# Safety of children as motorcycle passengers

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# 1. INTRODUCTION

This report reviews information on motorized two-wheeler (MTW) crashes in general and injuries sustained by MTW children passengers in particular. This has been done to prepare a state-of-the-art report on the biomechanics of head impact injuries and safety of children transported on motorcycle with special reference to the South-East Asia Region. This effort is a part of the following work undertaken by the author of this report:

- To review existing theories, documents and evidence on injury biomechanics and road safety addressing motorcycle injuries sustained by children transported by motorcycle with special reference to the South-East Asia Region.

- To draft recommendations for child transport safety focusing on motorcycle use by children in the South-East Asia Region.

# 2. METHODODLGY

1. The road traffic safety situation in the SEA Region was reviewed to understand the gravity of public health burden of road traffic injuries (RTI) in the region.

2. Significant scientific papers dealing with motorcycle crashes published worldwide were scanned to get an overall view of children's involvement in motorcycle crashes. Children were defined as those below 14years old with special reference to the age group 5-9 years. A list of the papers scanned is given in Appendix 1.

3. Those papers dealing specifically with motorcycle associated RTI involving children were reviewed in detail to assess the magnitude of the problem, trends and associated issues.

4. Scientific reports and publications dealing with biomechanics of paediatric injury with special reference to head injuries and helmet design were reviewed to understand the present situation and possibilities for implementing countermeasures in the future.

# 3. ROAD TRAFFIC INJURY SITUATION IN SEARO

## INTRODUCTION

Injuries account for an estimated 1.4 million deaths and 54 million disability-adjusted life-years (DALYs) in South-East Asia. This Region alone accounts for 27 per cent of the global mortality and 31 per cent of the global burden of injuries. The proportion of road traffic deaths in the SEA Region are shown in Figure 1.



Total no. of deaths = 1 260 000
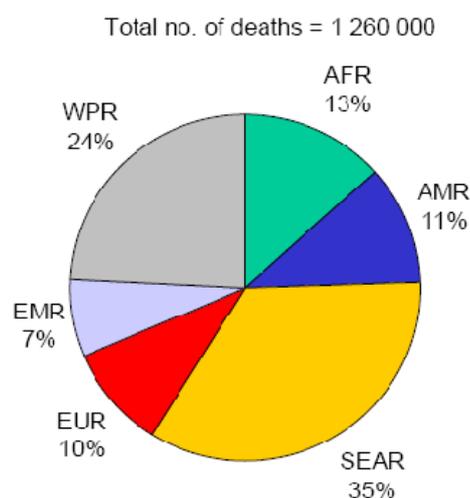
**Figure 1. Regional Distribution of global RTI mortality, 2000.**

Estimated number of Deaths and Disability Adjusted Life Years (DALYs) due to injuries, South-East Asia Region are shown in Table 1 (1). Of the 5.1 million deaths from injuries globally, more than a quarter estimated to occur in the countries of the SEA Region (2). In fact, road traffic injuries alone were ranked as the primary cause of disease among children in the age group of 5 to 14 years, and the third leading cause among people between the age of 15 to 29 years in 2000. Injuries are a leading cause of death in the working age group and in India the years of life lost (million) due to injury for individuals older than 4 years, is greater than that for neoplasms, cardiovascular causes and infectious and parasitic diseases (Figure 2)[1]. It is an irony that thousands of children saved from nutritional and infectious diseases were killed or maimed by injuries. Over a period, such a heavy burden can have a major impact on the quality of life and economy of nations. Injuries can occur everywhere, on the road, at home, at work, at public places or during recreational and leisure time activities.

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[1] Estimate based on statistics on medical certification of cause of death. Source: Health Information of India 1997 &1998. 1-344. 2000. New Delhi, Central Bureau of Health Intelligence, Directorate General of Health Services, Ministry of Health & Family Welfare.

| Injury category | No. of Deaths | No of DALYs |
|---|---|---|
| Road traffic injuries | 435 000 | 14 033 000 |
| Poisoning | 82 000 | 2 399 000 |
| Falls | 39 000 | 5 085 000 |
| Fires | 128 000 | 5 630 000 |
| Drowning | 97 000 | 2 752 000 |
| Others | 274 000 | 14 780 000 |
| **Unintentional** | **1055 000** | **44 680 000** |
| Homicides | 77 000 | 2 241 000 |
| Suicides | 169 000 | 4 905 000 |
| War | 63 000 | 2 210 000 |
| **Intentional** | **317 000** | **9 557 000** |
| **Total** | **1 372 000** | **54 236 000** |

**Table 1. Estimated number of Deaths and Disability Adjusted Life Years (DALYs) due to injuries, South-East Asia Region, 2000 Estimates.**

Road traffic injuries and deaths have emerged as serious causes for concern in most countries of the South-East Asia Region. In the last three decades, the incidence of traffic crash fatalities and injuries has been reduced significantly in the high-income countries but not in this Region. The global burden of disease due to road traffic injuries is expected to move from the ninth position in 1990 to the third position in 2020 (3). Road traffic injuries are among the second to the sixth leading causes of death in the age groups 15 - 60 years. Recent estimates of national economic loss due to road traffic injuries show that these range from 1 - 2 per cent of the GDP of nations around the world (4).
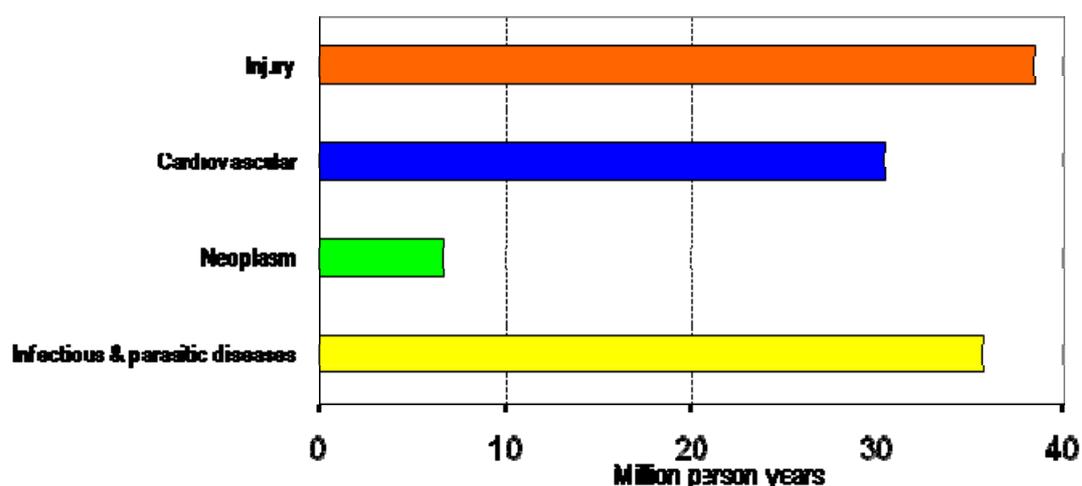


**Figure 2.   Million  years of working life lost for persons age > 4 years in India.**

In countries of the SEA Region, most victims of road traffic crashes face some special problems. These include (5):

- Reallocation of labour of family members and reduced productivity of the whole family;
- Permanent loss of job for the victim even if he/she survives;
- Loss of land, personal savings, household goods;
- Poor health and educational attainment of surviving members.

