Future research directions in injury biomechanics and passive safety research

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IRCOBI

The International Research Council on the Biomechanics of Impact is a leading group in the area of injury biomechanics and passive safety research. IRCOBI Council members come from all parts of the globe reflecting the international strengths of many organisations. Through the annual scientific conference, training courses and other activities, the IRCOBI Council provides an academically rigorous forum for dissemination of the latest research into injury causation and protective systems. Since its first conference in 1973, IRCOBI has played a pioneering role in the subject and has been the forum of choice for the publication of much seminal research in injury biomechanics, field accident data, protective systems and safety legislation. While the research domain primarily concerns automotive biomechanics it is increasingly covering a wider range of injury causation. Passive safety research has provided many of the most significant safety developments in recent decades and cars now offer considerably higher levels of protection than previously. Despite the nascence of active safety systems, there are still many more opportunities for further improvements in injury prevention but further research is needed.

The IRCOBI Council members are recognised specialists in their field and have considerable experience in biomechanics, crash investigation and passive safety research. Using the research work submitted and presented at the annual conferences as well as through other peer-reviewed technical literature, they are in a unique position to identify the state of current knowledge. They also have a commanding position to identify areas where further basic and applied research can produce substantial improvements in road user safety.

IRCOBI is an independent, self-financed organisation with no depending on other stakeholders relating to transport safety.

Introduction

There has been an increasing trend within the safety environment for funding to be directed towards applied research or towards research developing commercially-exploitable systems. Funding mechanisms such as the EU's 6th Framework Programme and many national programmes focus on research of likely immediate social benefit, reflecting the use of public finances. These programmes will continue to play an important role in funding safety research, but they typically do not have guidelines specifically directed towards fundamental research questions. Additionally, impartial advice is not always available to help programme managers identify research priorities.

This review of biomechanics and passive safety research is intended for use by researchers who may be contemplating research in certain areas and wish independent guidance on specific research questions. It is also intended for use by research funding groups and programme managers who would like impartial guidance on basic research to be supported. It covers engineering research directed at improving vehicles and safety systems for all types of road user. It includes the main research and development tools such as dummy development and humanoid modelling and the important area of crash injury data.

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Contents

EXECUTIVE SUMMARY
An Overview

This document provides an expert review of research needs in the domain of human injury biomechanics and passive safety research. The report deals specifically with the areas where improved knowledge can support the development of systems to reduce crash related injuries although the scope of IRCOBI extends beyond this.

The report is intended to be used by research funding bodies that receive requests for support and would value independent guidance on the research areas that have the greatest potential to reduce injuries. It is also likely to be valuable to the research community by providing further direction to the most pressing questions in impact biomechanics and passive safety research.

The review does not address the developing area of active safety research; this is somewhat beyond the area of research interest of IRCOBI and would be likely to conceal one of the primary messages of this report which is that there is still considerable value in working to improve passive safety and injury prevention. There remain large benefits to be gained by improving injury prevention that are not obtainable with active safety systems in the same timescale. This approach to casualty reduction has been shown to be effective and the underlying research methods are well established in contrast to active safety approaches which are essentially untested.

The review is in two parts dealing with injury biomechanics research and passive safety research. In the first part the areas of agreement over the injury biomechanics of each body region are reviewed and the key areas where further knowledge is needed are then highlighted. In the second part the key research issues of each road user type are addressed. These sections are not intended to give a comprehensive review of the state of knowledge – such reviews can be found in the wider research literature. In a similar way the areas for further knowledge do not specify the exact research methodology to be used; this is something researchers have to consider within the scope of an individual study. Nevertheless this review provides research directions at a greater level of detail than any other research review or roadmap.

The purpose of biomechanics research is to improve our understanding of the human body so that we can build better tools to assess the risk of injury. These tools can be physical – crash test dummies –or numerical – computer simulations. The research issues and needs for further knowledge demonstrate a series of more general questions in our understanding of injury biomechanics that apply to each of the body regions:-

- How can we better describe the biophysical characteristics of the variety of human structures, components and subsystems that can be injured?
- How can we better characterize the dynamic *response* of these components and structures to external insult?
- How can we better characterize the *mechanisms* by which these structures undergo mechanical failure?
- How can we better define and measure the *limits* at which these structures begin to fail?
- How can we better take into account the *variability* of human beings in terms of age, sex, race, etc.?
- How can we better take into account the fact that humans are *not inanimate* systems but rather ones which can react, via muscle response, to impending insults?

Passive safety research also exhibits consistent themes across the needs of each road user type. Principle of these is that real-world crashes show a wide variability in terms of the people involved, the characteristics of the vehicles and the crash configuration. To protect all road users systems should not be optimised for one specific crash test, instead they should have versatile and robust designs that together provide the optimum protection for the full crash population. A prerequisite of this is rigorously collected and detailed real-world crash injury data that can be used to specify performance requirements of future safety systems and to provide feedback of those already in use. There are special groups of road users, such as children, the elderly and vulnerable road users where the need for injury causation data is still particularly pressing although the rate of technical development of safety systems remains so rapid there is also a constant need for up to date research on the most modern systems. Historically their injuries have been assessed using threat-to life scales but there is an increasing need to evaluate long-term impairment and the economic and health costs of injuries.

Finally the review also addresses the research needed to improve the basic tools used for biomechanics and passive safety research. The further development of dummies and humanoid models depends of improving the characterisation of human biomechanical properties at tissue level and at structural level. Future development of injury assessment functions is expected to depend on experimental approaches using dummies to measure the forces to which the body is exposed and simulations to assess the human responses and the specific nature and locations of injury.

SECTION 1:
THE EPIDEMIOLOGY OF TRAFFIC INJURY

Introduction and state of knowledge

Fundamental to developing an effective and rational research agenda, clear qualitative and quantitative definitions of the problems to be addressed are required. Unlike other diseases, the epidemiology of road traffic injuries is inadequate in describing the dimensions of this man-made disease. Indeed the concept of describing road traffic crashes and their consequences as a disease is relatively new. Historically, in most countries road traffic crashes were the exclusive purview of Ministries of Transport. Ministries of Health did not, and many still do not, consider that traffic injury prevention and mitigation should be within their sector. For this and other reasons, the epidemiological knowledge of traffic injury is inadequate.

Within the OECD countries traffic deaths are counted with reasonable completeness, but elsewhere in the world serious underreporting is prevalent. For the survivors, however, serious underreporting is present in virtually all national databases. More fundamentally, great differences in definition of the various levels of injury severity exist in national databases across the world (Mackay 2005).

Most national databases use police information as the raw input. Traffic police, however, do not have a research agenda, and thus many issues of interest to researchers are missing from such sources. Because of this, a hierarchy of studies has evolved. These range from longitudinal, large-scale sample studies, using insurance sources for example, through major interdisciplinary sample studies such as the Fatal Analysis Reporting System (FARS) and the National Automotive Sampling System (NASS) in the United States, the Cooperative Crash Injury Study (CCIS) in the UK and the German In-depth Accident Study (GIDAS), down to much smaller detailed studies of specific injuries or categories of traffic crashes. Notably absent from our current knowledge of traffic injury, though, is the assessment of the long-term consequences. There are no accepted parameters for describing and quantifying the disabilities arising from traffic injuries, particularly those involving neurological trauma.

From a biomechanical perspective, detailed knowledge of the response of the actual live human to collision forces is fundamental in validating the surrogates used in design, in evaluating the effectiveness of design changes and in optimising the regulatory requirements to produce the greatest benefits across the populations of collision types and severities as well as the populations of road users. Yet, biomechanical requirements historically have been specified in terms of single-point requirements. For example, the Head Injury Criterion (HIC) should be less than 1000, or the loads on the femur in compression should be less than 10 kN. The reality is that such requirements are only one point on a population risk curve specifying the probability of a certain level of injury for a given population.

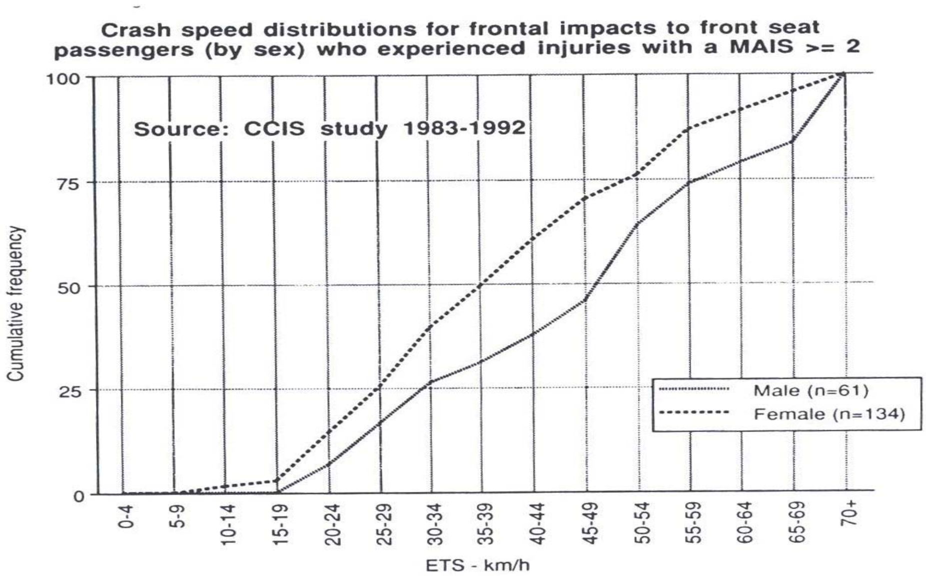
The injury outcome from a traffic crash is the result of combinations of many factors, both intrinsic and extrinsic to the casualty, and permanent or temporary in nature. For a car occupant they can be categorised in the three phases of the event--the pre-crash, crash and post-crash phases--as follows:

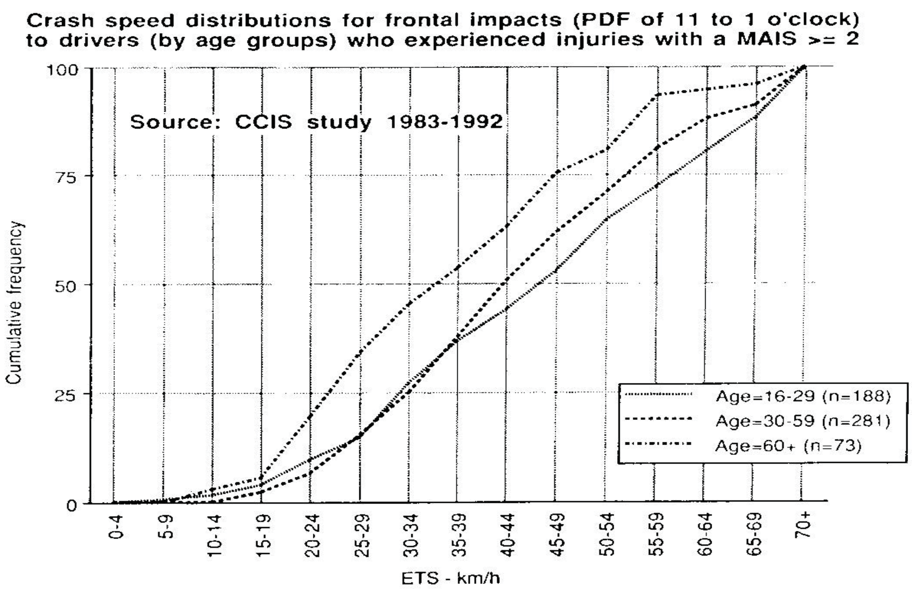
Pre-crash factors: sex, age, height, weight, body-mass index (BMI), pre-existing medical conditions, biomechanical tolerance, muscle tone, stomach contents, bladder volume, alcohol, drugs, clothing, seat position in the vehicle, sitting posture, belt position, pre-impact braking.

