; Sarkar et al. 1995; Johnson et al. 1995; Thom & Hurt 1993).
- Helmets were found to provide protection from craniofacial injury suffered in motorcycle crashes (Johnson et al. 1995).

- There was no correlation of neck injury with helmet weight (Richter et al. 2001; Johnson et al. 1995; Konrad et al. 1996).
- Only 40% of the head impacts were found to fall within the test area of the standard. The majority of the remaining impacts were to the face and chin (Richter et al. 2001; Dowdell et al. 1988).
- There was no added benefit or harm in wearing a full-face helmet relative to an open-face helmet, in terms of cervical spinal cord injury (O'Connor et al. 2002).
- Injuries occurring remote from the point of impact were often the result of impacts against the anterior part of the head of the motorcyclist, especially against the face (Krantz 1985).
- Helmets may promote disruption of the junction of the head and neck, where no sign of impact against the head could be detected (Krantz 1985).
- Facial fractures in motorcyclists may protect the head and neck in facial impacts (Cooter & David 1990).

For BSF:

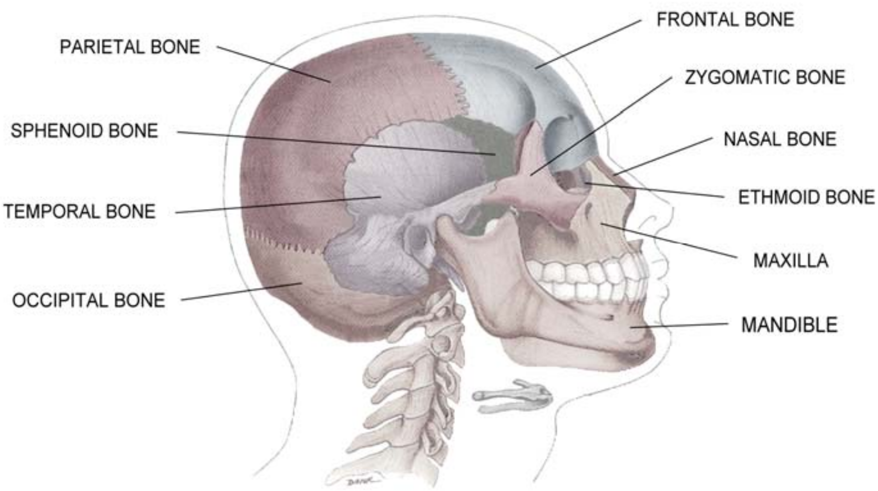
- There may be a greater prevalence of some types of fractures to the base of the skull in full-face helmeted riders (Bly 1994; Cooter 1988).
- Severe impacts to the head, cervical axial loading and hypermotion of the neck are all likely to lead to BSF with or without a helmet (Thom & Hurt 1993).
- A correlation has been demonstrated between BSF and helmet weight (for >1.6kg) (Konrad et al. 1996).
- Fractures of the base of the skull and injuries to the brain stem were somewhat more common in non-helmeted riders (Sarkar et al. 1994).Paragraph text starts here

3 BIOMECHANICS OF BASILAR SKULL FRACTURE

3.1 Anatomy of BSF

The human skull contains 22 bones that are generally divided into two sets: the fourteen facial bones and the eight cranial bones. The cranial bones are further divided into the cranial vault and the skull base or floor. The cranial vault includes the frontal bone, two parietal bones, the superior aspects of the squamous portion of the temporal bones, and the superior third of the occipital bone. The base of the skull consists of the sphenoid, ethmoid and inferior parts of the frontal, temporal and occipital bones. It is characterised by three fossae: the anterior, middle and posterior cranial fossae (see Figures 4 and 5**.**).

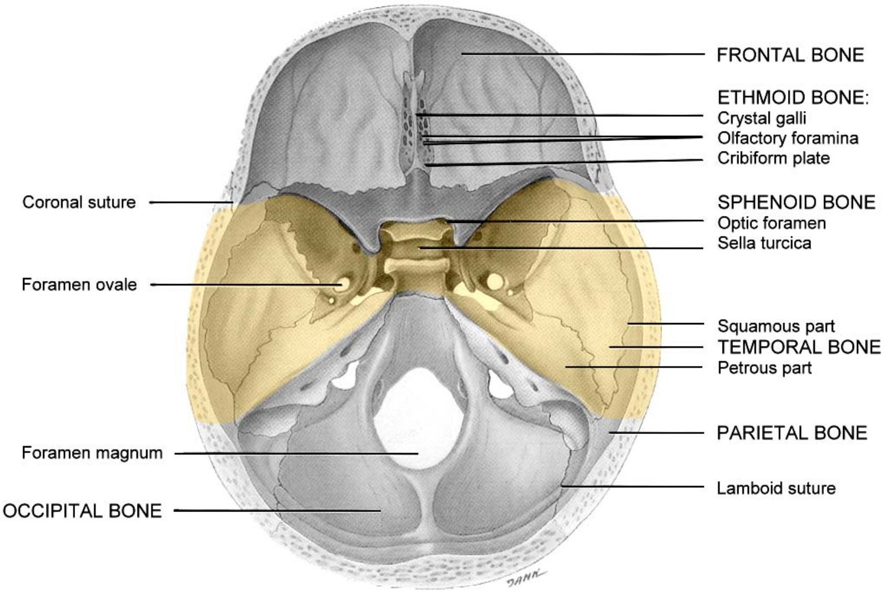
Figure 4 Bones of the skull, after Tortora & Grabowski, 2001



BSF is any fracture, which originates in or propagates to the bones in the base of the skull. A more severe type of BSF is a ring fracture, so called as it surrounds the foramen magnum, the aperture at the base of the skull through which the spinal cord passes. A complete ring fracture is usually immediately fatal due to associated injuries to the brain stem. An incomplete ring fracture is more “typical” (Hooper et al. 1994). Death is usually instantaneous owing to the brain stem injuries being accompanied by avulsion and laceration of the large blood vessels in the base of the skull.

Basilar skull fractures have been attributed to various mechanisms including impacts to the mandible or face and the cranial vault, or due to inertial loading by the head (often called whiplash type injury). Such inertial loading occurs, for example, when the chest of the motorcycle rider comes to a sudden stop on contact with an object such as a vehicle or guard rail. The head is then slowed by loading of the neck. Ring fractures may also result from vertically directed contact forces applied either inferiorly to the crown (compressive forces) or from superiorly directed forces applied to the occiput or the mandible.