Such losses have an adverse impact on the well being of our societies. However, none of the above issues is taken into consideration in the standard economic calculations done for estimating the cost of road crashes in poor societies. Research has revealed that in the countries of the SEA Region, the vulnerable road users, including pedestrians, bicyclists and motorized two-wheeler riders, sustain a vast majority of fatalities and injuries due to road traffic crashes (6). Unless we ensure the safety of these vulnerable road users, we will not be able to make any significant reduction in the health burden of road traffic injuries. Therefore, exposure control, intelligent separation of non-motorized traffic on major roads, safer vehicle designs, speed control and use of helmets by two wheelers are likely to play a much more important role.
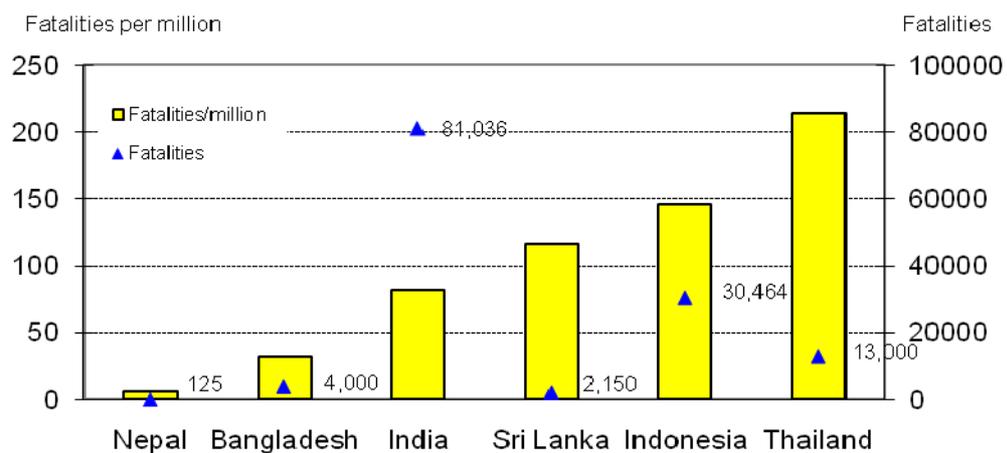


**Figure 3. Road traffic fatalities in selected SEAR countries (2001-2004).**

Figure 3 gives the fatality rates in selected SEAR countries. The details of distribution by road user category are not available for any country. A literature search of published articles done by Hyder et al (7) on road traffic injuries among children and adolescents in urban South Asia, found that age distributions of victims by road user type are not available. They report that that the majority of injuries occurred in males (67–80%) and the most frequent age group injured was between ages 0 and 9 representing 40% of cases. Among those injured a majority were pedestrians. Salient features for road traffic crashes are given below for some of the countries represented in SEARO based on national reports available.

## COUNTRY STUDIES

### Bangladesh

Motorized two wheelers occupy the largest share of the vehicle population in Bangladesh (41%), followed by cars/jeeps 24%) and auto rickshaws (14%). This indicates that MTW riders would form a significant proportion of the fatalities. Table 2 gives the age distribution of road traffic fatalities in Bangladesh.

| Age, years | 0 - 5 | 6 - 10 | 11 - 15 | 16-45 | >45 |
|---|---|---|---|---|---|
| Proportion, percent | 4 | 10 | 6 | 59 | 20 |

**Table 2. Age distribution of road traffic crash victims in Bangladesh (Source: Key road safety facts in Bangladesh, 2004)**

A road accident costing study estimated the casualties by road user type in Bangladesh and the results are shown in Table 3 (8). These data show that motorcycle occupants constituted only 3 percent of the fatalities and 10% of the serious injuries. The age specific data shows that children 0-10 years were only 14% of the road crash victims and majority of these were pedestrians.

| | Death | Serious | Slight |
|---|---|---|---|
| Pedestrian | 41% | 24% | 24% |
| Bicycle | 4% | 6% | 13% |
| Rickshaw/pushcart | 7% | 23% | 31% |
| Motorcycle | 3% | 10% | 9% |
| Babytaxi/scooter | 8% | 13% | 10% |
| Car | 3% | 2% | 2% |
| Taxi | 2% | 1% | 1% |
| Minibus/bus | 23% | 15% | 9% |
| Truck/lorry | 6% | 3% | 0% |
| Others | 2% | 3% | 0% |

**Table 3. Distribution of road traffic injury victims in Bangladesh**

If we combine these two statistics, it is possible that children under 10 years may be between less than 2% of the total road crash victims in Bangladesh

## India

| Year | Fatalities | Population, million | Fatalities/million persons |
|------|-----------|---------------------|----------------------------|
| **1997** | 77,000 | 955 | 81 |
| **2007** | 114,590 | 1,136 | 101 |

**Table 4. Road traffic fatalities in India (Source: National Crime Records Bureau, Delhi).**

Table 4 shows the road traffic fatalities in India in 1997 and 2007. Official road traffic crash data do not include fatalities by road user category in India. Such data are only available from a few cities and research studies done on selected locations on rural highways. Table 5 shows traffic fatalities by category of road users in Delhi (capital city of India) and selected locations on national highways (9;10). These data show that car occupants were a small proportion of the total fatalities, 3 percent in Delhi and 15 percent on rural highways.

| Type of road user | Location (percent) | |
|-------------------|---------------------|-------------------|
| | Delhi 2001-2005 | Highways* 1999 |
| Truck | 2 | 14 |
| Bus | 5 | 3 |
| Car | 3 | 15 |
| Three-wheeled scooter taxi | 3 | - |
| Motorized two-wheeler | 21 | 24 |
| Human and animal powered vehicle | 3 | 1 |
| Bicycle | 10 | 11 |
| Pedestrian | 53 | 32 |
| *Total* | *100* | *100* |

*The data are for 11 selected locations, and thus might not be representative for the entire country.  (Tractor fatalities are not included).*

**Table 5.  Traffic fatalities by category of road user in Delhi and selected locations on national highways (Reference 9,10).**