Crash factors: impact direction, velocity change (delta V), peak vehicle deceleration, pulse duration, peak belt load, posture at peak belt load, airbag interactions, point in the cycle of the heart, loads and durations of localised contacts, rear loading, interaction with other occupants.

Post-crash factors: severity of injuries, combinations of injuries, response time of emergency medical services, quality and timeliness of diagnosis of injuries, quality of treatment, resulting disabilities.

Given the number of such variables, it is perhaps surprising that relatively crude crash injury data, which post facto can only address a small number of these variables, can detect trends at all. Age and sex, for example, are both sensitive to crash severity as is illustrated in the following two figures (Mackay et al., 1994).





However, there are probably subtle combinations of some of the other factors listed above which lead to especially high or low levels of risk (Ydenius 2002). Small female drivers currently have to sit close to the steering wheel and thus have been found in field studies to be at higher risk of airbag-related injuries. Tall, thin males have been found to have a greater number of belt-related chest injuries than smaller males, probably because the path of the shoulder belt is lower across the rib cage and is thus loading the lower ribs which fracture more easily than those higher in the rib cage where the rib attachments to the sternum and spine are more substantial and less cartilaginous (Hill et al., 1994).

These few examples illustrate the profound importance of population variations and therefore the need for sound epidemiological data to complement experimental work.

Experimental Biomechanics: Since the early work of Yamada in the 1970s (Yamada 1970), experimental work on human tissue and on complete cadavers has contributed the greatest amount of knowledge to the variation in human response to crash forces. In particular, the variation in bone strength and its relationship to bone mineralisation is well documented (Cavanaugh, 1993). Age effects have similarly been well documented (Yoganandan et al., 1997, Kent et al., 2003). As a gross generalisation, fracture tolerance varies by a factor of between 3 and 5 between the strongest and weakest in the population exposed on the roads. An overview of the state of the art of injury biomechanics is found in Schmitt et al. (2004).

Such experimental work has also demonstrated the complexity of human response to blunt dynamic crash forces in that peak loading is only one variable. Duration and rate of application of load are also important underscoring the fact that injury criteria are complex functions of numerous variables. Several chest injury criteria are available such as peak chest acceleration, the Thoracic Trauma Index (TTI), the Combined Thoracic Index (CTI), standardised chest deflection and the Viscous Criterion (VC). Threshold tolerance levels are proposed for various injury levels, AIS 3+ or AIS 4+ (Abbreviated Injury Scale, 2005). More importantly in the context of population issues, age effects are recognised and lower tolerance values are proposed for older people (Eppinger et al., 1984, Kent et al., 2003).

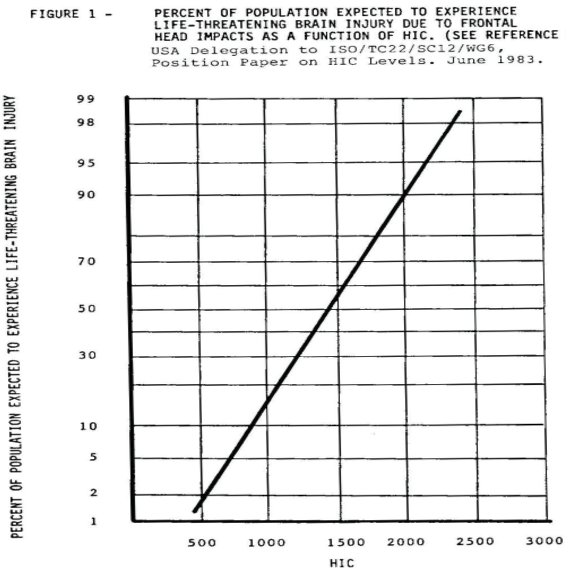
For injuries unrelated to fractures, population variation is less well researched. In the absence of actual biomechanical tolerance data on children and small females, scaling techniques have been used to produce injury criteria tolerance levels for these two populations (Kleinberger et al., 1998). Geometrical and material properties (e.g., height, mass, modulus) are used to scale down to the various smaller sizes from the 50^{th} percentile adult male. This technique has resulted in the various head, neck, chest and femur tolerance levels specified in the most recent Federal Motor Vehicle Safety Standard (FMVSS) 208 requirements governing out-of-position situations with various sized dummies. Such techniques involving mathematical procedures and "engineering judgment" have allowed progress to be made in specifying the requirements of advanced restraint systems. However, their relationship to the real populations at risk is still to be tested.

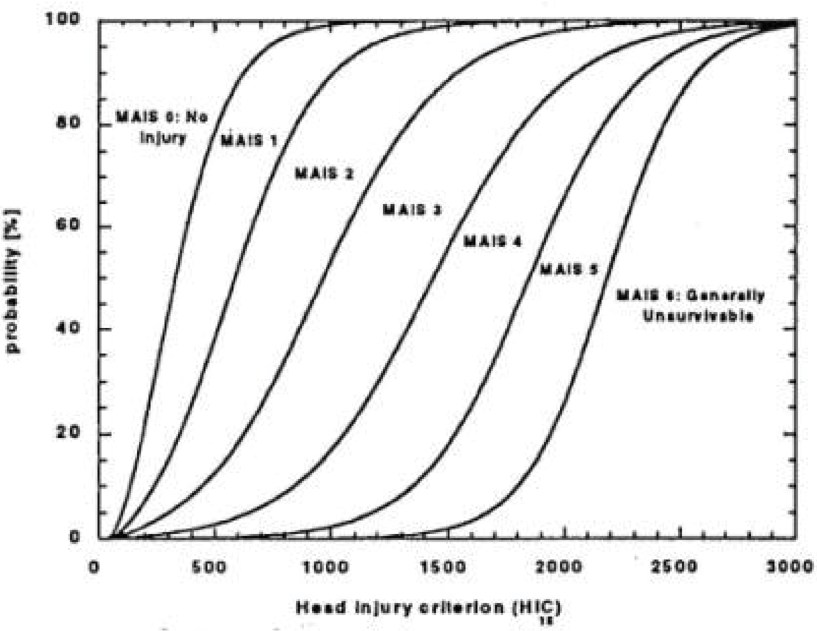
For the brain, abdominal organs, the neck, and soft tissue muscle and skin trauma, there is little documentation of actual population variation. Females are shown to be more susceptible to soft tissue neck injury. Skin in older people is somewhat more resistant to threshold lacerations, perhaps a unique example of a biomechanical benefit of growing old (Mackay, 1984).

For several of the major body regions, distribution curves of the probability of injury to various levels of severity are available (two figures below). However, how those probabilities shift with age is ill-defined.

The Need to Recognise Population Variations in Design and in Regulations

At the present time, there is a mismatch between current biomechanical knowledge on the one hand, and the requirements of current regulations which control vehicle design, or are a strong influence on vehicle design, such as the various New Car Assessment Programmes around the world, on the other. These regulations or requirements specify single values for the HIC, for chest acceleration and for femur loads in a specified frontal crash, with similar requirements for a side impact configuration. This leaves the impression that it is a pass/fail requirement, when in reality it is merely specifying an ill defined point on a distribution curve. Thus an HIC of 1000 in the NHTSA curve above indicates an 18% probability of a severe (AIS 4) head injury, a 55% probability of a serious (AIS 3) injury and a 90% probability of a moderate (AIS 2) head injury, <u>to the average adult</u>. How those probabilities shift across the spectrum of the population is largely unknown.

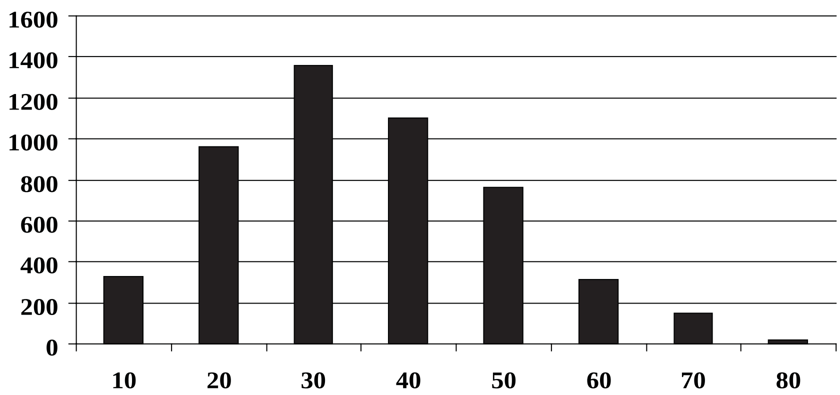




Injury Probability versus HIC

NHTSA. FMVSS 201 Upper Interior Head Protection. Final Economic Assessment, Office of Regulatory Analysis. IV-48, June 1995

A further issue is illustrated particularly with the EuroNCAP frontal crash test requirements. The 64 km/hr offset deformable barrier sets the gold standard car design in Europe. Car manufacturers clearly design and tune their cars to do well in that test. However, field accident data show that most collisions that cause AIS 3+ injuries to restrained occupants in frontal crashes are at crash severities much lower than the EuroNCAP condition. The mean value for the delta V is around 38 km/hr (Mackay and Hassan, 2000)



Delta-V (km/hr) for AIS 3+ Belted occupants – Frontal Crashes

These data suggest two things. First, the crash severity of the test represents an extreme condition compared to the real world of serious injury collisions. This may well be producing vehicles that are not optimal for the mainstream serious injury crashes, being unnecessarily stiff for the bands between 20 and 40 km/hr. Second and more important, it suggests that because the majority of AIS 3+ casualties are occurring below the conditions specified in the EuroNCAP test, in vehicles which predominantly meet the test requirements, the injury tolerance levels in the test are inappropriate and should be lowered. Perhaps an HIC ‹750, chest accelerations ‹45 g and femur loads ‹750 kg would be appropriate. To address this issue properly requires a more detailed analysis of the in-depth field accident data available, but also the development of injury probability curves for the age bands of the adult crash-involved population.

The situation is different for the EuroNCAP side-impact test requirement. Field accident studies show that the typical side-impact delta V is substantially in excess of the current regulatory and NCAP requirements (Thomas and Frampton, 2003). Hence, meeting those test requirements does not address the majority of the serious injuries in real-world side impacts.

A quite separate factor related to population variation concerns the changing demographics of the world population. In Europe, the United States and Japan, life expectancy is continually rising and the proportion of elderly people in the population is steadily increasing. These road users tend to have greater expectations of personal mobility and consequently the numbers of older drivers is expected to increase. In Europe, for example, the population over 65 is expected to increase from 14% in 2000 to 28% in 2050. Older drivers have a higher crash involvement risk, and also a lower tolerance to impact loads so they will be more likely to be injured in a crash than a younger driver. These factors will tend to increase the numbers of road casualties and the totals killed. Conversely however, older drivers can be expected to have a reduced remaining lifespan and this too needs to be taken account of when evaluating the overall effect of fatal and non-fatal injuries

CONCLUSIONS:

This short review indicates that there are important gaps in our biomechanical knowledge of population variations of injury tolerance levels. This is especially true of non-bony injuries and especially for the head. More generally, the whole question of the optimisation of vehicle crashworthiness will only be achieved if the various populations of crash severity and injury tolerance variation are considered together. Optimising design to a single point on only one of those distribution curves is clearly incorrect. This requires particularly more accurate and more representative real-world crash injury studies that will outline the necessary population characteristics and their variations (Kent and Crandall, in press).

Areas for further knowledge

1. Better knowledge of the population differences in injury tolerance especially for the head, chest, and abdominal regions is fundamental. Curves of population variations, associated with age effects, need to be developed for each injury criterion.

2. Analytical research is needed to optimise crashworthiness design across the ranges of crash types, crash severities and populations.

3. More realistic test requirements that reflect population variations in injury tolerance must be developed to recognise the tradeoffs between the strong and the vulnerable.

4. More detailed in-depth research on injury mechanisms and crash conditions for cars that perform well in NCAP and EuroNCAP tests should be undertaken. More generally, this requires greater collaboration between in-depth field crash injury research and experimental crash testing.