Figure 5 Bones of the skull base, after Tortora & Grabowski, 2001



3.2 The Mechanisms of BSF

Published literature on the mechanisms of injury for basilar skull fracture is sparse.

Huelke et al. (1988) investigated the commonly held view that basilar skull fracture was the result of cranial vault impacts. Case histories of non-cranial vault impacts, which presented in a variety of motor vehicle crash types, were documented. These researchers found basilar skull fractures could also be caused by facial impacts alone.

In an experimental series based on cadaver testing, Gott et al. (1983) examined in detail the skulls of 146 subjects who had been subjected to head impacts. The 45 skull fractures observed were described in detail. There were 22 BSF in this group and the causation included impacts to the frontal bone (5), the temporo-parietal area of the skull (1), the whole face (2) and a variety of other head impact types (14).

While examining neck response to axial loading in tension, Sances et al. (1981) observed BSF without any ligamentous damage at 1780 N quasi-statically in an isolated cadaveric spine and at 3780 N in a dynamically loaded intact head, neck and spine.

Several researchers have subjected the head-neck complex to superior-inferior impacts. In general, the testing has shown that localised skull fractures are likely to result from unpadded impacts. When the head was padded, the neck became the region most susceptible to injury at a force level of just above 4 kN (Alem et al. 1984). These researchers tested 19 supine cadavers and were only able to produce a single BSF. The BSF required a low duration (3 ms), high energy (33 J) impact with an impact force of 17 kN at an impact velocity of 9 m/s.

Hopper et al. (1994) performed two experimental studies on cadavers aimed at understanding the biomechanical mechanisms that result in basilar skull fractures when the head is subject to a mandibular impact.

1. In the first study the injury tolerance of the mandible was evaluated when subjected to mid-symphysis loading on the mental protuberance (chin). Five dynamic impacts with a vertical drop track and one quasi-static test were performed. The impact surfaces were varied to

assess the influence of loading rate. It was found that the mean mandibular fracture tolerance for the six tests was 5270 ± 930 N and appeared insensitive to loading rate. In each test, clinically relevant mandibular fractures were produced but no basilar skull fractures were observed.

2. The second study assessed the BSF tolerance when a direct load to the temporo-mandibular joint was combined with tensile loading imposed locally around the foramen magnum, simulating the effect of the neck. The peak force and energy to failure were determined in each test. For the four specimens that sustained either complete or incomplete basilar skull ring fractures remote from the sites of load application, the mean load at fracture was found to be 4300 ± 350 N. The researchers were able to calculate the energy to fracture in three of these tests at an average of 13.0 ± 1.7 J. The injuries produced in this manner were consistent with clinical observations of basilar skull fracture. When the loading point was changed to the maxilla combined with the tensile loading to the foramen magnum, a Le Fort I[1] fracture of the face was found to occur.

The researchers concluded that the results of this study supported the hypothesis that mandibular loading alone usually leads to mandibular fracture. Further, complete and partial ring type BSF requires temporo-mandibular loading in conjunction with neck tension loading .

3.3 Fracture Tolerances of the Neck, Face and Skull

The accepted injury tolerance values for peak short term loading of the upper neck are summarised in Table 2, from Mertz et al. (2003). These values are derived from the injury assessment reference values IARVs used with the HIII dummy in testing of automotive safety systems and are design limit values. If the values are not exceeded in the test then the risk of the associated injury would be unlikely for an occupant of that size.

Injury assessment reference values of this type do not exist for the face and skull fractures, so for the purposes of comparison, some representative values for experimentally measured fracture forces of the face and skull have been collected and tabulated here in Table 2. The values are based on cadaver test data from the references nominated.

Table 2 Injury assessment reference values IARV for the neck of a 50th percentile male Hybrid III dummy, Mertz et al. (2003).

Load Type at the Upper Neck	IARV
Tension Force	4170 N
Compression Force	4000 N
Shear Force	3100 N
Flexion Moment	190 Nm
Lateral Flexion Moment	143 Nm
Extension Moment	96 Nm

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[1] A Le Fort I fracture is a mid-facial fracture that extends horizontally from the piriform fossa across the maxilla to the pterygoid fissure.

Table 3 Experimental fracture strength of the human face and skull.

Bone	Force (N)		Sample Size	Impactor Area (cm²)	Reference
	Range	Mean			
FACE					
Mandible					
AP	1890-4110	2840	6	6.5	Schneider 1972
Lateral	818-2600	1570	6	25.8	Schneider 1972
Mandible	4460-6740	5390	5		Hopper 1996
Maxilla	623-1980	1150	11	6.5	Schneider 1972
Zygoma	970-2850	1680	6	6.5	Schneider 1972
SKULL					
Base (under neck tension)	3950-4650	4300	6		Hopper 1996
Frontal	4140-9880	5780	13	6.5	Schneider 1972
Temporo-Parietal	2110-5200	3630	14	6.5	Schneider 1972

Table 3 demonstrates that the fracture strengths of the facial bones, except for the mandible in certain directions of impact, are less than for the skull. As a result it has been observed that, in an impact, the facial bones typically will fracture first and act as an energy absorber for the head in facial impacts, Cooter and David (1990). Similarly, the neck in shear, as shown in Table 2, has a higher strength than the fracture strength of the facial bones. Hence in a facial impact the neck is protected to some extent by the failure of the facial bones.

Table 4 presents the stiffness to fracture for the various regions of the head and skull. The values demonstrate the low stiffness of the facial bones adding support to the hypothesis that the facial bones protect the head and neck from injury.

Table 4 Experimental measured stiffness to fracture of the human face and skull.