Vulnerable road users (pedestrians, bicyclists, and motorized two-wheeler riders) accounted for 84 percent deaths in Delhi and 67 percent on highways. This pattern is very different from that obtained in all high-income countries. The low proportion of car occupants can be explained by the low level of car
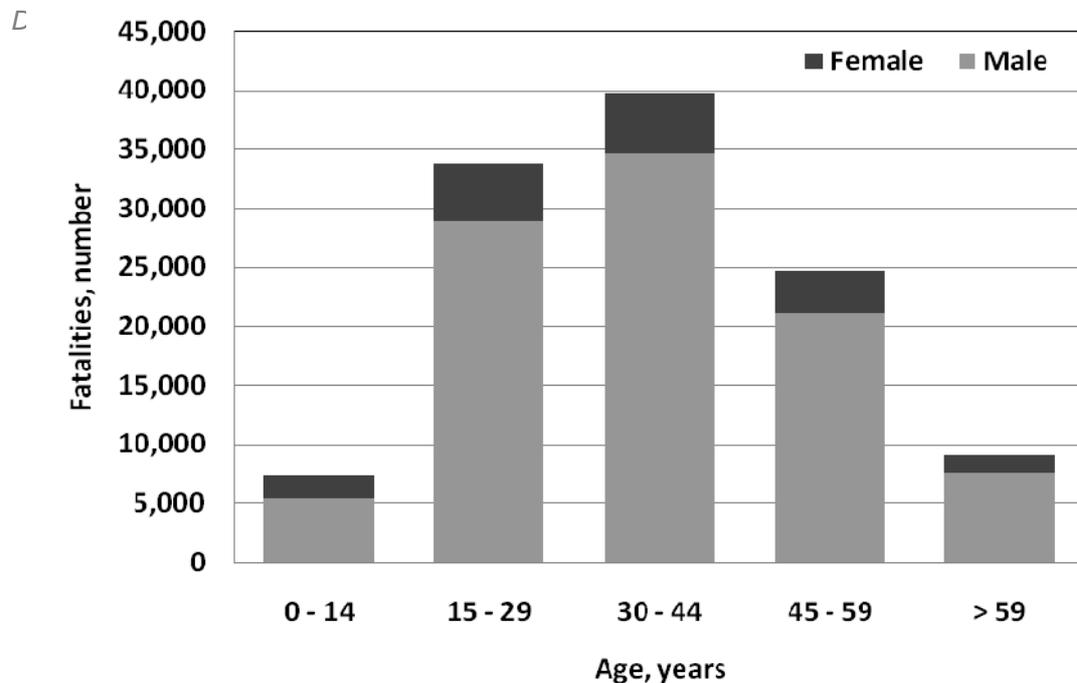
**Figure 4. Traffic fatalities by age and sex, India 2007 (Source: National Crime Records Bureau, Delhi).**

ownership at 7 per 100 persons as compared to more than 50 per 100 persons in most high income countries.

Figure 4 shows the distribution of road traffic fatalities in 2007 by age groups and sex of victims (11). Only 15 percent of the victims were females in 2007. Children age 14 years and younger comprise only 6% of the fatalities, though their share in the population is 32%.

One way of estimating the proportion of children involved in MTW traffic is to estimate their presence in medical treatment in hospitals. A review of the medical records of 2,748 patients treated for maxillofacial injuries at Sri Ramachandra Medical and Dental College and Hospital in Chennai between January 1999 and December 2005 showed that 1,332 (42%) had soft tissue injuries, 1,176 (37%) had mid face fractures, and 512 (16%) had mandibular fractures. Of these patients, MTW riders comprised 62%, and children (0-10 years) only 3% of the total respectively (12). Since MTW fatalities comprise about 20-25% of the total it is likely that children under 14 constitute less than 2-3% of MTW rider fatalities in India as pedestrian fatalities form the major bulk of the total. This is supported by a study from Delhi in which 3% of the MTW victims hospitalized were in the 0-14 age group (13).

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**Indonesia**

| Vehicle Type | Year 2001 | | Year 2002 | |
|---|---|---|---|---|
| | Number of Accidents | Percentage | Number of Accidents | Percentage |
| Passenger Car | 3,261,807 | 15.38 | 3,868,579 | 15.71 |
| Truck | 1,759,747 | 8.30 | 2,015,347 | 8.18 |
| Bus | 687,570 | 3.24 | 731,990 | 2.97 |
| Motorcycle | 15,492,148 | 73.07 | 18,016,414 | 73.14 |
| Total | 21,201,272 | 100.00 | 24,632,330 | 100.00 |

Source:  Indonesian National Police, 2003.

**Table 6. Road traffic accidents by vehicle type in Indonesia.**

Table 6 shows that MTW constitute a vast majority of road traffic crashes in Indonesia and Table 6 the age distribution of fatalities (14). The proportion of children involved is about 3% and their number below 10 years would be less than 2% (Table 7). However, the proportion of reported motorcycle RTI in Indonesia is much higher than that in India or Bangladesh.

| Age | Death | % |
|---|---|---|
| 5-15 | 955 | 3.13 |
| 16-20 | 7928 | 26.02 |
| 21-30 | 10185 | 33.43 |
| 31-40 | 7008 | 23.00 |
| 41-50 | 3307 | 10.86 |
| 51-60 | 1082 | 3.55 |

**Table 7. Age distribution of road fatalities in Indonesia (Source:  The cost of traffic accidents in Indonesia, 2004).**

## Sri Lanka
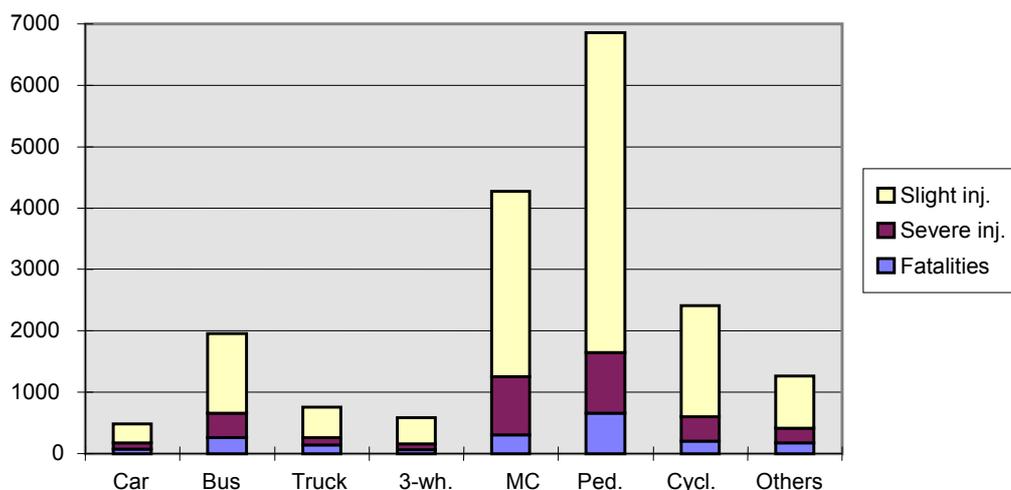


**Figure 5. Road casualties in Sri Lanka in 1994.**

Figure 5 shows that MTW involvement in fatal crashes in Sri Lanka was less than that of pedestrians (15), but more than cars, and Table 8 shows that children comprised 9% of the fatalities.