5. Epidemiologists should be engaged in the structuring of crash injury data collection and analysis. More trans-national analysis of current data sources is needed, especially within the European Union.

6. Better, quantitative assessment measures of the long-term consequences of traffic injury are needed.

7. The safety needs of elderly road users need to be evaluated more thoroughly to take account of changing demographics. Baseline information on the physiological changes of the elderly and the identification of injuries of special interest is required. Issues of optimisation will need to be addressed to ensure that protective systems optimised for a younger population are as effective with older groups.

8. The slight/serious/fatal categories currently used for injury severity scaling in large databases are inadequate. A simple injury scale is needed that is useable by police and first responders and that is compatible with the AIS currently used in in-depth and hospital-based studies.

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SECTION 2:
HEAD AND BRAIN INJURIES

Introduction and state of knowledge

Frequency: Injuries to the head involve the scalp, skull, brain and the nerves and blood vessels entering and exiting the skull. Many studies have documented that these head injuries are frequent, are commonly severe and are as large a cause of death and of disability as are injuries to the rest of the body combined (Gennarelli et al., 1994). The head is the most commonly injured body region and accounts for a large part of resulting impairment and disability.

Biomechanical Issues: A considerable amount of research into the nature and causation of head injuries and a large degree of consensus has been achieved over the basic biomechanical questions. This agreement can be summarised as follows:

- The many different types of head injuries have been described and classified (Graham et al., 2002).
- General agreement has been reached on the severity and the importance of the various types of head injuries regarding the potential for death and disability. These are adequately described in the Abbreviated Injury Scale (Gennarelli et al., 1982, Abbreviated Injury Scale 2005).
- A general understanding exists of the underlying mechanisms that cause altered brain function post injury (Ommaya et al., 2002).
- Frequencies of single and combinations of head injuries have been identified in various injury-producing circumstances.
- The biomechanics of head injuries are reasonably well understood from a qualitative perspective (Goldsmith 2001).
- Regarding the mechanisms and levels of stress or strain that cause injury (i.e., the biomechanical tolerances), there is general agreement regarding scalp injuries and some types of skull injuries.
- There have been estimates from limited sources regarding mechanical tolerances for all head injury globally and for various specific levels of diffuse brain injury (concussions and prolonged traumatic coma) (Gennarelli et al., 2003).
- Injury assessment: The prevailing injury assessment functions based on linear acceleration such as HIC have served a useful function over the years and continue to be used as legislative requirements. Nevertheless, it is now clear they are adequate measures of brain injury probability or severity. Criterion functions still need to be developed that take account of the complex three dimensioned motion of the head following impact
- The applicability of the HIC is limited in understanding certain types of brain injury and there is a need to develop more suitable injury assessment functions.

Thus, future research into brain injury can be structured as follows:

Host Factors: First, age plays an important role in brain injury. The response of the head-brain complex differs markedly in the very young and in the elderly, thus resulting in different types and combinations of brain injuries and with different severities and outcomes than in young adults. Second, it is now known that some of the biological variability in susceptibility, response and outcome from injury is due to the genetic makeup (genotype) of the host.

Environmental Factors: The principal causes of head injuries are vehicular, falls, assaults and penetrating mechanisms, each of which has its own special injury-producing situations. Primary emphasis should be placed on prevention of injury-producing situations. Mitigation of forces applied to the head, when injury situations cannot be prevented, is also fundamental.

Biomechanical Factors: A better understanding is needed of the variables and their combinations that are important in injury production (e.g., stress versus strain, relative displacement, velocity, acceleration, jerk, deformation and their combinations).

Areas for further knowledge

1. Realistic and verifiable mathematical models of the material properties, geometry and tolerance data for various ages for all injuries should be established. Detailed research needs to be conducted to improve the modelling of the interfaces between brain structures. These models must be validated experimentally.

2. The development of mechanical tolerance data for specific types of focal brain injury needs to occur, especially for coup and contrecoup contusions, subdural haematoma, intracerebral haemorrhage and diffuse brain swelling.

3. Injury-specific criteria for structural failure of components of the head and especially of the brain, also related to the entire spectrum of age, must be developed based on the complete 3-dimensional motion of the head

4. Tolerance limits for individual injuries as well as an envelope to encompass all injury types is needed taking account of combined lumbar and rotational head motion

5. Tolerance data for skull fracture and the diffuse brain injuries need to be solidified and generally agreed upon in a quantitative manner.

6. The specific contribution of skull deformation, relative motion between various structures within the head, tissue deformation and wave propagation needs to be established quantitatively for all head injuries at various ages

7. Age-specific measurements of the static and dynamic material properties of the tissues of the head, particularly of the very young and the very old, using contemporary methodologies are needed.

8. A more complete understanding of the qualitative and quantitative differences in injury mechanisms and tolerances across the age spectrum is necessary. Differences in injury produced by inertia, contact events and large deformations must be quantified.

9. Further knowledge is needed concerning the long-term consequences of minor brain injury.

10. Scaling methods to support the development of injury assessment values for a range of ages and sizes should be further developed.

11. The influence of various host factors, especially of genetic heterotypia, on the various age-related specific injury tolerances must be established.

12. Improved animal models are required to more accurately examine the progression of injury.

13. Simultaneous with the issues above, there should be research to identify or develop new materials or new designs that could protect the head from injury in various circumstances.

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SECTION 3:
NECK INJURIES
Introduction and state of knowledge

Frequency and Crash Circumstances: Cervical spine distortion (CSD) injuries play a major role in car-to-car collisions worldwide. The high rate of CSD represents not only an economic burden but also a medical challenge. A particular characteristic of so-called "whiplash" injuries is that they can occur in car crashes at low velocity (Krafft et al., 2002). During such an event, vehicle occupants are prone to hyperextension of the neck, particularly at the level of the C6-C7 cervical vertebrae (Kaneoka et al., 1999).

Research into vehicle safety is making progress, but nevertheless the incidence of cervical spine injuries in motor vehicle collisions is not falling. The motor vehicle industry tends towards the production of stiffer car bodies that appear to protect the car's outer shell rather than the occupants themselves in the event of a collision. The incidence rate of neck injuries remains high despite the belief that hyperextension of the cervical spine would not occur as long as the occupant is using a head restraint (Lovsund et al., 1988, Olsson et al., 1990, Ono and Kaneoka, 1997). This strongly suggests that factors other than the improper use of head restraints must be involved as a cause of neck injuries. For example, current seat systems including the head restraint are not adequately designed to prevent or mitigate neck injuries.

The potential for long-term impairment, including paraplegia and quadriplegia, is always inherent in injuries to the spine and particularly to the spinal cord. Of all spinal segments, the cervical spine is the region most frequently injured. As the head and the neck form one functional entity, head loading often also implies neck loading and almost always vice versa.

In a rear impact, the occupant is subjected to various forces which tend to differ among individual occupants due to differences in seat position and seat cushion stiffness which are presumably related to the incidence of neck injuries (Lovsund et al., 1988, Olsson et al., 1990, Ono and Kaneoka, 1997, Hell et al., 2003). While research has focused on the relationships between neck muscle responses, motions of cervical vertebrae and injuries to intervertebral discs and articular surfaces, detailed information about these relationships, ranging from relatively minor neck injuries to those resulting in impairment, are still not well understood.

Severe (head-contact) cervical injuries occur to unbelted car occupants not only in rear impacts but also in frontal, lateral and oblique impacts. Half of all minor neck injuries occur in frontal impacts (Hell et al., 2003). The vast majority of cervical spine injuries, however, are minor soft tissue AIS 1 injuries. These injuries, while not associated with overt structural injury to the cervical spine or the central nervous system, are both a common and potentially debilitating injury. In fact, they are the most frequently occurring injuries in automobile collisions and more often to females than to males (Bunketorp et al., 2004, Jakobsson and Norin, 2004). Thus, soft tissue neck injuries are a major concern in road traffic.

Although most sufferers will make a complete recovery within a short period of time, some cases will develop prolonged medical problems placing soft tissue neck injuries among the most prevalent causes of medical disability in car occupants. This can result in long sick leave times and disability payments. The influence of the different legal compensation systems is also a factor. Hence, the socioeconomic significance of these injuries is tremendous. Consequently, a greater understanding of the vehicle, collision and occupant parameters that are prevalent in soft tissue neck injuries is needed in order to develop preventive measures.

Injury Mechanisms: The mechanisms of the so-called "whiplash" injury have not been clearly understood, and the relationship between the objective physical/medical observations and the subjective symptoms remains unclear (Carlsson et al., 1985, Schrader et al., 1996).

The human neck is a complex structure consisting of skeletal frames, ligaments, blood vessels, muscles and soft tissues such as nerves with diverse strengths. Their forms tend to change continually and in a potentially injury-producing situation, neck muscle strength can depend upon level of consciousness. An impact is transmitted directly to each vertebra or dispersed through the soft tissues, then transmitted to the lower torso. The influence of a head impact on the neck differs significantly depending on the direction of the impact and the orientation of the neck when the impact occurs. In other words, the neck injury mechanism is roughly classified by the direct transmission of the head impact to the neck (Yamada 1970) and by the inertial head motions around the neck acting as a pivot (Society of Automotive Engineers 1986).

Specific injury mechanisms related to cervical vertebrae are flexion (bending), compression, extension (tension), rotation (torque) or shear force (Figure 1). In general, injuries to the lower vertebral region result from flexion or extension whereas an injury such as a Hangman-type fracture or Jefferson-type fracture, again depending upon the orientation of the neck, results from a shear force. An intervertebral disk or vertebral anterior aspect is likely to be injured by flexion, and the bending moment tends to be greater than in the case of extension. With flexion, however, the impact load against the vertebra changes as the chin contacts the chest (chin-chest impact). In the latter case, the so-called "whiplash" injury may occur without a direct impact to the head. A typical example of such impacts is a vehicle rear-end collision. In the initial stage of a rear-end collision, the occupant's spinal column is rounded by the seatback reaction force, then straightened upward, causing the torso to move upward along the seatback at the same time. As the head remains in the initial position due to the inertia, an axial compression force is applied to the lower cervical vertebra due to the straightening of the spinal column and the upward motion of the torso. A shear force is then applied to the lower cervical spine due to the collision between the seatback and the upper portion of the torso, resulting in head retroflexional rotation around the lower cervical vertebra acting as the pivot. The phenomena created from the initial impact, the resulting motions of the spinal column and torso, and the retroflexional rotation of the head are becoming more complex due to the specific detail of head restraint installation in recent years.

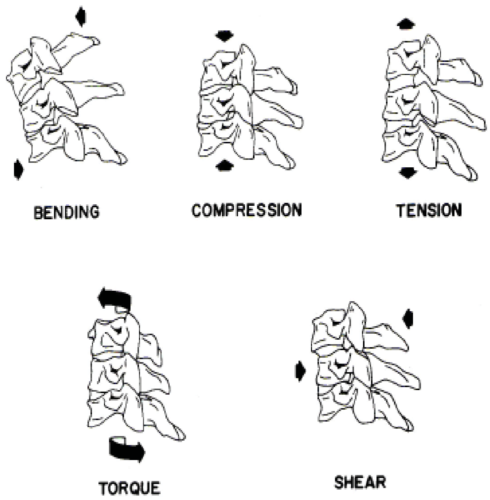

Figure 1 Loading patterns for cervical spine

Generally, the impact time zone during which a neck injury occurs is in the order of several-tens to several-hundreds seconds from the moment of impact. The injury severity also depends on the duration of the impact. In some cases, the duration that causes the "whiplash" can be as long as 200ms. These are important considerations to a better understanding of these minor but frequent and sometimes debilitating neck injuries.

Injury Criteria and Tolerance to Injuries: Early work by Yamada (1970) on physical properties and strengths of biological materials such as cervical vertebrae, intervertebral disks and ligaments has contributed significantly to the field of impact biomechanics. Table 1 summarises experimental data on tensile, compression and torsional strengths of vertebrae and the intervetebral discs.