Bone	Stiffness (N/mm)		Sample Size	Impactor Area (cm²)	Reference
	Range	Mean			
FACE					
Mandible		721	1		Hopper 1996
Maxilla	80-180	120	6	20mm bar	Allsop 1988
Zygoma	90-230	150	8	20mm bar	Allsop 1988
SKULL					
Base (under neck tension)	545-633	589	2		Hopper 1996
Frontal	400-2200	1000	13	20mm bar	Allsop 1988
Temporo-Parietal	700-4760	1800	20	6.45	Allsop 1991

3.4 Summary

Based on the laboratory studies reviewed here, we can summarise the main points as follows:

- A BSF is any fracture, which originates in or propagates to the bones in the base of the skull. A more severe type of basilar skull fracture is a ring fracture, so called as it surrounds the foramen magnum, the aperture at the base of the skull through which the spinal cord passes.
- BSF have been shown in laboratory tests to be due to various mechanisms including impacts to the mandible or face, lateral impacts and the cranial vault, or due to inertial loading by the head (often called whiplash type injury). Ring fractures may result from vertically directed contact forces applied either inferiorly to the crown (compressive forces) or from superiorly directed forces applied to the occiput or the mandible.
- In a padded impact to the crown of the head, the neck (rather than the skull) is the region most susceptible to injury at a force level of just above 4 kN. BSF due to crown impact has been shown to require a high velocity, low duration, high energy impact (Alem et al. 1984).
- Direct impacts to the mandible only have been shown to produce fractures of the mandible but no basilar skull fractures were observed, unless combined with tensile loading at the foramen magnum. This combined loading produced BSF at a neck distraction load of 4.3 kN (Hopper et al. 1994).
- The fracture strengths of the facial bones, except for the mandible in certain directions of impact, are less than for the skull and the neck in shear. In a facial impact the head and neck may be protected to some extent by the failure of the facial bones.
- The stiffness of the facial bones, the zygoma and maxilla, apart from the mandible are much less than for the skull bones, base of skull, frontal temporo-parietal and occipital. This adds further support for the hypothesis that in a facial impact the head and neck may be protected to some extent by the failure of the facial bones.

4 ANALYSIS OF THE CASR DATABASE

4.1 Aim of the Analysis

The researchers were able to access to a database collected by the Road Accident Research Unit, RARU (now the Centre for Automotive Safety Research, CASR) of the University of Adelaide. The database contains in-depth investigations of 174 mainly fatal motorcycle accident cases collected in the Adelaide metropolitan area between 1983 and 1994. The database includes accident information collected at the scene, police reports, post mortem reports and some helmets.

The aim of the database review in this study was to verify the reported skull base injury mechanisms in helmeted head impacts. The difficulties with the use of fatal motorcycle accident data due to the high impact severities are acknowledged.

4.2 Results

The CASR database contains 174 motorcycle casualty cases, 130 (74.7%) of which received an impact to the helmet or head. Table 5 is a breakdown of the helmet types worn by riders. In this study, less than 3% of riders failed to wear a helmet. Sixty-nine percent of motorcyclists wore full-face helmets, while 8.6% wore the open-face variety, Table 4.

Table 5 Helmet type worn by riders

Helmet type	All cases		Head impact cases	
	No.	**%**	**No.**	**%**
Full-face	120	69.0	91	70.0
Open-face	15	8.6	14	10.8
Unknown	34	19.5	20	15.4
None	5	2.9	5	3.8
Total	174	100	130	100

Of the 125 head impact cases involving use of a helmet, 34 helmets (27.2%) were ejected during the crash. These included 30.8% of full-face helmets, and 14.4% of open-face helmets worn, Table 6.

Table 6 Helmet retention in head impact cases (n=125)

Helmet Type Helmet Retention	Full-face helmet		Open-face helmet		Unknown helmet type		Total	
	No.	%	No.	%	No.	%	No.	%
In Place	59	81.9 64.8	12	16.7 85.7	1	1.4 5.0	72	100 57.6
Ejected	28	82.4 30.8	2	5.9 14.3	4	11.8 20.0	34	100 27.2
Unknown	4	21.1 4.4	0	0.0 0.0	15	78.9 75.0	19	100 15.2
Total	91	72.8 100	14	11.2 100	20	16.0 100	125	100 100

Fifty-one (70.8%) of the 72 helmeted head impacts resulted in skull or facial fracture. In comparison, 53.8% of unhelmeted head impacts were linked with skull or facial fracture, Table 7.

Table 7 Skull fractures by helmet type worn

Skull fracture	Full-face helmet on (n=59)		Open-face helmet on (n=12)		Any helmet on (n=72)		Helmet ejected or not worn (n=39)	
	No.	%	No.	%	No.	%	No.	%
Basilar skull	35	59.3	10	83.3	46	63.9	21	53.8
Skull vault	14	23.7	6	50.0	21	29.2	14	35.9
Facial	14	23.7	2	16.7	17	23.6	12	30.8
No fracture	21	35.6	0	0.0	21	29.2	18	46.2

Open-face helmets did not protect the wearer from skull fracture. BSF was seen in 35 (59.3%) cases in which a full-face helmet was worn. Twelve (34.3%) of these cases also received facial fractures, Table 8.

Table 8 Facial injuries in cases with basilar skull fracture

Facial injury	**Full-face helmet on (n=35)**		**Open-face helmet on (n=10)**		**Any helmet on (n=46)**		**Helmet ejected or not worn (n=21)**	
	No.	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**
Facial fracture	12	34.3	4	40.0	16	34.8	11	52.4
Superficial injury	26	74.3	10	100.0	37	80.4	16	76.2
No injury	9	25.7	0	0.0	9	19.6	3	14.3

Fewer facial injuries were seen in cases without basilar skull fracture, Table 9. In particular, there were very few facial fractures seen in this group.

Table 9 Facial injuries in cases without BSF

Facial injury	**Full-face helmet on (n=24)**		**Open-face helmet on (n=2)**		**Any helmet on (n=26)**		**Helmet ejected or not worn (n=18)**	
	No.	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**
Facial fracture	2	8.3	0	0.0	2	7.7	1	5.6
Superficial injury	14	58.3	0	0.0	14	53.8	14	77.8
No injury	10	41.7	2	100.0	12	46.2	4	22.2

It is important to note that the high incidence of skull fracture, and in particular BSF, may be related to the high severity of accidents recorded in the CASR database (94% fatal).

A subset of thirty cases was selected for detailed analysis. Details of the cases are available in Appendix I - Motorcycle Accident Case Studies. The cases selected had the following characteristics:

- A head impact was involved;
- The helmet was on at the time of impact;
- The helmeted rider suffered fracturing to the base of the skull;
- The helmet was available for inspection.

For each case, the case file was reviewed to examine the accident factors and injuries received in the crash. Post-mortem reports were examined in detail to define the injuries. Of particular interest were head injuries, including superficial head and facial injuries, skull vault fractures, skull base fractures, fractures to the facial bones, brain injury and neck injury. The helmets were then located and visually examined for markings and damage.