| Age | Death % |
|---|---|
| <10 | 9 |
| 10-20 | 6.5 |
| 20-30 | 6.2 |
| 30-40 | 10 |
| 40-50 | 11 |
| 50-60 | 10.8 |
| >60 | 17.2 |

**Table 8. Age distribution of road traffic fatalities in Sri Lanka.**

**Thailand**

| Year | Number of fatalities | Population | No.of vehicles | Death rates /$10^5$ pop |
|------|------|------|------|------|
| 1984 | 2908 | 50583105 | - | 5.75 |
| 2003 | 14446 | 63079765 | 26706357 | 22.96 |

*Source: Thailand Road Safety Action Plan,2004*

**Table 9. Road traffic fatalities in Thailand.**

Table 9 shows the statistics of road traffic fatalities in Thailand. Head injuries are a major cause of death and disability related to RTI, and 70-75% of traffic crashes in Thailand involve motorcycles (16).

According to Phuenpathom et al. most patients were aged between 11 and 40. A study based on data derived from a trauma registry at the Khon Kaen Regional Hospital in the northeast Thailand showed that children 0-9 comprised 1.8 to 3.9 % of the MTW patients treated at the hospital (17). This proportion is similar to the total RTI fatalities for this age group as shown in Table 9 (18).

| Age (yrs) | Fatalities percent |
|------|------|
| <5 | 1.6 |
| 5-9 | 1.8 |
| 10-14 | 2.7 |
| 15-40 | 60.4 |
| >40 | 33.5 |

**Table 10. Age distribution of traffic fatalities in Thailand.**

**SUMMARY**

In the SEARO region road traffic injuries of MTW riders comprise a reported 25% to 70% of the total victims. Of these victims, children less than 10 years appear to be 2-3% of the MTW victims.

# 4. EVIDENCE ON CHILDREN AND MTW INJURIES IN COUNTRIES OTHER THAN SEARO

## ASIA AND AFRICA

- A study of 1160 cases of MTW riders suffering craniofacial injuries taking treatment in 12 hospitals in Taipei showed that children 0-15 years old comprised 2% of the total victims (19).

- A study on the effect of the Taiwan motorcycle helmet use law on head injuries showed that the proportion of children 0-9 years involved in MTW crashes remained relatively unchanged at 1.0-1.2% of the total and that there were higher rates of head injuries among those aged 20 to 29 years and 70 years and older than among those in the rest of the population (20).

- Helmets reduce the probability of death in a crash by 40%, the percentage of fatalities accounted for by motorcycle deaths remain as high as 55% (21).

- A study of 314 cases of mandibular fractures in two urban centres in Nigeria showed that RTI were the leading cause (67.5%) and the commonest site of fracture was the body of the mandible. The age group 0-10 comprised 1.6% of the patients (22).

- The commonest mechanisms of paediatric injuries in Jos in Nigeria were RTI (41%). Of those injuries resulting from RTI, 87% were pedestrian related. Even though children ride as passengers on MTWs, their proportion was low (23).

## AUSTRALIA, EUROPE AND USA

- A comprehensive prospective injury registration was carried out at the Central Hospital and Emergency Clinic in Rogaland county in Norway 1990 to 1996 among a defined population aged 0–24 years and incidence of traffic injury by the type of transport of the victim was analysed. Moped injuries represented 9% of all (hospitalized and non-hospitalized) traffic related injuries and brain concussion was suffered by 8% of the population. Children under 10 years were a small proportion of the population (24).

- A study of severe paediatric motorbike-related injuries in Ohio showed that unhelmeted riders had significantly higher injury severity scores than helmeted ones (11.5 vs 8.4). Of all injuries, the most commonly injured body parts were lower extremity (23.4%),head (22.2%), abdomen/pelvis (13.4%), upper extremity(12.4%), and face (11.8%). The 0-9 year age group comprised only 19% of the 0-25 sample (25).

- A study of the incidence and risk factors of severe traumatic brain injury resulting from road accidents in the Rhone region of France showed that children 0-14 had an incidence rate of ~1 per 100,000 persons as compared to 10-15 for the 15-34 year age group. The odds ratio for severe injury was lower for the youngest age group than older persons (26).

- A study of 3163 children aged 16 years and younger with motorcycle-related injuries who attended Victorian (Australia) emergency departments in a 4-year period showed that most were off road riders and those 0-9 year sold were 22% of the total (27).

**SUMMARY**

In all countries, the use of helmets by MTW riders reduces head injury rates substantially. Children do not constitute a significant proportion of motorcycle riders in most countries, but even where they do their involvement in serious injury crashes is generally less than 2-3% of the total victims.

# 5. INJURY BIOMECHANICS AND CHILDREN

**INTRODUCTION**

The knowledge of injury biomechanics is used to assess and reduce injury potential in the design of all kinds of products and environments. These include motor vehicles, aircraft, protective clothing and devices, and risky risk environments like highways, playgrounds, etc. This is done by assessing the human body's capability to withstand external inputs in the form of forces, accelerations, heat, electric currents, chemical reactions, and radiation. The attempt is to understand the physical properties of the human system and the relationship between the magnitude of the external input and the severity of injury sustained. Though human beings have been interested in such relationships for millennia, the actual work of quantifying these phenomenon is relatively recent. Most of what we know today is the result of work done over the past 70-80 years.