Table 1 Breaking strength of cervical neck elements in tension, compression and torsion by age group

	Age group (years)		
	20-39	40-59	60-79
Cervical vertebrae			
Tension (kN)	1.12	0.89	-
Compression (kN	4.09	3.3	1.89
Cervical disc			
Tension (kN)	1.03	0.78	-
Compression (kN	-	3.13	-
Torsion (Nm)	5.5	4.7	-

These data are fundamental to the field of impact biomechanics and often referred to as useful data in various other fields. The injuries that occur in line with the flexion, compression, torsion and/or shear forces applied to the cervical vertebrae described above are classified (Society of Automotive Engineers 1986) and shown in Table 2.

Table 2 Types of neck injuries based on neck injury mechanisms

○ Compression injuries	○ Tension injury	○ Torsion injury
・Jefferson's fracture ・comminuted fracture of atlas ・compression fracture ・burst fracture	・atlanto-occipital dislocation	・atlanto-axial dislocation
○ Compression and flexion	○ Tension and flexion injury	○ Shear injuries
anterior wedge fracture cervical sprain unilateral facet dislocation bilateral facet dislocation teardrop fracture	・bilateral facet dislocation	・atlanto-axial subluxation ・odontiod fracture ・Fracture of articular process?
○ Compression and extension	○ Tension and extension	○ Bending injuries
・Fracture of posterior element	Whiplash ・tear of facet joint ・tear of intervertebral disc ・chip fracture ・Hangman's fracture ・teardrop fracture	・narrowing of intervertebral foramen ・compression of articular process
○ Other injury		
・Clay-shoveler's fracture		

Mertz and Chou (1976) proposed neck injury tolerance curves in 1976 based on experimental data from volunteers and cadavers. These curves determine the limits for torque, flexion angle and extension angles relative to the occipital condyle. The test data of axial load, shear force and bending torque are summarized and shown in Table 3.

Table 3 Maximum static forces and bending torques developed at the occipital condyles by human volunteers

	Bending torque [Nm]
Forward flexion	50.2
Extension	20.3
Lateral flexion	47.5
	Force [N]
Anteriot-posterior shear	845
Posterior-anteriot shear	845
Lateral shear	400
Axial tension	1,134
Axial compresion	1,112

Moreover, Mertz (1990) also proposed neck injury criteria based on dynamic experiments conducted using cadavers, and accident simulations using Hybrid III dummies. The proposed tolerance level to the occipital condyle torque is 190 Nm for the forward flexion, and 57 Nm for the backward extension. These injury criteria are applied at present to the evaluation of neck injuries in automobile safety evaluation tests using the Hybrid-III crash test dummy. Injury criteria values for axial compression, tension and shear force are shown in Figure 2.

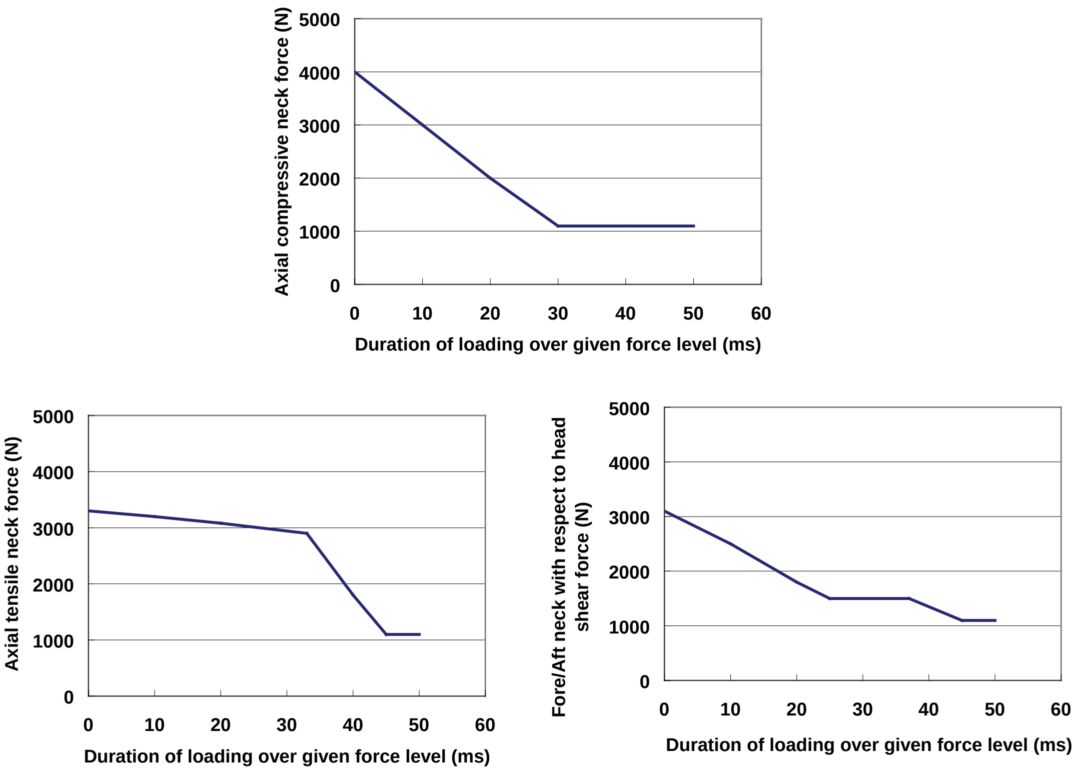

Figure 2 Neck Injury Criteria for ATD dummy

It should be noted, however, that the data obtained with these injury criteria values are applicable mainly to experiments and studies on head inertia loads. These values do not provide injury criteria for human biological impact responses where human heads are subjected to direct impacts (Xu et al., 2000). The values being used at present as the injury criteria (Federal Register 2000) are listed in Table 4.

Table 4　Neck injury criteria based on ATD dummy (Nij)

Criteria / ATD dummy	Fzc (N) Ten.	Fzc(N) Comp.	Myc (Nm) Fl.	Myc (Nm) Ex.
50% Adult Male Dummy	6,806	6,160	310	135
5% Adult Female Dummy	4,287	3,880	155	67
12 M. CRABI Dummy	1,460	1,460	43	17
3 Y. Child Dummy	2,120	2,120	68	27
6 Y. Child Dummy	2,800	2,800	93	37

Fzc :Limitation of axial force　　　　Nij=(Fz/Fzc)+(Mocy/Myc)

Myc：Limitation of bending moment

Fz : Measurement value of axial force

Moyc：Measurement value of bending moment

Recently, quite extensive studies on minor neck injury (i.e., "whiplash") caused by head inertial impacts were conducted in addition to the above, and the "whiplash" injury evaluation parameters and the criteria are proposed as shown in Table 5 (IIWPG 2001).

Table 5 Proposed Injury Evaluation Parameters and Injury Criterion for Whiplash Prevention

NIC (Neck Injury Criterion)
$NIC(t)=a_{rel}(t)*0.2+(V_{rel}(t))2 < 20\sim25m^2/s^2$ $a_{rel}(t)=a_x^{T1}(t)-a_x^{Head}(t)$ $V_{rel}(t)$: $a_{rel}(t)$Integration $a_x^{T1}(t)$: T1 X-axis acceleration $a_x^{Head}(t)$: Head CG X-axis acceleration
Nkm Criterion (Neck Moment and Shear Force Criterion)
$Nkm(t)=Fx(t)/Fint+My(t)/Mint < 0.5\sim1.0$ Fx(t):Shear force,My(t):Bending moment Fint : Limited force(845N) Mint : Limited bending moment (Flexion : 88.1Nm, Extension : 47.5Nm)
VT1 (Velocity of T1)
T1 rebound velocity $< 2.5\sim3.0$m/s
NDC (Neck Displacement Criterion)
X and Z-axes deformations and rotational angles of Occipital Condyle relative to T1

In many cases of minor neck injuries, stresses are concentrated locally on the facet joints, capsules and ligaments of individual vertebrae due to, for example, the impact caused by rear-end collisions. As a result, nerve tissues contained in the facet joints (synovial folds), capsules and ligaments are said to be irritated and cause pain. Thus, the mechanism is being gradually clarified, but symptoms related to nerves involve many factors that depend mainly on subjective symptoms. Hence, knowledge about minor neck injury tolerance is still limited.

Areas for further knowledge

1. Important questions remain about the nature and biomechanics of "whiplash" injury. The precise injury mechanism of this injury, which oftentimes does not heal, still needs to be established.

2. The relationship between NIC, Nkm and neck bending moments and specific injury mechanisms requires further clarification.

3. As people age, there is a progressive deterioration of the neck and it is believed this may affect injury risk, but further research is still required.

4. The precise mechanism of neck injuries sustained in frontal and side collisions needs to be determined. Improved lateral bending criteria are still needed.

5. Specific research is needed into the effect of head contact and the influence of neck musculature on neck injuries.

6. The higher risk for neck injury in females still needs further research.

7. In frontal impacts, there is frequently a head contact with an airbag and the results of these interactions still require better understanding.

8. It is possible that related research into pain control and anaesthesia may provide new directions since so far, many therapy paths are inefficient or even counter-productive.

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SECTION 4:
THORACIC AND ABDOMINAL INJURIES
Introduction and state of knowledge

Frequency: Skeletal injuries to the thorax have been relatively well researched and there is a substantial body of knowledge, particularly relating to frontal impacts. Yet injuries to the thorax still account for 22% of the economic costs with a further 17% associated with abdominal injuries. Thoracic injuries remain important not only because of the associated threat to life but also because of the increased possibility of pneumonia in older casualties. Additionally, field accident data have indicated that thoracic injuries are often associated with injuries to other body regions and this multi-trauma effect can have significant consequences on threat to life.

In frontal impacts, the thorax is exposed to relatively complex loading conditions from seatbelts and airbags, for example. The development of force limiters integrated into restraint systems, associated with airbags, has reduced the risk of thoracic injuries in frontal impacts. However, since this risk increases with age, the growing number of older car occupants will give even more importance to thoracic injuries in frontal impacts.

Field crash injury studies underscore the importance of thoracic injuries in side impacts. Rouhana and Foster (1985) found that thoracic injuries accounted for 38% of AIS 3-6 injuries, 24% of AIS 4-6 injuries and 25% of AIS 5-6 injuries while Mackay (1989) found that thoracic injuries (57%) were more frequent than head injuries (55%) at AIS≥4. Fildes and Vulcan (1990) found that of AIS>2 injuries, 53% of total injuries were to the thorax. A study by Haland and Lindqvist (1994) found that the chest was the most commonly injured body region for AIS 3-6 injuries. Chest injuries are even more important in fatal crashes. Thomas and Frampton (1999) found that 89% of the total fatalities in their sample sustained a thoracic injury of AIS≥3.

The improvement of belt systems together with seat design has reduced abdominal injuries related to submarining which was a primary cause of injury in frontal impacts. In side impacts, however, around 20% of severely and fatally injured car occupants sustain abdominal injuries. Most of these injuries are in the upper abdomen with a high frequency of liver and spleen injuries.

Injury Mechanisms: Research into side-impact injury biomechanics conducted using sled tests and padded surfaces is similar to the conditions under which injury is typically sustained in the real world. Nevertheless, the material properties of thoracic and abdominal organs and their injury mechanisms are still not fully understood. Some predictors of thoracic and abdominal injury, such as the Viscous Criterion (VC), do have a direct link with injury mechanisms, but others are merely obtained statistically with no direct causal link.

In frontal impacts with belted occupants, thoracic injuries are directly related to restraint load. Improvement of restraint systems has increased the protection against thoracic and abdominal injuries. The biomechanics of thoracic injuries in frontal impacts has been widely investigated through experimental research and the following table summarises the results of the most relevant studies.