The group included 23 full-face helmets and 7 open-face helmets. In 21 (70%) of these cases, BSF was the primary injury resulting in death, Table 10.

Table 10 The primary causes of death in the cases examined in detail (n = 30).

Case	Major cause of death
1	Brainstem injury after BSF
2	Internal brain haemorrhage, spinal cord contusions
3	Brain laceration, ruptured heart & aorta
4	Massive head injury, ruptured aorta
5	Crushed head
6	Head injury and inhalation of blood
7	Neurogenic pulmonary oedema and BSF
8	Open head injury
9	Traumatic brain stem and aortic ruptures
10	Skull fracture and brain lacerations
11	Ruptured aorta & cervical spinal cord
12	Inhalation of blood after BSF
13	Transection of upper cervical spine
14	Head injuries
15	Closed head injury
16	Complete transverse rupture of descending aorta
17	Brain trauma due to BSF
18	Laceration to heart & aorta
19	Brain stem transection
20	Brain laceration and blood ingestion
21	Lacerations to brain due to skull fracture
22	Brain injuries due to closed head trauma
23	Traumatic brain damage & haemorrhage
24	Brain laceration contusion due to extensive fracturing
25	Brain trauma - subarachnoid haemorrhage, lacerations
26	Ruptured aorta
27	Brain lacerations due to extensive fracturing
28	Ruptured heart & aorta
29	Intra-abdominal haemorrhage complicating traumatic rupture of liver
30	Cerebral trauma

The head impacts in these thirty cases involving BSF are listed in Table 11, along with the type of impact, radial or tangential to the surface of the head, the part of the head struck in the major impact, the type of object struck by the head and whether the facial bones or vault were fractured and if the neck was injured. In some cases there was more than one major head impact, 39/30. The majority of impacts were with hard objects, 28/30 or 93% in this group with BSF (mainly road surface, rigid vehicle structures, utility (Stobie) poles and trees, with only 6 possible impacts with more yielding surfaces (5 cars and a helmet).

Table 11 Position of the helmeted head impacts in the cases examined in detail (n = 30).

Case	Helmet type	Head impact	Region of head impacted	Surface impacted	Facial fracture	Vault fracture	Neck injury
1	FF	Radial	Forehead/ facial	Car roof edge	Y	Y	Y
2	OF	Radial	Forehead/ facial	Rendered brick fence	Y	Y	Y
3	FF	Tangential	Right side	Tree/ ground	Y	Y	N
4	OF	Crushing	Whole head	Truck wheels	Y	Y	Y
5	FF	Radial	Right chin bar	Truck	Y	Y	N
6	FF	Radial	Crown	Edge truck tray	N	Y	N
7	FF	Tangential	Facial	Road surface/car	Y	N	N
8	FF	Radial	Left chin bar/right frontoparietal	Xmember behind bumper	Y	N	Y
9	FF	Crushing and/or radial	Right chin bar/ right temporo-parietal	Car wheels	Y	N	Y
10	FF	Radial	Right mid facial	Pylon cross-brace	N	N	N
11	FF	Radial	Right chin bar/face	Road surface/car	N	N	N
12	FF	Radial	Right chin bar/face	Kerb or road	N	N	Y
13	OF	Radial	Crown	Utility pole	N	N	Y
14	OF	Radial	Crown/ forehead	Truck	N	Y	Y
15	FF	Radial	Forehead	Tree	N	N	N
16	FF	Radial	Facial	Car/road surface	N	N	N
17	OF	Radial	Facial	Car	Y	N	Y
18	FF	Tangential	Hyperextension	Truck wheels/ underside	N	N	Y
19	FF	Radial	Left occipital/ chin bar	Utility pole	N	N	N
20	FF	Radial	Right frontal	Car	N	N	Y
21	FF	Tangential	Rear parieto-occipital	Tree	N	N	N
22	FF	Radial	Left/right temporo-parietal	Road surface	N	Y	N

Table 12 Facial injuries in the n=30 cases.

Case	Superficial facial injuries	Facial fracture
1	Gross lacerations	Shattered from eyebrows to nose
2	Forehead, mid-facial laceration, abrasions and contusions	Maxillae, mandible, nasal
3	None	Bilateral mandible fractures
4	Mutilated, right eye proptosed, enucleated	Mandible fracture. Facial bones detached from base, crushed forwards and to the left
5	Laceration right cheek and temple, right cheek and eye socket diffuse abrasions.	Mandible, maxilla, nasal, zygomatic arches
6	Bleeding from mouth, nose and ears	None
7	Laceration left forehead extending to scalp, bilateral orbital bruising, laceration bridge of nose	Nasal bones
8	Vertical laceration L forehead, bilateral orbital bruising	Nasal bones
9	Chin abrasions	Mandible midline, right condyle, and right zygomatic arch
10	Bruising and abrasions right forehead and temple. Faint bruising around eyes.	None
11	Singeing & charring of face at facial aperture	None
12	None	None
13	Laceration abrasions under chin	None
14	Abrasion nasal bridge, scrape left cheek, bruised & swollen lips, cut above right lip, gouge on right chin.	None
15	Slight bruise on forehead	None
16	Extensive laceration (7x6 cm) right eye and temple, bruised left orbit, lacerated nose, neck anterior abrasions.	None
17	2 cm laceration point, small abrasion over lateral left eyebrow, bruising nasal bridge, left upper lip, left cheek	Right central incisor of upper partial denture.
18	None	None
19	None	None
20	Minor bilateral bruising under eyes.	None
21	None	None
22	None	None
23	Linear abrasion under chin	None
24	Right face deformed around right orbit with bruising, abrasions and depression, multiple abrasions over chin.	Right orbital walls
25	None	Chipped upper incisor teeth.