The need for such data became critical when motor vehicle safety standards had to be established in the mid twentieth century. The initial standards focussed on adult drivers and so most of the biomechanical collected up to now are for adults. In any case, it is not easy to collect data on children for many reasons including ethical concerns. Consequently we have little concrete information, as adult



**Figure 6. A child is not an adult in miniature. For a new born, the head represents about a quarter of the body, whereas for an adult the proportion is about one-eighth.**

data cannot just be scaled down for application to children. This is because children are not just smaller adults (Figure 6). Not only do children differ from adults substantially in body segment proportions, but so do the material properties of both hard and soft tissues and skeletal structures. Unless we have
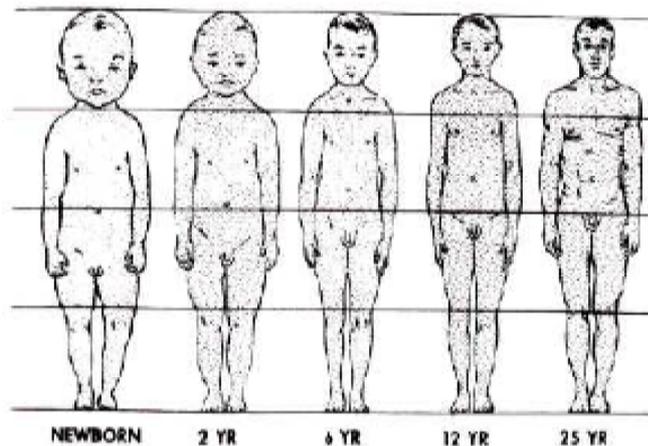
good knowledge of injury producing events from the real world for children and the associated physical inputs, it is impossible to determine reliable injury biomechanics criteria for them.

In this report, we summarise the present state of knowledge for injury biomechanics for adults and its applicability for children with special reference to motorcycle crashes. We focus and head injuries because they are the cause of a majority of disabling and fatal injuries.

## HEAD INJURY BIOMECHANICS

Head injury tolerance issues have concerned scientists and medical professionals for centuries, but quantitative studies have been done only for the past eighty years or so. One  of the first studies documenting the injuries sustained by MTW riders was published by Cairns in 1941 and then another one on the effectiveness of helmets in 1943 (28;29). Cairns and Holburn concluded:

> *"The site of the blow on the helmet and the injury to the underlying scalp and skull correspond. Over 50% of the blows are on the front of the helmet. The least common site of injury is the crown of the helmet. Blows on the occipital region are least dangerous and those on the temporal region most dangerous to life. Blows on the crown may be associated with crush fractures of the vertebrae.*
> *In 40% of the cases the head receives more than one blow. In motor-cyclists it is very rare that brain injury results from a blow limited to the face. The crash helmet is effective in diminishing local damage to the brain and its coverings at the site of impact, and it tends to lower the incidence of cases of prolonged amnesia.*
> *Though our figures are rather small they suggest: (a) that the incidence of fractures of the skull is quartered by the better (pulp) type of helmet: the severity of those that do occur is less; (b) the incidence of prolonged amnesia (one day or more) is only one-third of that in accidents in which no crash helmet is worn; (c) in non-lethal accidents the pulp crash helmet so alleviates the injury that one-half of the dispatch riders who without its protection would have to go to hospital do not need to do so.*
> *Of the two types of crash helmet in common use the pulp helmet is superior to the vulcanized rubber helmet. Further improvements in the design of helmets offer a profitable field of preventive medicine."*

Almost all of these observations made 66 years ago are still valid. Since then, a great deal of work has been done to understand the mechanisms of head injury mainly with the objective of setting evidence based head injury criteria for

motor vehicle and helmet impact standards.  A large number of studies determining human tolerance to impact has focused on the frontal bone because frontal crashes received principal attention during the early years of biomechanical research; the currently adopted worldwide standards to assess head injury use biomechanical criteria based on frontal impacts to human cadavers (30). Loading to the lateral region of the head, in contrast to the frontal bone, has been investigated less frequently in laboratory research and promulgated to a lesser extent from standards perspectives. Helmet standards use peak acceleration at the centre of gravity of a dummy head as the measure of head injury. Frontal impacts use a criterion derived from the integration of the resultant linear accelerations at the centre of gravity of the head as a measure of injury. The applicability of these indices to temporo-parietal impacts is not proven (30).

Biomechanical tolerance data are collected in four different ways: analyses of real-world events (e.g., athletic, fall, and motor vehicle), human volunteer experiments, animal tests and human cadaver studies, and mathematical simulations. Real-world events provide information on the injury and characteristics of the impact event, but do not give us accurate information on forces, accelerations, etc. Human volunteer experiments, though very useful, provide information on situations which are pre-injury. Animal tests provide physiological and injury data although scaling laws are necessary to translate to the in vivo human. Precise scaling laws do not exist. However, these experiments have also helped us to understand relationships between in-vivo and cadaver experiments. Mathematical simulations are now used to perform parametric studies and to understand effects of changes in design of helmets. However, the validation of these results must be based on experiments. Head injury criteria were developed largely based on studies conducted between 1960 and 1980. A summary of the head injury criteria as they exist is given below based on an excellent review by Yoganandan and Pintar (2004).

Several mechanical parameters are used for head injury determination: peak forces, peak acceleration, Gadd severity index, and head injury criterion. exist for head injury quantification. However, none of them give a unique, complete or sufficient understanding of all impact situations and resulting head injury severity. Figure 7 shows how sufficient overlap exists in the



**Figure 7. Side (red) and frontal (blue) impact tolerance data from various experiments. Each bar represents the range in the experimental data for the side and frontal bones of the human head (Source: Yoaganadan & Pintar 2004).**

values between side and frontal impacts. In addition, ranges in the force data demonstrate overlap for various contact areas and cadaver preparations. SAE has specified tolerance data as function of contact area for the human head derived from literature (31). The SAE corridors for fracture thresholds of the human head to flat impact surfaces as a function of contact area are shown in Figure 8. These corridors are a first step in the understanding human tolerance. However, though force values are very useful in understanding mechanisms of mechanical failure, they have not been found adequate for setting head and brain injury tolerance standards. Acceleration values, absolute and weighted, have been found easier to use and to roughly represent the severity of head injury sustained and for use in standards.
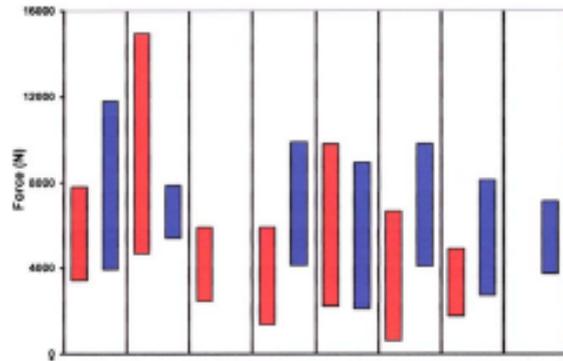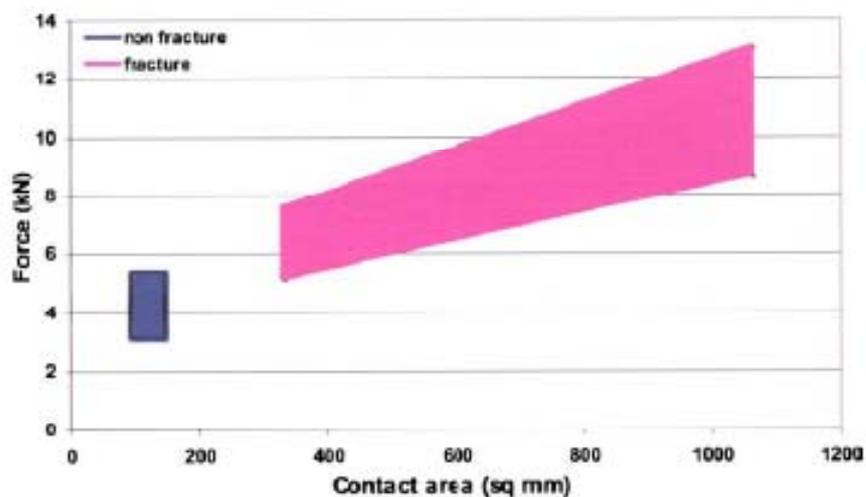