Injury Risk Parameters: Frontal Impact Tolerances for the Thorax

Tolerance Level	Injury Level	Reference
Force		
3.3kN to sternum	minor injury	Patrick et al. (1967)
8.8kN to chest & shoulders	minor injury	Patrick et al. (1967)
Deflection		
58mm	no rib fracture	Stalnaker & Mohan (1974)
Compression		
20%	onset of rib fracture	Kroell et al. (1971, 1974)
40%	flail chest	Kroell et al. (1971, 1974)
VC_{max}		
1.0 m/s	25% probability AIS ≥4	Viano & Lau (1985)
1.3 m/s	50% probability AIS ≥4	Viano & Lau (l985)
Combined Thoracic Index (CTI)		
A_{max}/60g+D_{max}/76 mm	50% probability AIS >3	Kleinberger et al. (1998)

In side impacts, injuries to struck-side occupants are directly related to contact with the car's intruding side door panel. The contact of the thorax with the door panel during the intrusion process accelerates the torso which generates, in addition to rib cage deformations, loads to the internal organs which may cause injury. Considerable research devoted to the biomechanics of the human thorax in side impacts has been conducted over the years and the following table summarises the results of these studies.

Injury Risk Parameters: Side-impact Tolerances for the Thorax

Tolerance Level	Injury Level	Reference
Force		
7.4kN	No injury	Tarriere et al. (1979)
10.2kN	AIS 3	Tarriere et al. (1979)
5.5kN	25% risk of AIS ≥4	Viano (1989)
Acceleration		
T8-Y 45.2 g	25% risk of AIS ≥4	Viano (1989)
T12-Y 31.5 g	25% risk of AIS ≥4	Viano (1989)
60 g	25% risk of AIS ≥4	Cavanaugh et al. (1993)
Thoracic Trauma Index (TTI)		
TTI 145 g	25% risk of AIS ≥4	Cavanaugh et al. (1993)
TTI 151 g	25% risk of AIS ≥4	Pintar et al. (1997)
Compression of half thorax		
35%	AIS 3	Stalnaker et al. (1979);
		Tarriere et al. (1979)
33%	25% risk of AIS ≥4	Cavanaugh et al. (1993)
Compression to whole thorax		
38.4%	25% risk of AIS ≥4	Viano (l989)
VC_{max} to half thorax		
0.85 m/s	25% risk of AIS ≥4	Cavanaugh et al. (1993)
VC_{max} to whole thorax		
1.0 m/s	50% risk of AIS ≥3	Viano (1989)
1.47 m/s	25% risk of AIS ≥4	Viano (1989)

Areas for further knowledge

1. Further information is needed to understand the differences between cadaver and live responses related to both the influence of muscle tension and the pressures in the arterial system. Conventional research using cadavers may be producing misleading results as they are unlikely to be capable of realistically reproducing organ injuries. Hybrid approaches using real-world crash injury data, cadaveric responses and simulation appear to offer a better way of developing improved understanding of organ injuries.

2. Improved knowledge of the material properties of internal organs, their injury mechanisms and injury predictors is still needed. The aorta in particular is frequently a cause of death, yet knowledge of its injury mechanisms is incomplete. Because organs such as the aorta, liver and spleen are highly vascular, conventional simulation methods may not be sufficiently capable of realising the fluid-dynamics effects.

3. New technologies show promise in reducing skeletal injuries. For example, systems such as bone-strength sensors are capable of offering personalised restraint performance. The rib cage does have a marked sensitivity to age effects and further information is needed about the deterioration of rib strength in older road users.

4. Further evaluation of the relationship between impactor tests and restraint loading is needed.

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SECTION 5:
UPPER EXTREMITY INJURIES
Introduction and state of knowledge

***Frequency*:** Injuries to the upper extremity of vehicle occupants have been observed in frontal, offset, oblique and side impacts as well as rollovers. Otte (1998) showed that upper extremity injuries to belted drivers ranked fourth in frequency behind thorax, lower limb and head trauma. Similarly, Martin et al. (1997) showed that the upper extremity was among the top four body regions in terms of human capital costs as well as life-years lost for drivers. While the use of airbag systems as supplemental restraints has significantly reduced the risk of fatality in automobile collisions, there is evidence of increased upper extremity injuries for drivers, including severe fractures, following airbag deployment (c.f. Marco et al., 1996, Freedman et al., 1995, Huelke 1995). Kuppa et al. (1997) analysed several accident databases to determine the incidence of upper extremity injury for crashes with and without a driver-side airbag deployment. They found that 1.1% of drivers who were restrained by a seat belt but no airbag experienced upper extremity injury. In contrast, 4.4% of drivers experienced upper extremity injury in the presence of a deploying airbag. For side airbags, case studies (Langwieder et al., 1998), computational investigations (Sieveka et al., 1997) and experimental tests (Duma et al., 2001a) have demonstrated injury due to side airbag interaction with the lower limb, but to date insufficient field data exists to estimate exposure and injury frequency.

Frampton et al. (1997) investigated automobile crashes in the United Kingdom and found that the forearm is the most often injured region of the upper extremity in frontal crashes and accounts for 46% of the total upper extremity injuries. In side impacts and rollovers, however, the humerus was the most often injured region accounting for 50% and 64% of the total upper extremity injuries, respectively. Otte (1998) examined multiple crash modes and found the long bones (humerus, radius and ulna) to be the most frequently injured upper limb regions; of those with arm fractures, 16.7% had a fractured humerus, 20.7% a fractured radius and 27% a fractured ulna. The hand bones were fractured in 41.8% of the cases. Comparing airbag-deployed cases to non-airbag deployed cases, Dischinger et al. (1996) found the radius and ulna to be the most frequently injured regardless of restraint. However, the radius and ulna were twice as likely to be injured in cases of airbag deployment. Bass et al. (1997, 1998) conducted experiments with the forearm placed across the upper extremity and correspondingly observed primarily radius and ulna fractures when injury occurred.

In addition to the injuries experienced by vehicle occupants, upper extremity trauma is a frequent consequence of pedestrian and motorcycle crashes. Pedestrian upper extremity injuries comprise approximately 8-9% of all AIS 2+ injuries (Mizuno et al., 2001). While findings vary depending on inclusion criteria and injury severity, Foret-Bruno et al. (1998) and Mizuno et al. (2001) found the upper extremity to be the third most common injury site for pedestrians after the lower extremities and head. Similarly, motorcycle studies have found the upper extremities to be the third or fourth most frequently injured body region for riders involved in crashes (Hight et al., 1973; O'Malley et al., 1985).

***Injury Mechanisms*:** Relatively little is known about the injury mechanisms of non-airbag induced upper limb injuries. This lack of knowledge likely results from the variety of potential contacts for the upper limb within the vehicle and the associated loading possibilities. Based on a retrospective analysis of field data, Otte (1998) concluded that 36.2% of the upper limb injuries could be attributed to a direct impact while 31.9% could result from bending. A slightly smaller number, 21.3%, resulted from axial loads. Other types of load appear to be relatively rare with crush responsible for 8.5% and torsion for 2.1% of all upper extremity fractures. In terms of specific loading types for specific regions of the upper limb, bending was considered the most frequent mechanism for the elbow and wrist, axial loading for the shoulder, torsion for the phalanges, direct impact for the humeral shaft, forearm shaft and metacarpals, and crush for the carpal bones.

For upper extremity injury resulting from interaction with frontal airbags, two modes of injury have been suggested in the literature. The first type is an indirect loading, typically referred to as a flinging type of injury, in which the airbag propels the limb into an object in the vehicle interior (e.g., B-pillar, roof or occupant's body). The second type is primary contact with the airbag or airbag flap. This injury, for example, could be produced while executing a left turn with a continuous motion of the right forearm directly over the module. For upper limb injuries resulting from indirect loading, virtually any type of interaction with the vehicle interior is possible and no study of injury mechanisms has been performed to investigate which loading modes are most frequent. For indirect loading, the airbag typically produces bending-type fractures of the long bones of the forearm.

For seat-mounted side airbags, the initial deployment typically results in contact with the humerus if the limb is in close proximity to the seat edge. Bending fractures of the humerus have been produced in laboratory experiments (Kallieris et al., 1997, Duma et al., 2001a). If humerus fracture does not occur, osteochondral injuries of the flexed elbow may be produced when the humerus is forced into the head of the radius and ulnar notch. For upper limbs constrained by a hand rest, compression-extension injuries of the wrist and compression injuries to the bones of the hand have been observed experimentally (Duma et al., 2001a).

Even without a side airbag, intrusion of the door during a side impact has been shown to produce upper extremity injuries. Otte (1998) hypothesized that intrusion of the door and lateral deceleration resulted in load transmission to lateral parts of the extremities resulting in injuries of the whole upper limb.

The complexity of pedestrian and motorcycle crashes complicates interpretation of specific injury sources and mechanisms. Despite the relatively frequent occurrence of upper extremity injuries for these vulnerable road users, no systematic studies have been conducted to detail injury mechanisms for pedestrians or motorcyclists to the extent done for occupants.

***Population Issues*:** It is known that the injury tolerance of bone is dependent on gender, age, bone mineral content, and loading rate and direction. Baron et al. (1996) showed that females had a higher risk in general of upper extremity fracture. Case studies and NASS investigations suggest that more severe airbag-induced upper extremity injuries occur predominantly in women. It may be hypothesized that this represents the effects of three factors: shorter female stature leading to greater proximity to the wheel and module, greater age-related loss of bone mineral density and generally smaller bones, and, hence, less energy to failure. In non-airbag cases, Otte (1998) found that males in his sample were involved in higher speed crashes and therefore had larger overall frequency of upper extremity injuries.

***Factors*:** Injury outcome is likely strongly influenced by the initial position and condition (i.e., bracing or tensing) of the upper limb, but, because of the complexity of the loading, injury predictors have not as yet been developed. Response by the muscles leads to increased force transmission across the joint surface (Buckwalter et al., 1998), but co-contraction of the muscles across a joint stabilizes the joint and makes it less susceptible to rotational injuries (Granata et al., 1995). Meanwhile, muscle tensing acts to increase the effective mass of segments by effectively linking adjacent structures through contraction of the muscles crossing joints. Given the magnitude of the muscle-induced loads relative to the external loads applied in a crash, more research is needed into the influence of muscle forces on injury outcome.

***Tools*:** While limited in biofidelity, several instrumented dummy upper extremities exist for use in examining loading of the upper limb. A 50th percentile male and a 5th percentile female limb (commonly referred to as the SAE arms) possess qualitatively the correct ranges of motion and sufficient instrumentation to assess the major loading scenarios. However, long bone compliance and joint moment-angle relations are largely non-biofidelic. Entry-level finite element models have been developed but require considerably more validation and material property data to increase their utility (van Rooij et al., 2003).

Most emphasis for upper limb injury criteria has been placed on airbag-induced injuries. For the frontal airbag environment, bending tolerances have been developed for the forearm (Bass et al., 1998) in both the pronated and supinated positions (Duma et al., 2001b). For side airbag loading, bending tolerances of the humerus have been generated as have contact loads for the wrist and elbow (Duma et al., 2001a). Given the vulnerability of the small female population, all injury criteria have been tailored to this group.

Areas for further knowledge

1. While upper limb injuries are frequent, more information (e.g., detailed aetiology of upper limb injuries by specific anatomic locations) is needed to determine their relative importance in terms of disability and impairment measured on such research tools as the Functional Capacity Index (FCI) and Life-years Lost to Injury (LLI).

2. For different crash modes, detailed information is needed about the specific injury sources and injury mechanisms for particular upper limb sites as well as patterns of injury and loading relative to variations in initial position of the upper limb.

3. Given the preponderance of joint injuries and a presumed bending mechanism, injury criteria for the wrist, elbow and glenohumeral joint need to be developed.

4. The effects of musculature bracing should be examined in terms of upper limb injury potential as well as the role in altering occupant kinematics and influencing restraint loading.