Case	Superficial facial injuries	Facial fracture
26	Facial skew deformity downwards to left, lacerations and abrasions along right eyebrow, lacerations along line of entire mandible, glass chip marks right side face.	Bilateral mandible and maxilla, orbital walls.
27	Bruising left orbit, lacerated upper lip, bruising & abrasions around chin.	Depression & deformity right orbit
28	None	Depressed right orbit & both zygomatic bones, depressed mandible at midline.
29	Transverse laceration on chin 1.5 cm	None
30	Bleeding R upper lip.	None

Table 13 Head and skull injuries in the cases examined

Case	Head superficial injuries	Skull vault fracture
1	None	Egg-shell fracture of frontal and parietal bones
2	Transverse laceration 7cm above eyelevel on forehead, abrasions & contusions	Frontal bone
3	Laceration behind right ear, abrasions right neck to scalp	Right occipital, parietal
4	Mutilated. Massive coronal laceration 15 cm in length with minimal bruising.	Crushing fractures with left skew
5	3 cm oblique laceration right occiput	Comminuted crush fractures
6	Transverse laceration to crown/vertex	Frontoparietal fractures along suture lines, fracture lines traverse the vault across right temporal bone
7	Left frontal scalp bruising	None
8	None	None
9	Diffuse contusions over right temporal region	None
10	Frontal scalp bruising & abrasions	None
11	Minimal bruising in occipital region	None
12	None	None
13	None	None
14	None	Frontal crush fracture
15	None	None
16	None	None
17	None	None
18	Minimal bruising right occipital.	None
19	None	None
20	Bruising right frontal, 6 cm diameter. Bruising right temporalis muscle.	None

Case	Head superficial injuries	Skull vault fracture
21	Min. bruising occipital region.	None
22	None	Left parietal/occipital and left parieto-temporal.
23	Marked bruising right scalp over cranial vault.	Comminuted fracturing of right squamous temporal bone & right parietal.
24	Laceration right frontal area. Missing tissue with depressed bone on right forehead (6x8 cm)	Compound comminuted fracture right fronto-parietal bone.
25	Bruising left vertex of skull.	Left temporo-parietal fracture
26	Extensive bruising in the left occipitoparietal area.	None
27	Laceration near scalp vertex	Extensive comminuted fractures right frontoparietal area.
28	Massive transverse contusion over scalp vertex.	Shattered with numerous radiating fractures and separation of coronal suture lines.
29	None	None
30	None	Fracture left occipital region

The fractures to the base of the skull for the 30 cases are described in Table 14. Only four of these fractures were designated as ring fractures (in bold) and all these cases had significant impacts to the helmet. There were no obvious fractures due to inertia loading by the head alone. Of the four cases of ring fracture, 3 were due to facial impacts and one was due to a crown impact with a utility pole.

Table 14 Injuries to the skull base in the n=30 cases examined, (ring fractures in bold).

Case	Basilar Skull Fracture
1	Comminuted fracture anterior and middle cranial fossae
2	Anterior fossa
3	Massive base fracture
4	Crushed fracture along base between anterior & middle fossa.
5	Comminuted crush fractures
6	fracture orbital plates, extensive fracture across anterior fossae and mid and posterior left fossae, extends to left occiput
7	Comminuted fracture both anterior cranial fossae - more marked on left, transverse anterior fossae fracture midway, shattered cribiform plate
8	Main transverse fracture anterior cranial fossae across posterior aspect of cribiform plate, thru lesser wing of sphenoid on right into middle cranial fossae across foramen ovale and along anterior border of petrous bone. Extensions - sagittal anteriorly, posterior extension into optic canals
9	Extensive comminuted fractures across all 3 fossae on both sides
10	Fractured olfactory plate & right lesser wing of the sphenoid.

Case	Basilar skull fracture
11	Massive ring fracture following occipito-parietal suture line on both sides, extending across skull base at mid. & post. fossa junction along post wing of the sphenoid bone.
12	Fracture traversing posterior third of middle cranial fossa on both sides, extending just anterior to petrous temporal ridges and across the clivus. Lateral limits in close proximity to mandibular condyles. Transverse bi-temporal hinge fracture.
13	Ring fracture, bi-temporal and bi-occipital
14	Hairline fracture right orbital plate
15	Small hairline fracture left orbital plate with bleeding beneath, anterior to sphenoid ridge, oval in shape
16	Multiple closed fractures of anterior and middle fossae on both sides of midline
17	Complete ring fracture about the foramen magnum along left suture line of occipital bone, through base of occiput and through right petrous temporal bone.
18	Minor fracture occipital bone at margin of foramen magnum (hyperextension).
19	Complete ring fracture starting behind ears involving mastoid processes of the temporal bone travelling to occipital bones then the petrous temporal bone and crossing pituitary fossa of the sphenoid bone.
20	Extensive fracture through junction of anterior and mid. on edge of wing of sphenoid extending rearwards to occipito-parietal suture line
21	Massive fracture with separation of sphenoid bone. Fissure from cranial cavity into posterior naso-pharynx, fractures extend laterally to include petrous temporal bone.
22	Comminuted and linear fracture right and left sphenoid, occipital sagittal, and around pituitary
23	Fracture extending from squamous bone down and rearward to right occipital bone in posterior cranial fossa.
24	Comminuted fracturing of anterior cranial fossae and right middle cranial fossa, fracture line passing through pituitary fossa.
25	Hinge fracture bitemporal. Occipital fracture into foramen magnum, fracture through anterior pituitary fossa.
26	Extensive comminuted fractures. Major fracture line extends obliquely from left anterior cranial fossa, across middle cranial fossa and across to right middle cranial fossa.
27	Comminuted fracture of anterior and middle cranial fossae, fracture line passing through pituitary fossa.
28	Extensive fractures held together by soft tissues and dura.
29	Distracted transverse fracture extending across each sphenoidal ridge bisecting the pituitary fossa. Skull was effectively split in half through the base.
30	Left-sided fracturing

Effort was made during the autopsy to examine the neck for injury. There were 14/30 cases with some form of neck injury and 8/30 (27%) were connected with significant neck injury, which are shown in bold in Table 15. The significant neck injuries were either in the upper region with 5 dislocations and fractures between C0 and C3 or at the base of the neck with fractures between C5 and C7. There were 6 cases (20%) that had fractures or dislocation of the cervical vertebrae, and two cases with rupture or transection of the cervical spinal cord. Four cases had only minor superficial injuries to the neck (abrasions, contusions or lacerations) and 3 cases had moderate disruption to the neck structures without fracture or dislocation. One case showed signs of a torsional disruption to the neck due to a right sided impact to the chin bar of the helmet.

Table 15 Neck injuries in the n=30 cases (significant neck injury cases in bold).