**Figure 8. Head impact response to flat rigid surface (SAE J1460). Peak forces for non-fracture are shown in blue and for fracture are shown in magenta colour (Source: Yoaganadan & Pintar 2004).**

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**Summary – head injury criteria**

Over the years, researchers have suggested many criteria for explaining the relationship between input variables and resulting severity of head injury. These include maximum strains, stresses, accelerations and weighted integrals of resultant head acceleration. However, for setting head impact injury criteria, the most common indices used are maximum head accelerations for helmet standards and weighted integrals of acceleration for vehicle occupant head impact standards.

**HELMET STANDARDS**

For helmet standards peak linear acceleration is used by most agencies and peak linear acceleration associated with dwell times are suggested for motorcycle helmet standards by the US federal government. Bicycle helmet standards use similar criteria. A comparison of four bicycle helmet impact standards is given in Table 11. All the standards use a limit of 300 g acceleration as a pass-fail criteria. The mass of the helmet for children is not changed in two of the four tests. This subject to considerable debate and is discussed in a later section.

Some motorcycle helmet standards also use the Head Injury Criterion (HIC) and Gadd severity index for football helmet standards. The Gadd severity index uses an integral of the resultant acceleration response measured at the centre of gravity of the head :

$$\text{SI (Severity Index)} = \int [\, a(t)\, ]^{2.5}\, dt$$

where a($t$) represents the resultant acceleration in g's at the centre of

| | CPSC | ASTM F1447 | SNELL B-90S | SNELL B-95 |
|---|---|---|---|---|
| Drop height on flat anvil | 2.0 m | 2.0 m | 2.0 m | 2.2 m |
| Adult headform | 5 kg | 5 kg | 5 kg | 5 kg |
| Child headform | 4 kg | 3.2 kg | 5 kg | 5 kg |
| Failure threshold | 300g | 300g | 300g | 300g |

**Table 11. Comparison of bicycle helmet impact standards.**

gravity of the head at time t. Values of 600g-1000g are considered the limits in different standards.

The more common index used in standards is the HIC based on the integral of the resultant acceleration at the centre of gravity of the head, and remains as the most widely used metric impact crashworthiness assessment. The criterion uses time-averaged, weighted acceleration data, and represents the kinetic energy transfer over a selected period:

$$\text{Head Injury Criterion (HIC)} = \text{MAX} \left[ 1/(t_2 - t_1) \int_{t_1}^{t_2} a(t)\, dt \right]^{2.5} (t_2 - t_1)$$

However, for side impacts, the dependence of HIC on the impacting boundary condition is not experimentally evaluated. Many authors have criticized the applicability of HIC in all head impact situations as it does not take into account the influence of rotational accelerations and local forces on the head (32). However, as far as helmet standards are concerned, acceleration based values, HIC or a combination of both are used for setting limits.

The US standard for motorcycle helmets (FMVSS 218) specifies a peak acceleration of 400g and that acceleration in excess of 200g not to exceed 4 ms totally. The United Nations regulation 22 for motorcycle helmets specifies that the resultant acceleration should not exceed 275g and HIC be less than 2400.

Many other criteria have been suggested for head injury biomechanics:
- Applied brain pressure tolerance (ABPT)
- Brain von-Mises shear stress (BMSS)
- Cumulative strain damage measure (CSDM)

None of these measures are likely to be in widespread use in the near future and technical discussion on the same is out of the scope of this report.

**Summary**

Almost all adult motorcycle helmet standards specify a peak resultant acceleration of 275-300 g as the limit with some standards setting additional criteria like the maximum period over which the acceleration can exceed 200 g (usually 3-4 s). Some standards also require that HIC should not exceed 2200-2400.

**CHILDREN'S HELMETS**

**Biomechanics**

The biomechanics of safety for children has been mainly evaluated using child dummies in the field of car crash safety. However, dummies have limited biofidelity and don't offer detailed injury mechanism. A project called CHILD (standing for Child Injury LED Design) was started in Europe to increase the knowledge in areas specifically regarding children, and for application in child restraint systems design, testing and regulation. The CHILD project's objectives were to enable the investigation of injury mechanisms and tolerances for different ages of children and the establishment of injury criteria and corresponding risk curves:

- To determine the physical parameters corresponding to various child injury mechanisms,
- To prescribe limits under which severe injuries can be avoided.
- To develop new test procedures for determining the effectiveness of child restraint systems for cars, using biofidelic dummies fitted with reliable instrumentation.

However, the efforts are still at the research stage and all helmet standards for children are still using HIC and acceleration values based on work done more than a decade ago.

**Recent standards**

Snell Foundation

| Head Form | Circumference | Mass | Crown to Basic Plane | Basic to Reference Plane |
|---|---|---|---|---|
| A | 50 cm | 3.100 kg ± 100 g | 113.5 mm | 24.0 mm |
| C | 52 cm | 3.600 kg ± 100 g | 118.0 mm | 25.0 mm |
| E | 54 cm | 4.100 kg ± 100 g | 122.0 mm | 26.0 mm |
| J | 57 cm | 4.700 kg ± 100 g | 130.0 mm | 27.5 mm |
| M | 60 cm | 5.600 kg ± 100 g | 136.0 mm | 29.0 mm |
| O | 62 cm | 6.100 kg ± 100 g | 140.0 mm | 30.0 mm |

**Table 12. Head form sizes in proposed Snell helmet standard for motor sports.**

The Snell Foundation in association with FIA recently announced a draft standard for children's motorsport helmets. Salient features of this standard are (33):

*a. Headform:*

The smallest two sizes have head forms that are substantially lower in mass than the adult head forms (Table 12).