5. The effects of the introduction of second generation airbags on projections of airbag-induced injuries suggesting upper limb injury frequency and cost should be studied.

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SECTION 6:
LOWER EXTREMITY INJURIES
Introduction and state of knowledge

Frequency: Lower limb injuries frequently result from automobile crashes. They comprise nearly a third of all non-minor (i.e., AIS 2+) injuries for occupants involved in frontal crashes (Crandall and Martin, 1997). Despite their frequency, the prevention of lower limb injuries has historically been viewed as a relatively low priority due to their non-lethal nature. Before recent increases in seat belt usage rates and wider implementation of airbags, crash victims who sustained severe lower extremity injuries often did not survive the life-threatening head and torso trauma (Dischinger et al., 1994). More recent crash statistics have demonstrated not only the life-saving effectiveness of the belt and airbag combination but have also shown a relative increase in the number of crash- related lower limb injuries requiring medical treatment (Burgess et al., 1995).

Additionally, and in some ways perhaps more important than lower limb injuries sustained by vehicle occupants, the lower limbs of vulnerable road users—pedestrians and cyclists—are the most frequently injured body region (Mizuno and Ishikawa, 2001, O'Malley et al., 1985).

***Significance*:** The significance of lower limb injuries lies not only in their frequency but also in their likelihood to lead to long-term disability and impairment. The weight-bearing nature of the lower limbs coupled with their essential role in locomotion mean that any injury to this region potentially compromises one's ability to perform routine activities. Thus, it is crucial to assess not only the immediate threat associated with lower limb injuries but also to account for permanent consequences. Owing to the low friction design and poor healing capabilities of the joint surfaces, injuries to the hip, knee, ankle and foot joints are particularly problematic as they can lead to degenerative arthritis. Arthritis is the leading cause of disability in the US and Europe with staggering economic consequences. A reasonable percentage of the cases, especially for persons under the age of 45 years, are trauma-related. Due to the disability associated with lower limb injuries, cost estimates involving measures for quality of life project that lower limb trauma will be the most expensive of all crash-induced injuries, thus constituting a significant health problem (Martin et al., 1997).

Injury Distribution: A recent study by Kuppa et al. (2001) examined both the frequency of and the functional life-years lost (LLI) from lower limb injuries to occupants in non-fatal frontal crashes (see table below). While the exact distribution of injuries is dependent on the database and associated inclusion criteria, the most frequent site of fracture or soft tissue damage is consistently the ankle joint (Pattimore et al, 1991, Dischinger et al., 1994, Taylor et al., 1997, Sherwood et al., 1999, Kuppa et al., 2001).

Distribution of lower limb injury frequency and disability (Kuppa et al., 2001)

Lower Limb Region	% AIS 2+ Lower Limb Injuries	% Total LLI of the Lower Limb
Hip	12	24
Femur	9	11
Knee	34	8
Tibial Plateau	7	8
Tibial Shaft	4	8
Foot/Ankle	33	41

Countermeasures: For the most part, seat belts and airbags do not strongly influence either the likelihood or distribution of lower limb injuries relative to an unrestrained occupant. One exception is that lap belts have been shown to reduce forward pelvic excursion that reduces contact forces of the knee into the instrument panel. Similarly, the design of airbag systems to accommodate unrestrained occupants has frequently included a concurrent redesign of the knee bolster for improved femur loading. For the foot and ankle, structural adaptations of the vehicle coupled with energy-absorbing toepan padding address both the magnitude of the deformation and acceleration associated with intrusion (Kallina et al., 1995, Bass et al., 1996). Adaptive structures, such as inflatable padding devices for the toepan, have been researched with some promising results but have not been widely implemented into the vehicle fleet.

Subsystem test procedures for pedestrian countermeasures have been incorporated into vehicle evaluations (EEVC 2002). While problems with the biofidelity of the current legform have been widely noted, refinements in impactor design should lead to improved bumper and vehicle front-end designs for energy absorption and more controlled kinematics of the knee. The combined nature of the “upper” legform encompassing the thigh and pelvis introduces additional complexities that may complicate the design of countermeasures for this region of the vehicle.

Vehicle Crashworthiness: The frequency and nature of lower limb injuries are inextricably bound to the vehicle crash characteristics. In particular, contact with the instrument panel, knee bolster, steering wheel, pedals and floorpan/toepan structure occur frequently. In addition to forward excursion of the occupant instigating contact, structural intrusion of the instrument panel and toepan can reduce occupant compartment space and introduce high local accelerations that are not seen by the overall vehicle structure. Lower limb injuries have shown sensitivity to the timing, duration, rate, magnitude and angle of the deformation. Frontal-offset crashes are particularly prone to intrusion since only a portion of the vehicle’s front structures are engaged and more crush is required to absorb equivalent energy to a full-frontal collision.

Tools: The advent of a dummy lower limb with improved biofidelity should provide a research and design tool for the development of lower limb injury countermeasures. The THOR-LX has been developed by the National Highway Traffic Safety Administration (NHTSA) in the US for the average male and small female dummy and has demonstrated biofidelity under a variety of loading environments (Petit and Troisseille, 1999, Sokol-Jaffredo et al., 2000, Rudd et al., 1999, Wheeler et al., 2000, Ito et al., 2001). In addition to the limb, a provisional set of injury criteria have been developed by Kuppa et al. (2001).

As previously noted, legform impactors for pedestrians are available and are being used to develop vehicle countermeasures. More complex and detailed models of the legform incorporating compliance of the long bones and increased sensing capabilities have recently been developed (Konosu et al., 2005). Finally, the influence of the upper body kinematics on lower limb injury can only be evaluated by finite element models or full-scale dummy tests. While a number of computational models have been developed to address this problem, the Polar II pedestrian dummy is the only physical model exhibiting acceptable biofidelity (Akiyama et al., 2001).

Injury Predictions: Injury criteria have focused primarily on the long bones given the relative simplicity of testing and analysis involved. In particular, femur force criteria have been developed to protect the knee-thigh-hip region. The complexities associated with the inertial distribution of forces within this region, however, necessitate that local criteria be developed for the distal and proximal regions of the femur as well as the shaft. Recent research conducted by Rupp et al. (2003) addresses the injury tolerances for each region of the knee-thigh-hip and characterises the biofidelity of dummies in this body region. For bending tolerance of the femur that may be applicable to pedestrians and motorcyclists, a number of recent studies can be used to predict injuries for different size persons (Kennedy et al., 2004) and different loading locations along the bone (Kerrigan et al., 2004).

Mid-shaft leg injuries are predicted by a combined axial force and bending moment interaction formula known as the tibia index (Mertz 1993). While this formula correctly incorporates both moment and force into the failure equation, it does not address the curvature and asymmetry of the tibia or the eccentricity of loads applied through the knee and ankle. A maximum-allowable axial force of 8 kN is superimposed on the critical values used in the tibia index to account for the weaker distal and proximal ends of the tibia. For lateral bending of the leg that might occur in a side impact or pedestrian-vehicle collision, Kerrigan et al. (2004) summarized the literature and combined published results with new experiments to provide injury risk functions.

Injuries to the calcaneus, tibial plafond and talus have been generally characterized by the maximum-allowable axial force applied to the foot (Yoganandan et al., 1996, Funk et al, 2001). Several studies have demonstrated a difference in tolerance and injury pattern when internal muscular forces are superimposed on the externally-applied load (Kitigawa et al., 1998, Funk et al., 2001). For this reason, the THOR dummy design has incorporated a posterior leg muscle and a load cell sensor capable of recording internal and externally-applied forces.

Rotational ankle injuries are predicted by a maximum moment or angle generated. Injury tolerances have been developed for dorsiflexion (Begeman et al., 1990, Rudd et al., 2004) as well as inversion/eversion (Begeman et al., 1993, Sokol-Jaffredo et al., 2000, Funk et al., 2002). Despite these injury criteria, recent studies have shown the interdependence of combined rotational motions (e.g., dorsiflexion combined with inversion) or combined rotations and axial loads on injury outcome. Additional experimental and computational studies are required to develop an injury surface incorporating simultaneous types of loading.

The complexity of the mid- and forefoot regions has limited the development of injury criteria. To date, only one dynamic study has been performed to impact injuries to the forefoot (Smith et al., 2005).

Areas for further knowledge

1. Overall, the priorities for the lower limb will continue to be in the weight-bearing joints. A further refinement from bony fractures to more subtle damage to the cartilage should be the logical progression in order to address the long-term disabilities associated with these injuries. More definitive injury classification from field data will be facilitated by new injury coding options such as the AIS 2005. An important complement to understanding the disabling nature of the lower limb injuries requires a greater focus on post-injury evaluations of the victim's level of disability.

2. In order to develop an improved understanding of the lower limb response and resulting injury during impact, muscle forces must be incorporated into computational and physical models. Given that lower limb muscle forces influence overall kinematics of the body, active musculature is probably best evaluated through finite element models with accurate passive and active components.

3. In terms of body region-specific research priorities, the following areas deserve attention:

   - **Hip** – Research findings to date show a sensitivity of fracture tolerance to the direction of load and the orientation of the femur in the hip joint at the time of impact. More studies are required to examine this relationship and to evaluate dislocation versus fracture potential.

   - **Leg** – While most injuries to the leg are not typically difficult to repair or heal, they are moderately frequent for vehicle occupants and the most common moderate injury for pedestrians and motorcyclists. The tibia index evaluates combined loading but does not incorporate the complexities of the leg geometry or tolerance changes along the shaft of the long bones. A refined tibia index is required.

   - **Ankle and Knee** – Research should continue into characterizing the stiffness, geometry and material properties of the articular surfaces and their resistance to impact loading.

   - **Ankle** – Structural characterization of the ankle should examine multiple loading directions and ankle orientations. Ultimately, a finite element model of the ankle should be used to consolidate experimental data in the development of a injury threshold surface that incorporates ankle orientation about three axes combined with dynamic plantarflexion/dorsiflexion, inversion/eversion and axial load.

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SECTION 7:
CHILD BIOMECHANICS
Introduction and state of knowledge

As car occupants, children tend to represent a small portion of the total fatality group. In the EU only 3% of all fatally-injured road users and only 2% of car users are under age 15 (National Academy of Sciences 2000, CARE). However, as pedestrians and other vulnerable road users, children account for 7% of fatalities. In motorising countries the proportion can be much higher. In Malaysia, 11% of fatal pedestrians are under 15 and in Papua New Guinea, 24% are children (Jacobs, et al.) Nevertheless, most countries attach a much greater importance to child safety than the total numbers would generally indicate and child injury prevention is normally seen as a major target.

In Europe, the most common road-user types for child fatalities under age 15 are as car occupants (51%), pedestrians (33%) and cyclists (12%). In the US, 42% of fatalities in children under 16 are as car occupants, 29% as light truck occupants, 17% are pedestrians while only 6% are cyclists. Initiatives to reduce child casualties are focussed on increased child restraint use and improved child restraint effectiveness (EU 5th Framework), particularly in side impacts (EEVC). The development of the EC Pedestrian Safety Directive did incorporate specific provisions for child head injury prevention and these will come fully into force as part of the Phase 2 proposals. In the meantime, the requirements have been amalgamated with adult head protection requirements.

There is a significant variation of child occupant protection systems across countries. Some countries such as Sweden use designs of child restraint that keep children rearward-facing until age 4. Other countries, such as the US and Australia, use top-tether systems that have the potential to reduce forward movement of the restraint. In all cases, there is a high level of misuse of child restraints and in some accident cases, misuse has been shown to severely reduce the protection offered.

Child dummies are available to be used to evaluate child protection as car occupants and in child restraints. While early devices were simply used to load the restraints, current designs have significant injury measurement capabilities. These dummies are still limited in their biofidelity and a major gap in knowledge concerns the biomechanical characteristics of children. There are obvious difficulties in conducting relevant experiments using children. Thus, typical injury assessment values are, of necessity, based on scaling methods from adults or animal substitutes.