Case	Neck injuries
1	Abrasions and contusions, vertebrae intact
2	Fracture dislocation C7/T1
3	None
4	Bruising of all neck structures
5	None
6	None
7	None
8	Haemorrhage into muscles adjacent C7 & T1 spinous processes
9	Sliding abrasions over left side to chin. C1 shattered & dislocated.
10	None
11	None
12	Cervical vertebrae rotated such that spinous processes have shifted laterally to right
13	Transection of upper cervical spine
14	Scrape on right anterior neck
15	None
16	None
17	Abrasions, 6 cm laceration right lower anterior neck adjacent to clavicle
18	Fracture dislocation of atlanto-occipital joint (C0/C1). Rupture of spinal cord at C1.
19	None
20	Fracture C5/C6 with bruising posterior to larynx
21	None
22	None
23	None
24	Abrasions over anterior surface.
25	None
26	None
27	Fractured C1 & C2
28	Fractured atlanto-occipital joint.
29	None
30	None

4.3 Discussion

Investigation of the CASR database was consistent with the discussion in the literature on the incidence and type of BSF in fatal motorcycle crashes. It is important to note that the helmets in this sample were from fatal motorcycle crashes and hence were from the severe end of the crash spectrum. In such cases, there may be little practical means of ameliorating the crash. It is not possible to design a helmet capable of protecting a rider in all circumstances.

In this group there were no cases of BSF without a significant head impact. The impacts within the protective area of the helmet standard, based on AS/NZS 1698, were to the forehead (4/39), crown (7/39), occipital region (2/39) and laterally (5/39). These impacts were of such severity that the helmet had insufficient protective capability and as a result significant skull fractures occurred. Further, the impacts were of sufficient severity for the fractures to propagate into the basilar region of the skull. Although the resulting injuries were severe, they are not necessarily an indication of poor performance of the helmet, but of the severity of the impact. General improvements in the impact absorption capabilities of the helmets will have some effect on reducing this type of injury. An example of a high-performance helmet standard which will give better protection to the wearer in these types of impacts is the FIA 8860-2004 Advanced Helmet Test Specification, which is designed for use in motor racing. These impacts are not within the area of interest of this report.

The study included eighteen cases (60%) with a total of 21 impacts to the facial area, which is outside the protective area in AS/NZS 1698. Nine of these 21 impacts were on the chin bar which is within the protected area in the ECE 22.05 helmet standard. These impacts are within the area of interest of this report.

Of the 18 facial impact cases, nine sustained some neck injury of which only 5 were significant (AIS ≥ 2). Eleven (85%) of the 13 cases without significant neck injury involved significant chest impacts resulting in injury. Of interest is the only case (Case 12) in which a significant neck injury occurred as a result of facial impact only, that is, there were no other impacts to the helmet. This case involved a rider wearing a full-face helmet who dropped his bike before sliding on the road and impacting the kerb with the right side of the chin bar. The rider suffered a transverse bi-temporal hinge fracture of the skull base, with no further head or facial injuries. On examination the cervical vertebrae had rotated such that spinous processes had shifted laterally to the right.

In facial impacts, neck injuries can occur due to shear loading, flexion, extension, rotation, tension and compression, or some combination of these. The resulting injury depends on the location, direction and severity of the impact, as well as the motion of the rest of the body. The head and neck responses to impact are complex due to the ligaments and musculature controlling the articulations. Where a simultaneous impact to the head and chest occurs this may reduce neck loads by reducing the articulation.

The complexity of the load on the neck due to a head impact was demonstrated by Ono et al. (2001), who analysed head and neck responses using human volunteers subjected to low-level impacts loads applied to the face via a strap. The peak loads applied were approximately 150 N with duration of 50 ms. The researchers found that when a vertical load was applied to the chin, the resulting loads at the OC were combined extension, tension and anterior-posterior shear. When the rearward load was applied to the chin, the resulting loads at the OC were combined flexion, tension and anterior-posterior shear. Finally, when a rearward load was applied to the forehead, the resulting loads at the OC were combined flexion, compression and posterior-anterior shear.

Eleven cases in the study involved only impacts to the facial region of the helmet. Of these, 10 resulted in significant brain injury (AIS ≥ 3).

The review of the crash-involved helmets clearly demonstrates that the protective area offered by the motorcycle helmets in Australia needs to be increased to cover the facial area. It is also clear that the protection offered in this area needs to be capable of providing the similar levels of protection as the rest of the protective area of the helmet.

The European chin bar tests were reproduced using a 50th-percentile male anthropometric dummy headform (from a THOR dummy) rather than the rigid metal ISO headform. The THOR headform has a softer chin (more human-like) than the ISO headform, which may have lead to a lower peak acceleration being measured in the test. The helmeted headform was dropped in free-fall onto a rigid steel plate such that the chin bar impacted at 5.5 m/s. The peak resultant accelerations measured at the headform centre of gravity averaged 57.5G, with an average HIC of 153. It was not possible to obtain photographs of the deflection during these tests, however based on the test accelerations, the deflection of the chin bar was about 50 mm with the headform in place.

Although the sample helmets do not claim to meet the requirements of either Snell M2005 or ECE 22.05, the chin bars, when tested, appeared to be able meet the requirements of both helmet standards.

5.3 Discussion

The two chin bar test methods described extend the protective coverage of the motorcycle helmet to the facial region as recommended by Dowdell et al. (1988). These two methods have significant differences in their demands on helmet design and do not directly address the issue of BSF. For this reason it is worth discussing the differences and similarities found between the two test methods.

The Snell test method limits the movement of the chin bar towards the face to less than 60 mm. The aim of the standard is therefore to set a minimum allowable stiffness for the chin bar. It does not attempt to address the complication of the chin bar hitting the chin during the test impact.