*b. Helmet mass*: Helmets intended for use by persons ages 6 years through 11 years shall not weigh more than 1100 grams or 1200 grams if configured with face shields . Helmets intended for use by persons ages 12 years through 15 years shall not weigh more than 1250 grams or 1350 grams if configured with face shields.

*c. Impact velocities*: The helmet impact velocities for different age groups are different as shown in Table 13.

| Impact Velocities | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Head Form | | | | | |
| | | ISO A | ISO C | ISO E | ISO J | ISO M | ISO O |
| Certification | 1st all ages | 7.75 m/s | 7.75 m/s | 7.75 m/s | 7.75 m/s | 7.75 m/s | 7.75 m/s |
| | 2nd (12-15 yrs) | 6.59 m/s | 6.27 m/s | 6.18 m/s | 5.90 m/s | 5.40 m/s | 5.29 m/s |
| | 2nd (6-11 yrs) | 4.43 m/s | 4.43 m/s | 4.43 m/s | 4.43 m/s | 4.43 m/s | 4.43 m/s |
| Deviation | 1st all ages | 7.48 m/s | 7.48 m/s | 7.48 m/s | 7.48 m/s | 7.48 m/s | 7.48 m/s |
| | 2nd (12-15 yrs) | 6.44 m/s | 6.13 m/s | 6.04 m/s | 5.77 m/s | 5.28 m/s | 5.17 m/s |
| | 2nd (6-11 yrs) | 4.43 m/s | 4.43 m/s | 4.43 m/s | 4.43 m/s | 4.43 m/s | 4.43 m/s |

**Table 13. Impact velocities for helmets in proposed Snell standard for motorsports helmets.**

*d. Impact Test Interpretation*:

The proposed standard only uses the peak acceleration of the head form and specifies that it shall not exceed 290 g's for any valid certification impact nor 300 g's for any other valid test impact. The helmet's protective structures shall not break apart throughout the testing.

The full text of the proposed standard is given in Appendix 2.

Consumer Product Safety Commission

The U.S. Consumer Product Safety Commission (CPSC) issued a new federal safety standard for bike helmets in 1998 (16 CFR Part 1203).  The standard provided one uniform mandatory safety standard that all bike helmets

must meet. The standard includes two important provisions that will help provide greater protection for bicyclists -- especially children: additional head coverage for children up to age five to protect the child's brain and skull; and chin strap stability to prevent the helmet from coming off in a crash. The standard specified that all recorded impacts shall fall within the range of 380 g to 425 g.

**Recent biomechanics research**

Several recent papers have presented research findings on differences or similarities between adult and children's biomechanical properties.  Thibault et al. (34;35) have provided some data on age dependent properties and suggest that the elastic and viscous components of the complex shear modulus of frontal brain tissue  increased significantly with the development of the cerebral region of the brain. Using an idealized model of the developing head, the age-dependent material properties of brain tissue were shown to affect the mechanical response of the brain to inertial loading. For skull properties, initial work concludes that the elastic modulus, ultimate stress, and energy absorbed to failure increase with age for sutures. The computational simulations demonstrated that the comparatively compliant skull and membranous suture properties of the infant brain case are associated with large cranial shape changes, and a more diffuse pattern of brain distortion than when the skull takes on adult properties.

Properties of paediatric flat bone and cranial bones have also been investigated (34;36;37) and they find differences with adult bone. Crandall concludes   that based on results from their own experiments with porcine skull bone specimens and results from earlier investigations using adult human skull bone specimens: The quasi-static ultimate stress of cranial bone in tension increases from 10 MPa at birth to 43 – 70 MPa at maturity, the quasi-static ultimate strain of cranial bone in tension decreases from 3.4% at birth to approximately 0.52% at maturity.  But these ranges can not be considered accurate enough for an estimation of the age dependent tensile ultimate stress and strain of flat bones in children aged 2 -14 years. Consequently, the only two properties for which we can derive fairly accurate age dependent estimates are the elastic modulus and ultimate strength in bending.

Cory et al. (38), in a review of head impact models that skull fracture and brain tissue injuries are age dependent but they are not able to give any specific guidelines or properties.

Recently Shuaeib et al. have also reported new work on head impact modelling and helmet design with special reference to children, but no specific details are available (39).

**Recent discussions on helmet design for children**

A conference on *Review of Pediatric Head and Neck Injury: Implications for Helmet Standards* was held in Philadelphia (USA) at the Children's Hospital of Philadelphia, on March 31, 2003. The proceedings of this conference include one of the better summaries on the subject of children's safety and helmet standards. For this reason the full text is given in Appendix 3, and only a brief review below (40)

- Studies suggest that older children may be more prone to focal impact damage than younger children, and that helmet standards for older children may need to be different than that for younger children or for adults. More research needs to be done to ensure that animal findings are relevant to children.
- Children are more likely than adults to suffer severe consequences from concussions. These consequences include second impact syndrome, which is often fatal or results in learning impairment.
- By age 4, the size of a child's head (as indicated by head breadth, depth and circumference) is 90% that of an adult and by age 12 it is 95% of adult size. It is not until age 20 that the bone plates of the skull fully close.
- Facial structure of children is vastly different from that of adults. Children's heads are smaller in vertical height than adults'. Consequently, adult-sized helmets can obscure children's vision and not fit properly on their heads. In a small child, the adult-sized motorcycle helmet may actually rest on his shoulders.
- The brain and skull of a child have different biomechanical properties than adults'. The greater water content in a child's brain makes it stiffer than that of an adult, noted Dr. Margulies. In addition, her research has found that skull stiffness increases with age. Based on her studies in pigs and young children, she concluded that the infant's less stiff skull properties are likely to increase the magnitude of intracranial strains that occur during head injuries involving impact. But she noted that whether that is also true for older children is not known.
- The neck, in contrast to the head, is only 75% of adult size at age 4 and 85% of adult size by age 12, according to UMTRI data. The head-volume to neck-area ratio at age 12 is still greater than what is seen for adults. In addition, the neck muscles of children are weaker than adults, and

children's neck ligaments can stretch more. Children bend their necks at higher vertebral levels than adults, and their vertebral joints are flatter so they don't restrict forward motion as much as in adults. Children's spinal columns also have more cartilage and less bone.

- Although children younger than 6 years of age participate in motorsports, many of the speakers and participants argued for not developing a helmet standard for such young children. Based on the discussion at the conference, Snell participants decided afterwards to focus on developing a paediatric motorsports helmet standard for children 6 years and older. For that standard, it was decided by conference participants that there was not enough information on how children differ from adults to justify changing the 300g acceleration limit that is currently the standard for adult motorcycle helmets.