In particular detailed knowledge in needed about the biomechanical properties of children both at tissue and at structural level. This data should relate to the range of loading conditions to which children are exposed as car occupants and other road users and to increasing stages of child development. As part of this process, further and more detailed crash-injury data is required which can be further analysed using computer-based reconstructions. Such data is scarce and multi-centre approaches are needed to gather data as widely as possible. The scaling methods used to assess injury risk functions also need further development. Recent developments (Mertz 2003) incorporate estimated age dependent changes in tissue properties as well as geometric effects but there is a major lack of validation methods and further improvement is still required.

Areas for further knowledge

1. Further research is needed to improve knowledge on the mechanical properties of child tissues, particularly the brain, to support improved dummy biofidelity and computer models. Associated with this is a need for improved anthropometric data covering all stages of child development and it has been proposed that the Visual Human Project (1996) should be extended to cover children.

2. Child physiology, stature and biomechanics vary considerably between birth and age 15 and a better understanding of the changes in tissue properties over this period is required. Better analyses of the effects of age and physical development separate from size and mass are needed to support, for example, decisions as to when a child should move from rearward to forward-facing restraints.

3. Further crash injury data are needed dealing with issues specific to children including the nature and causation of child injuries, the protection offered by child restraints of all types, the consequences of interactions with deploying front and side airbags, and improved information on the nature of restraint misuse. The detail available can be considerably improved in many cases by better cooperation between researchers, police, paediatricians and by the use of simulations of individual crashes.

4. It has been suggested that evaluation techniques of systems such as airbags should place greater emphasis on the need to reduce child injuries and this should be included in the interpretation of results.

5. Further information is needed on the nature and causation of child cyclist injuries.

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SECTION 8:
CAR OCCUPANTS

Introduction and state of knowledge

Car occupants are generally the most commonly injured of all road users in highly-motorised societies. In the European Union, they represent 56% of all fatalities (CARE) while in the US and Japan they represent 48% and 27% respectively (IRTAD). In comparison with the injury causation experienced by other road-user types, the car provides a relatively predictable impact environment and this has supported the development of countermeasures such as seat belts, airbags and head restraints. The mitigation of car occupant injuries has been a key priority and the success of the various New Car Assessment Programmes (NCAP) has demonstrated the effectiveness of engineering solutions.

It is still the case that the most effective countermeasure to prevent car occupant injuries is the use of seat belts which reduces overall casualties by about 40%. Seat belts have a beneficial effect in most impact directions by reducing peak accelerations, the likelihood of interior contact and occupant ejection. The continued introduction and enforcement of primary seat belt use laws will remain a priority for the mitigation of car occupant injuries.

Frontal Collisions: In 1997 Europe introduced a new frontal crash test regulation based on the use of a deformable barrier intended to reproduce more accurately the characteristics of the car-to-car structural interaction (EC Directive, 1996a). Subsequently, the deformable barrier has also been adopted for use in the European, Australian and other New Car Assessment Programmes. Intrusion, the reduction in “occupant survival space”, had been identified as a key injury risk factor separate from collision severity, and the characteristics of the deformable barrier were such as to promote new low-intrusion car designs. Results from the consumer rating tests have demonstrated that newer designs of car show considerably reduced intrusion when compared to older cars.

Side Collisions: In 1973, the US introduced FMVSS 214 to address protection in side collisions, and in 1993 this was extended to cover light trucks. In 1997, a related test procedure was introduced in Europe (EC Directive, 1996b) and subsequently introduced within EuroNCAP. Evaluations of FMVSS 214 indicated the systems were effective in single-vehicle crashes with little or no benefit in multi-vehicle collisions (Kahane 1982, Walz 2004). An evaluation of car occupant protection priorities of European vehicles has also identified that most side-impact fatalities occur at speeds significantly higher than the current test procedures (Thomas and Frampton, 2003). An additional problem is that up to 40% of the economic cost of side-impact injuries is sustained by occupants who are seated on the far side, away from the intruded area. These casualties are believed to receive very little benefit from current side-impact test requirements.

Rear Impacts: Impacts to the rear of a car are very uncommon as a cause of death. However, they represent the greatest risk of neck injury. Some field accident databases indicate that over 60% of car occupants in rear impacts sustain a “whiplash” injury compared to 17% overall.

Rollovers: Vehicle rollover as a cause of fatality is relatively rare in Europe. The greatest injury risk arises from partial or complete ejection from the vehicle, and high levels of seat belt use reduce the opportunities for this to occur. In the UK, rollovers represent less than 5% of all crashes, but 20% of these are fatal. In the US, where the large numbers of sports-utility vehicles (SUVs) have been shown to offer a greater risk of injury, about 20% of passenger vehicle deaths involve rollovers (Traffic Safety Facts, 2003). There are, however, no internationally-agreed definitions of a rollover and it is likely that data are not comparable across countries.

Areas for further knowledge

Active Safety Technologies: New technologies are being applied to a wide range of crash prevention systems for cars and the highway. Some of these, such as pre-crash sensing systems, may support improved deployment of restraint systems. Others, such as Electronic Stability Control, may prevent certain types of impact and so change the priorities for passive safety systems. There is a lack of knowledge concerning the highest priority systems for casualty reduction and no data concerning the changing accident population. Important factors needing further research concern limitations of human adaptation to new systems and the acceptability of the driver to relinquish control over the vehicle. There are no analytical strategies available to ensure that passive and active safety systems are optimised together to maximise the potential casualty reduction.

The use of a small range of crash conditions to specify the performance of cars in crashes opens the possibility that vehicles will be optimised for these tests rather than for the full range of real-world conditions. Research is needed to develop methodologies to engineer systems for maximum benefit, particularly for side-impact protection where safety systems are less developed. Additionally, a wider range of crash types needs to be incorporated into the development process of new cars, and methodologies based on physical or virtual testing are needed to support this. These methods should take account of the natural bio-mechanical variations between individuals as well as the range of vehicle types within national fleets.

***Frontal and oblique impact protection*:** Vehicle structures are key elements in the prevention of intrusion and the management of the collision energies in the form of the crash pulse. They also determine the load paths when one vehicle strikes another object. Specific questions to be addressed include:

1. how to develop versatile structures for the range of real-world conditions

2. how to design new structures to respond to low mass and improved fuel economy from environmental demands.

3. how to improve front and side-impact compatibility for car-to-vehicle (all sizes) and car-to-roadside object impacts (e.g., trees, poles, guardrails, median dividers)

4. how to develop adaptive and deployable structures to improve energy management

5. how to further reduce intrusion in real-world crashes, particularly in the footwell region

Restraint systems: Restraint systems, such as seat belts and airbags, have provided major benefits in preventing death and injury. The NHTSA in the US estimates that 2,500 lives were saved by airbags in 2003 and 14,900 by seat belts. A further 6,000 lives would be saved by 100% seat belt use (Traffic Safety Facts, 2003). Nevertheless, there are still opportunities to improve restraint effectiveness by further research and development. Specific areas include:

1. development of methods to provide continuous or stepwise-variable characteristics of interior restraint systems as a function of impact severity, occupant sitting posture, occupant size and susceptibility to injury

2. reduction of WAD ("whiplash" associated disorder) injuries through improvements in seat belts and airbags

3. assessment of the potentials of pre-crash sensing technology.

4. development of integrated child seats

5. new technologies to encourage seat belt usage, particularly in rear seats, by improving comfort, spool in and convenience

6. improved seat belt and airbag performance in oblique crashes

Side impact protection: UK field accident data indicate that side impacts are the single most common cause of fatality in recent production passenger vehicles (Thomas and Frampton, 2003) exceeding those killed in frontal collisions. While it is possible that ESP systems may reduce certain types of side impact, there are opportunities for improved crash protection. In particular, further research is needed into the following areas:

1. How can the sensing of side impacts be improved to permit side airbags to be deployed more effectively?

2. Are current restraint systems such as side-curtain airbags effective in preventing head injury to occupants of a car when struck by an SUV or pole?

3. What are the causes of far-side occupant injuries, how well are they represented by existing dummies and how can the injuries be prevented?

4. How do current front bumper standards and low speed crash repair cost tests affect bullet car aggressivity in side impacts?

5. How can structures be improved to benefit compatibility in car-to-car or car-to-SUV side impacts?

Rear impacts: Major research questions on rear impact safety concern the nature and biomechanics of "whiplash" injury. Additional research is needed on the relationship between rear structure design, rear impact crash pulses and "whiplash" injury risk.

Monitoring of the effectiveness of existing head restraints is needed to support further design improvements.

The integrity of fuel systems in rear crashes should be monitored and improved.

Rollovers: The primary means to improve rollover protection is increased levels of seat belt use. Improved restraints that reduce partial ejection and interior head contact would also be beneficial.

Further research into improved roof strength and the application of laminated glass in side windows and sunroofs is needed.

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SECTION 9:
PEDESTRIANS

Introduction and state of knowledge

Injury Frequency: Pedestrians generally represent a key group of traffic fatalities in most regions of the world although the proportion of the total they form varies according to the degree of motorisation and the mix of vehicle types in the fleet. For example, pedestrians represent 11% of all traffic deaths in the US, 15% in the EU and 29% in Japan (IRTAD 2004). In low and middle-income countries, they can account for 41-75% of all fatalities (Peden et al., 2004).

Injury Mechanisms: Early field accident studies identified the most frequently injured body regions of pedestrians to be the leg and head resulting from impacts with the bumper and bonnet (Ashton and Mackay, 1979). Subsequent aerodynamic developments in vehicle front-end design have changed profiles and changed the bonnet leading edge structures, which were a cause of pelvic injury (Ashton and Mackay, 2004, Cavallero et al., 2004). The typical pedestrian kinematic involved a first set of impacts with the vehicle followed by a second impact with the road, thus creating disagreement over the possible limits to pedestrian protection. Nevertheless, current crash data seem to identify the car as the most common cause of the severe injuries while the road impact is generally less severe (Otte 1999, Yang 1997, Liu 2003).

Tools: There have been attempts to use existing car occupant dummies or to develop new dummies to assess pedestrian injury risk. Several obstacles have been found, notably that car occupant dummies have not been capable of assessing some of the specific injuries sustained by pedestrians (e.g., knee ligament injuries). Furthermore, pedestrian dummy kinematics are highly sensitive to the exact test condition with very small differences in set-up sometimes making a significant difference in injury values. This means that test repeatability is particularly low when using full-scale dummies.

A recent EU Directive has been introduced to address pedestrian injuries. Implemented in two phases, it utilises sub-system tests to examine the risks of lower leg injury from the car bumper and head injury from the car bonnet (EU Directive, 2003a, EU Directive, 2003b). The second-phase tests increase the range of the zones assessed and introduce a test for upper leg injuries. Alternative test procedures, with an equivalent protective benefit, will be permitted for the second phase although these are as yet undefined, and there is the possibility that active safety measures will be permitted as substitutes.

There are two major constraints with the legal test requirements. One is that although the most important injury-causing areas of the car are addressed, there are others, including the windscreen, roof and A-pillars, that are also relatively frequent causes of severe injury. The second is that the tests are based on an impact velocity of 40km/hr which represents a speed where serious injury risk is high but it is below the typical speed for fatalities.

Areas for further knowledge

Although improvements in pedestrian protection are expected to derive from the recent directive in Europe, there are still several areas where further research is needed.

1. Detailed accident studies are required to monitor the introduction of the EC Directive and to develop an understanding of pre-crash and crash events.

2. There is still the need to understand the interaction between vulnerable road users and the front structures of vehicles with regard to secondary road impacts. More knowledge is required on the effect of modern front-end shape and on the biomechanics of the event so as to support developments in methods to control the impact with the road.