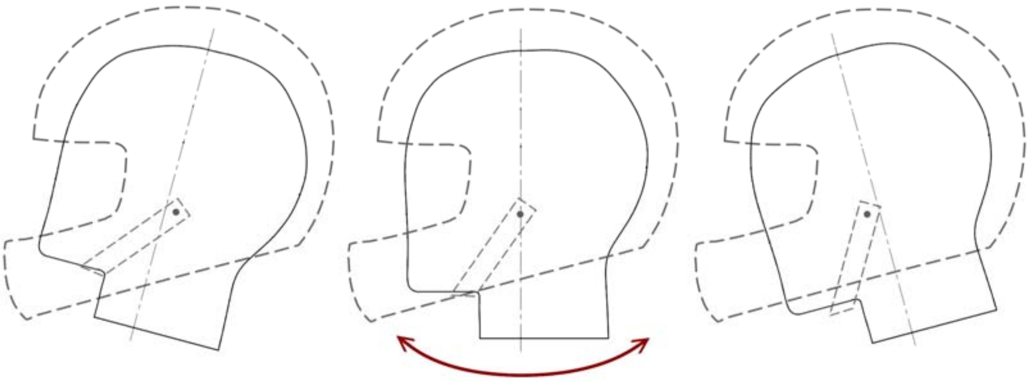
The European test extends the protective area of the helmet to include the chin bar, but at a lower drop energy requirement than the rest of the helmet. The chin bar test requires a velocity of 5.5 m/s while the remaining protective area of the helmet is tested at 7.5 m/s. The same 275 G test limit for the resultant acceleration at the headform centre of gravity is used. This test is aimed at preventing brain injury, similar to the rest of the helmet protective area.

These full-face helmets had 35 to 45 mm clearance between the chin of the wearer and the chin bar in the wearing position. 10 mm of this clearance was taken up by the soft closed-cell foam padding material.

Both the Snell and European standards include positional stability (roll-off) tests to limit the rotation allowed during impact. In the Snell test, a 2.4 J shock load is applied to the rear edge of the helmet so that it rotates forward on the headform. The helmet is allowed to shift but must remain on the headform. In the European test, a 5 J shock load is applied and a maximum of 30 degrees of rotation of the helmet on the headform is allowed. Similarly, in the Australian standard (AS/NZS 1698:2006) a shock load of 3 J is applied and a maximum of 30 degrees of rotation of the helmet on the headform is allowed.

The simple single pivot retention system, typically fitted to a motorcycle helmet, permits a significant amount of rotation between the head and helmet (Figure 11). With a firmly tensioned retention, it was possible to rotate the sample helmet forward on the head until the padding just touched the chin or backward to a stand off of about 75 mm. The results of the ECE 22.05 testing were analysed to reveal some forward rotation of the headform within the helmet during impact.

Figure 11 Sketch showing the rotation of the headform within the helmet with typical retention strap geometry and tension.



In the Snell M2005 chin bar test, the absence of a headform in the helmet allows it to bow significantly in the lateral direction (see Figure 10). Hence the measured stiffness of the chin bar is not necessarily related to its stiffness when on the head of the wearer. Bowing of the helmet will be resisted by mounting the helmet on a headform with a fastened chin strap as in the ECE 22.05 regulation.

The ultimate deflection of the chin bar of the helmet during an impact in reality is limited by the chin of the wearer, which will become involved in the impact, as a result of the rotation of the helmet on the head. The amount of rotation depends on the shape of the wearers head, the geometry of the retention system and helmet liner, the tension of the retention system adjustment, and the position of the chin within the helmet. There is no headform or retention system involved in the Snell test.

While the Snell test does not assess the padding in the chin bar area of a helmet, the European test does. The ECE 22.05 test includes an ISO headform retained in place by the retention system but the chin on the ISO headform is rigid metal. As has been shown by Hopper et al. (1994), see Chapter 21, the magnitude and direction of the load placed on the mandible during a crash is a critical factor in the BSF injury mechanism.

6 DISCUSSION

Helmets provide protection from all types and locations of head injury suffered by motorcyclists (Richter et al. 2001; Sarkar et al. 1995). In general, current motorcycle helmets are effective in reducing head injury in crashes. Anderson and Kraus (1996) demonstrated that helmets were 50% effective in reducing fatal head injury. Studies have refuted claims that helmets are associated with increased neck injury in motorcyclists (Richter et al. 2001; Sarkar et al. 1995; Johnson et al. 1995; Thom & Hurt 1993). With regard to cervical spinal cord injury, researchers have not been able to show any measurable benefits nor harm in using full-face helmets rather than open-face helmets, (O'Connor et al. 2002). There is no evidence to show that a typical helmet chin bar increases the incidence of neck injury in a crash, either due to the increased offset in the region of the chin or to an increase in stiffness in the facial region.

The current design of motorcycle helmets has been found to provide some protection from craniofacial injury suffered in motorcycle crashes (Johnson et al. 1995). In field crash data, only 40% of the head impacts have been found to fall within the test area of the helmet standards. The review of the series of 30 fatal SA motorcycle accidents in this report showed that a majority of the serious head impacts were to the face and chin. This is supported by other accident studies (Richter et al. 2001; Dowdell et al. 1988). Indeed, Cooter and David (1990) hypothesise that the resulting high levels of facial fractures in motorcyclists may be protecting the head and neck in facial impacts. To tackle this problem, Dowdell et al. (1988) recommended that specifications be developed for a test aimed at reducing the effect of frontal impacts to the face by improving the energy absorption of helmets in this area. A recommendation supported by the work of Chang et al. (2000), who investigated the protective performance of chin bars against facial impacts using simulation. The researchers found that the energy-absorbing capability of the chin bar liner was critical in protecting the user against facial injuries as a result of facial impact.

A common characteristic of all the studies reported here is that they were based on a motorcycle population where the majority of helmet users were wearing full-face helmets. Some researchers have found that in specific circumstances, full-face helmets may promote injuries. Reported helmet-associated injuries include disruption of the head and neck junction where no signs of impact against the head could be detected (Krantz 1985). Further, BSF due to inertia loading of the skull base by the head and helmet was reported by Konrad et al. (1996). In both of these injury types, the mass of the involved helmet appears to have significance. The evidence from the field data suggests that current full-face helmets do not increase neck injury related to head impacts in motorcycle crashes.

When the crash factors are combined with available biomechanical data regarding BSF injury mechanisms and fracture tolerance of the head and neck, it is possible to derive requirements for extra protection to be supplied by a helmet. The aim should be to increase the protective area of the helmet to cover the face region.

Testing of a typical full-face helmet model available in the Australian market demonstrated that the measured stiffness of the chin bar (80 N/mm) was of the same magnitude as measured for the facial bones (80-230 N/mm, Allsop et al. 1988), but significantly less stiff than the mandible (721 N/mm, Hooper et al. 1994). The stiffness and fracture tolerance of the mandible makes it the most capable region of the face to withstand impact forces, especially when clenched.