- Participants pointed out that low impact (resulting in concussion) and high impact (resulting in permanent brain injury) protection may be incompatible in a single helmet of a reasonable size and mass. Most agreed that the helmets must protect at least against high impact. It was suggested that well-designed epidemiological studies would reveal where the injuries are and provide guidance for the area of focus of helmet standards.

- To offer more protection from mild traumatic brain injuries, the padding of helmets must be made thicker. To keep the helmet the same size and weight, therefore, the outer shell must be made thinner. But a thinner shell has less space to provide energy attenuation and therefore has lower protective capability from permanent brain injuries. A few participants suggested this trade-off might be overcome with innovative materials. But others questioned the feasibility of this, especially whether the use of such materials is likely to result in a helmet that is too expensive for the average consumer. Another problem with increasing the padding thickness in helmets is that the thicker the padding, the greater the likelihood of neck injuries, as modeling studies of adult head and neck injuries at Duke University suggest. Their studies conclude the presence of head constraint can pocket the head and decrease the ability of the neck to escape the moving torso, thereby predisposing the neck to injury. Thus, injury prevention devices and environments (helmets, car interiors, crash mats, etc.) while providing protection to the head should be designed to consider head and neck motion. Dr.Michael Prange stressed that helmets be designed to facilitate head an d neck motion and cautioned that engineers be wary of adding thick padding to their helmet designs.

- Most of the discussion centred on how to lower the size and weight of a helmet for paediatric motorsports without compromising the degree of protection the helmet gives from brain injury. Other parameters such as liner thickness, liner density, and shell material can influence the relationship between helmet mass and head injury protection. The typical

motorcycle helmet mass is 1.5kg and the typical bicycle helmet mass is 0.3kg. User fatigue and acceptance limit the weight of helmets sold in the marketplace.

**Summary of issues concerning helmet design for children**

A great deal of biomechanical work has been done on the issue of head injury tolerance and helmet design in general, and with respect to children helmets in particular. However, the measures being used to judge impact severity only include peak/average acceleration and/or the Head Injury Criterion (HIC). The values being used for children are similar to those for adults, and there is no agreement on changes in these values at present. At present peak accelerations used for head-helmet impact are around 275-300 g.

Some standards are proposing lower headform masses for children helmets, but others do not. It appears that current bicycle helmets for children do provide protection to children and would do so in motorcycle crashes also except to for facial injuries. However, it is accepted that helmets for children should be much lighter and have different dimensions than adult helmets, especially so that they do not rest on the shoulders.

On most major issues there is still a great deal of disagreement. An example of this is given in Appendix 4 which includes a comment buy the Snell Foundation on different standards for paediatric helmets. We do not expect any major change in the current state of the art for the next few years.

**SAFETY OF THE TORSO AND EXTREMITIES**

A reasonable amount of work is being done to understand the biomechanics of children's neck, chest, arm and leg injury biomechanics from the point of designing seatbelts, airbags and child seats for cars. This is mainly to aid in the design of child dummies for car crash tests. This information is not particularly useful for the child motorcycle passenger, as no easy way to restrain motorcycle passenger of any age. Garments worn by motorcycle racing enthusiasts will be too uncomfortable and expensive for the occasional child riding a motorcycle.

Some evidence that (36;41-46):

- Children have a higher case fatality rate from heart injuries compared with adult patients. This is probably because children have proportionally larger hearts than adults.

- Rib fractures occurs less often, and is less associated with mortality in children. However, compared with the adult rib cage, the paediatric rib cage is weaker, more flexible, and more cartilaginous. The thoracic wall is thinner in children because of the incomplete development of the musculature.
- In adults maximum sternum compression is used as an injury severity criterion but there is a lack of correlation between maximum compression and severity of injury, and therefore, peak chest deformation is not necessarily a valid predictor of thoracic soft-tissue trauma in children.
- Although existing child injury criteria are sparse, a few exist. A T4 resultant acceleration criterion, promulgated by the European Union (ECE-R44), suggests an injury tolerance of 55 g for a 3 ms time clip. A comparable criterion in the United States for adults prescribes 60 g for 3 ms in the adult dummies. Again, the criteria used are similar.
- For children younger than 3 years of age, the neck being is more fragile than for older children. But there is little consensus on biomechanical criteria.
- Lower and upper limbs injuries are recorded in motor vehicle collisions but prediction is not very easy. However, they do not usually present a threat to vital functions.

**Summary**

Children's neck, thorax, abdomen, upper and lower extremities are different in size and properties from adults but definitive biomechanical injury criteria cannot be indicated at this time. We have to assume that they are more fragile and therefore act with caution. However, we cannot assume that they are much more or much less susceptible to injury than adults in motorcycle crashes. Since no protective structures or restraint systems can be provided for prevention of injuries to children as motorcycle riders, it is not necessary to worry about establishing biomechanical injury criteria for children as motorcycle riders.

# 6. CONCLUSIONS

1. The proportion of children involved in fatal  motorcycles crashes as passengers seems to be less than 1-3% of all motorcycle fatalities in most countries around the world.

2. Bicycle helmets have been shown to be effective in reducing injury among children in road traffic crashes (2;47-51). Therefore, these helmets would also be effective in reducing severity of head injuries for children on motorcycles.

3. There seems to be no evidence that children, especially ages 3-12 years, differ significantly from adults in impact patterns in motorcycle crashes either in the probability. Therefore, there is no reason to believe that they will suffer more or less head, neck or other injuries as compared with adults. However, since it is accepted that children are more fragile than children, their presence on motorcycles cannot be encouraged.

4. As motorcycle passengers, the most effective safety measure during a crash is the motorcycle helmet. Except for the head, there are no very effective safety measures for other parts of the body for adults or children.

5. Motorsport helmet standards as being developed by Snell Foundation may be a good base to think of standards for paediatric motorcycle helmets.

6. No consensus is likely to emerge in the near future for changing the indices used for helmet impact severity standards.

7. In the near future there is no likelihood of the development of a helmet for children less than 3 years old based on scientific criteria that will be acceptable to a majority of experts. It may be impractical to develop a

helmet for these children as their presence among motorcycle crash victims is almost negligible.

8.  There are no easy or economical ways to protect any other part of the body except the head for motorcycle riders.

9.  Current knowledge and standards should form the basis for developing a consensus for paediatric motorcycle helmets for the SEARO region and a committee of experts may be formed to do the same.

10. Research for developing guidelines for optimisation of motorcycle helmet shell and liner properties for paediatric helmets must be encouraged and funded in two or three centres.

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