The ECE 22.05 chin bar test requirement equates to a minimum allowable deformation of about 20 mm for the chin bar test. The force on the chin bar can be calculated from the equation:

$$\text{Chin bar force (N)} = \text{Drop mass}_{\text{helmet + headform}}\text{(kg)} \times \text{Acceleration}_{\text{measured}}\,(m/s^2)$$

In the testing performed for this report, the helmet mass was 1.6 kg and mass of the headform was 4.9 kg.

The maximum allowable force on the chin bar in ECE 22.05, for a headform acceleration of 275 G, is hence 17.5 kN. In our testing, the force on the chin bar from the measured headform resultant acceleration of 57.5 G was about 3.7 kN. By comparison, for injury to be unlikely, the maximum level of shear loading to the neck of a 50th-percentile male was suggested as 3.1 kN (Mertz et al. 2003) (see Section 3.3 of this Report). There appears to be a significant mismatch between the test requirement for the chin bar in the ECE 22.05 regulation and the likelihood of injury to the face and neck.

It is evident that there is scope for optimisation of the stiffness of the chin bar for improved protection to the facial region and neck, or at least to define the correct test requirements to minimise injury. Optimisation of the chin bar requires the control of helmet-related responses to impact on the chin bar. The first step is to control the stiffness of the chin bar, to ensure that it absorbs the maximum amount of impact energy possible without transmitting excessive shear force to the neck. If we can control the shear forces in the neck in this way at the beginning of the impact event, then the neck moments will also be reduced later in the event. The second step is to ensure the inclusion of effective padding material that will come into play when the deformation space between the chin and the chin bar is taken up. The available biomechanical data appears to be sufficient to allow better definition of these helmet stiffness and impact response requirements.

When assessed with these requirements in mind, the most relevant helmet chin bar test engages the format applied in the ECE 22.05 helmet standard. This requirement in effect extends the helmet coverage to the facial region, as recommended by Dowdell et al. (1988) and Chang et al. (2000). The protection offered is currently at a lesser level than for the remaining protective area on the skull vault, and the test requirement is defined in terms of likelihood of brain injury, which is not appropriate. Further work is required to select the optimum stiffness for the chin bar and the chin bar padding to maximise the protection to the face and base of skull, whilst avoiding potential neck injury.

Several lines of further research offer themselves as approaches to refining the requirements for testing of helmet chin bars to reduce the incidence of BSF and other face and neck injury in motorcycle crashes.

Assessment of Current Helmet Chin Bar Characteristics

A sample of current full-face helmets should be tested to the Snell and ECE 22.05 test criteria to ensure the helmet characteristics assumed in this report, based on a single sample, are typical of the helmets on the market.

Investigation of Helmet Chin Bar Characteristics and Injury

An extension of this project would be to undertake biomechanical testing of a range of current full-face motorcycle helmets. This testing would be aimed at understanding the characteristics of the available helmets during crashes in terms of our current biomechanical knowledge of human tolerance. The testing would not be based on the currently available test methodologies, from Snell and ECE 22.05, but would be aimed at assessing the trade off between chin bar stiffness and injury due to impacts to the facial region, based on field accident data. This is now possible due to developments in current automotive crash test dummies, for example the THOR (Haffner et al. 2001) or MATD (Van Auken et al. 2003) dummies could be used. Such dummies have an adequate level of biofidelity in the response of the head and neck to impact. Instrumentation to measure neck loads, facial loads and head accelerations can be used as a basis for assessing the likelihood of injury.

With the use of a THOR dummy as the test subject, it would be possible to explore the optimisation of the chin bar stiffness and energy absorption to minimise head and neck injury. The test impacts could be designed to related categories of crashes as suggested in the International Standard ISO 13232. Based on the data generated in testing, the adequacy of the available testing regimes for use in the standard could be assessed and refined as necessary.

Verification of Helmet Chin Bar Characteristics and Injury by Simulation

To extend the use of testing outlined above, it would be of benefit to use the injury risk/benefit methodology developed by Van Auken et al. 2003, which is again based on ISO 13232. In this methodology a validated dummy model would be used to simulate a matrix of motorcycle crash types with known injuries. This matrix has been based on representative motorcycle crash data (n=501) from Los Angeles and Hannover, with a further series of fatal motorcycle vs car accident cases (n=67) from the University of Southern California (USC). The motorcycle and helmeted rider simulation is based on the MATD riding a GPZ 500 motorcycle and has previously been validated by crash testing. This technique has sufficient accuracy to use in conjunction with the test program above to explore the characteristics of the helmet chin bar and the causation of injury.

7 CONCLUSIONS

In summary the following points need to be regarded when considering the requirements for testing of helmet chin bars:

- The aim of testing is to extend the protective coverage of the helmet to protect the wearer from facial injuries and fractures, which in severe impacts may lead to BSF.
- BSF is due to severe impacts to any region of the head. This study has only assessed the possibilities of further protection in the facial region.
- There are two types of injury to the wearer to be considered in the protective requirements for impacts to the face – brain injury and localised fracture of the face and skull.
- For realistic assessment of the chin bar stiffness, a headform must be included in the test, with a firmly fastened retention system.
- The current ECE 22.05 chin bar test criterion is focussed on brain injury and not facial fracture or neck injury, and needs to be revised.
- The current Snell chin bar test has little association with impact loading conditions and the wearer's head.
- The chin bar must not be so stiff that it leads to neck shear injuries. Indications are that current chin bar test method requirements are not appropriate for ensuring that the chin bar has a characteristics suitable for controlling neck injury risk in facial impacts.
- Energy-absorbing padding should be present to attenuate the residual impact energy when the available chin bar deflection space has been exhausted.
- The use of a chin bar is appropriate as the mandible is the stiffest and strongest region of the face.

Further investigation of the interaction of the chin bar and injury in motorcycle crashes is necessary. The first step would be to test a selection of helmets to ECE 22.05 and Snell chin bar test requirements. A more complex test program, using a biofidelic test dummy, could then be used to allow assessment of the optimum performance of the chin bar. The benefits of the new chin bar in the field could be assessed by means of the simulation based methodology developed by van Auken et al. (2005).

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APPENDIX I - MOTORCYCLE ACCIDENT CASE STUDIES

Available on request on CD-ROM.