3. The latest proposals from the Global Road Safety Partnership (GRSP) concerning pedestrian safety need to be reviewed and evaluated in the light of experience with the EU Directive. This Directive, once in force for new models in 2005, will require new crash data to be gathered to determine the effects on injuries. There is also the possibility of conflicts with protection requirements for motorcyclists and bicyclists and these will need evaluation (Maki et al., 2003).

4. Biomechanics of pedestrian impacts with trucks and buses needs much greater attention. This work should aim at developing bus/truck-pedestrian impact standards by 2010 (Kajzer et al., 1992, Chawla et al., 2000, Lefler and Gabler, 2004, Roudsari et al., 2004).

5. There is a need for an improved understanding of the relation between bumper height and knee-joint injuries. The implications for injuries in one body region, when loads are applied to another region, need to be assessed, particularly in relation to subsystem tests. Improved finite element dummy models will enable new research to be conducted that may address these issues.

6. There is still the need to improve knowledge on the biomechanics of pedestrian protection. Issues concerning long-term head injury sequelae (chronic headaches, behavioural effects) from impacts at $<$1,000 HIC need to be addressed.

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SECTION 10: MOTORCYCLIST CASUALTIES

Introduction and state of knowledge

Frequency and Injury Patterns: Motorcyclists account for 17% of European road deaths, 18% in Japan, but only 9% in the US. In rapidly-motorising countries, motorcycles can be the most common vehicle type purchased so the exposure of motorcyclists to risk is increasing rapidly. In many highly-motorised countries, the use of motorcycles is also increasing, particularly among older age groups and in some countries, motorcyclist fatalities have increased by as much as 14% in one year (UK Department of Transport 2003), but not in every European country; for example, Germany experienced a 1% reduction during the last decade.

The injury patterns typically sustained by motorcycle riders tend to differ from those sustained by other road users. Since the 99% usage of the integral face helmet, head injuries among helmeted cyclists have been reduced to about 20%. On the other hand, the risk of injuries to the lower extremity is high when compared to the neck and spine where injury risk is relatively low. Many of the injury types involving motorcyclists, especially those to the extremities, have considerable potential for long-term disability and impairment. Protection of the lower limb has become a priority (Otte, 1994).

The nature of injuries to motorcyclists differs from other road users and it is not clear that the injury assessment reference values used for car occupant protection, for example, are applicable to motorcycle riders. The frequent lower extremity injuries, including the pelvis, are in many cases sustained by lateral loading, and quite different injury mechanisms appear to be involved.

Protective Equipment: Approaches to rider protection include the use of helmets, protective clothing, special leg protection systems and most recently airbags. Helmets have been shown to be extremely effective in reducing the risks of fatal and disabling brain injury, yet their use is still not mandated uniformly. Different styles of helmets provide more or less head protection, even though each may meet the US Department of Transportation or Snell Foundation standards. In Europe, helmets have to meet European regulation ECE 22-06. Only relatively recently, the regulation has incorporated protection of the chin region in the test procedure. In hotter regions around the world, traditional systems can result in high heat build-up within the helmet and new designs, with increased ventilation, have been introduced in some tropical countries. However, the protective effect of these systems has yet to be fully evaluated. New research on this topic has just started (COST, 2005).

Helmet design has improved significantly over the last 30 years when about 70% of injured motorcyclists suffered head injuries despite helmet use. Today that number has been reduced to about 20%. A recent EU study (COST, 2005) investigated motorcycle crashes in three European countries–Germany, the UK and Finland–and found that of the total number of helmeted motorcyclists involved in an accident, only 18.4% had any head injury of which 9.7% were severe.

Many riders sustain soft tissue injuries from road impact, and suitable protective clothing systems have been developed. A European CEN standard now exists to promote higher levels of effectiveness in clothing (EN 13594 gloves; EN 13595-1 bis -4 jackets, trousers and combi-units; EN 13634 shoes). A drop-test prEN1621-2 is used to measure shock absorption. Special protector systems are used on the shoulders, elbows, arms and thorax, and special back protectors are used to protect the spine.

In the 1980s and 1990s, prototype systems of leg protectors on the bike to mitigate lower extremity injury were developed, but the designs were not uniformly acceptable and there were some indications that they raised the risks of injury to other body regions despite lowering leg injury risk (Otte, 1994)

A standard describing procedures to evaluate passive safety for motorcycles has been developed by an OECD working group following ISO Standard 13232, with procedures for testing and evaluating the required safety standard. This standard does specify the design of a test dummy with frangible leg forms to evaluate the injury risk, but there has been little validation and it has not been adopted as mandatory regulation anywhere.

While some motorcycle accident data are available, notably through the German In-depth Accident Study (GIDAS), Medical University Hannover (Otte et al., 2003) and the MAIDS in-depth investigation of accidents involving powered two-wheelers (EMMA, 2004), there are still aspects of the crash and injury causation scenario that require greater clarity. Much more work is needed to develop protective devices on the bike such as leg protectors, airbags and knee bolsters. Accident reconstruction methods are available for motorcycles, but accurate determination of rider kinematics and injury causation is complex and there is a need to develop improved modelling techniques.

Areas for further knowledge

1. Further research on the relative benefits of leg protectors should be conducted.

2. Further improvements in helmet design are needed to ensure that protection is optimised for the full range of real-world crash conditions and that tropical designs still offer the maximum protection in all European countries and worldwide.

3. The importance of rotational loading and helmet design needs to be further clarified although there are strong suspicions that they play an important role in injuries to helmeted riders. Moped and scooter riders may be subject to different head impact conditions and there is a need to ensure that helmets offer optimised protection for the full range of crash conditions of these special types of cycle as well.

4. While there is a tendency to look for traffic safety measures to reduce rider casualties, there are still significant opportunities to develop motorcycle-based techniques to reduce injury. Further improvements in rider protection are dependent on a satisfactory dummy being available. The rider dummy is only partially validated and requires further development before it can be used to assess the effectiveness of modern technologies in mitigating injuries. Field accident data and biomechanical studies are required to properly validate these dummies and finite element models are needed to improve injury prevention technologies. These dummies also require improved biomechanical knowledge concerning the relevance of car occupant-derived injury parameters to the injuries sustained by motorcycle riders.

5. The relationship between collision severity and injury severity needs to be determined more precisely. The influence of the collision angle is much more important for the kinematics of the two-wheeler than for other vehicles.

6. The changing distribution of rider age groups in many motorised countries may have implications for rider protection. Further field accident data are needed to clarify these issues.

7. Collision avoidance tools need further investigation as these have direct implications for injury reduction.

8. Quad-bikes are growing in usage, particularly off-road, and these vehicles have their own special collision and injury factors which should be studied. It is not immediately apparent that motorcycle injury prevention technologies are the most appropriate for quad-riders with the exception that helmet use should be mandatory.

9. Anecdotal cases have suggested that guardrails present a significant hazard to riders if they cause the rider and cycle to become separated post impact. Field accident data are needed to evaluate the magnitude and nature of this injury problem. Also, the effectiveness of foam pillar protectors, used occasionally in some countries, needs to be evaluated.

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SECTION 11: CYCLISTS

Introduction and state of knowledge

Cyclist fatalities are relatively rare in many highly-motorised countries. Across Europe, only 5% of road-user fatalities are cyclists and in the US they constitute less than 2% (IRTAD 2004). In the Netherlands and Japan, however, cyclists constitute 18% and 14% of the fatalities, respectively. There is much evidence that cyclist crashes are frequently under-reported in national statistics, particularly when the crashes are single-vehicle or non-fatal. A study from Sweden shows that bicycle fatalities were only 0.7% of the total number of those hospitalised every year (Bostrom and Nilsson, 2001)

Some studies over the years provide details of injury distributions and contact points of bicyclists with impacting vehicles (Fife et al., 1983, Ching et al., 1997, Eilert-Petersson and Schelp, 1997, Depreitere et al., 2004).

Normally cyclists are grouped with pedestrians and motorcyclists and are considered to be a homogenous group of vulnerable road users. Many of the casualty reduction estimates for the recent EU Pedestrian Safety Directive included estimates for cyclists calculated on a similar basis to pedestrians (Lawrence et al., 2004). But recent research suggests that there may be key differences and that engineering solutions to reduce pedestrian injuries may not have the same level of effectiveness for cyclists (Maki et al., 2003).

Casualty reduction methods have primarily concentrated on road engineering measures and rider training. More recently, several US states have mandated compulsory helmet use and there is the expectation that this will reduce fatal and impairing head injuries (Curnow, 2003, Thompson et al., 2003). Also, attempts are being made to optimise bicycle helmet properties (Willinger et al., 1998).

Areas for further knowledge

1. A fuller assessment of the protection offered by helmets in real-world collisions is needed to determine how helmet design could be improved.

2. A better understanding of cyclist kinematics and interaction with all vehicle fronts, aided by improved modelling techniques, is needed to properly evaluate front-end aggressivity.

3. Further accident data analysis is needed to evaluate the travel speed of the cycle, especially the influence on head trajectory and the role of injuries sustained from interaction with vehicles and secondary impacts with roads and roadside furniture.

4. Conflicts and synergy with pedestrian impact standards need investigation.

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SECTION 12:
HUMANOID MODELLING
Introduction and state of knowledge

Historically, most of the development of new car models has been based on a series of physical vehicles that are progressively refined until the production version has been reached. In recent years, computer simulation methods have been used in increasing quantities and levels of complexity to replace the development of physical prototypes by computer simulations. While simulations of dummies are needed to address legal compliance issues, improved safety more generally is dependent on improved models of the human. These humanoid models at a basic level can be used to specify occupant kinematics and to measure the loading conditions from restraints or vehicle interior structures. It is anticipated that further developments will enable injuries to be simulated under a more flexible and realistic crash environment. Such models will have application in both the legislative and research domains.

Crash tests are performed in limited conditions due to their cost and the tools used. In fact, adult dummies exist only in three sizes. With human models, size and weight can be made to vary separately and in narrower increments which would facilitate the assessment of protection for all the population at risk. The mechanical response (thoracic force/deflection characteristics) can also be adjusted to reproduce specific age-related characteristics.

Early humanoid simulations were multibody models aimed at reproducing the human kinematics (Canaple et al., 2002). Later finite element (FE) modelling techniques were used to simulate individual body segments (Cesari et al., 1994) Currently full-body models are in development or validation phase (Iwamoto et al., 2002). These models will predict injuries through stress/strain values, but they are not yet able to reproduce injuries (Zhang et al., 2001). The biofidelity/accuracy of models is limited by the simplifications made to represent all body tissues with their relevant mechanical properties.

Some human body components, for example the brain and internal organs, are so complicated that they cannot be designed as dummy parts and their representation in human FE models is more realistic. Thus, human numerical models would improve the assessment of injuries to such body parts (Miller et al., 1999) and would add to the current knowledge base on impact biomechanics and injury tolerance levels, especially as related to children (Arnoux et al., 2004).

Virtual testing, in addition to crash tests, will contribute to the development of optimised solutions for the protection of road users when fully-validated biofidelic human models become available. Virtual testing will not replace type-approval or consumer crash tests in the next few years, but will more likely be used to extend the protection assessment to non-tested conditions and provide a better prediction than what can be made with dummies alone of some specific injuries such as brain injuries. Over the long term, however, it is expected that humanoid models will be used to improve the protection offered to real people, bypassing the approximations and assumptions imposed by the use of crash test dummies.

Considerable benefit is expected once specific real-world collisions can be simulated. This will allow the precise loading conditions on the body to be estimated and used to derive real-world injury risk curves for much more stratified sections of the population. Before this can be done properly, however, there is a need for improved information concerning the pre-crash sitting posture of car occupants and for more specific crash pulse information.

It will never be acceptable to conduct injury-inducing tests on live human beings and mathematical surrogates offer a better opportunity to improve the understanding of injury mechanisms than do the current mechanical devices. To gain the full benefit from these models it is essential that there should be gathered full and detailed information on the physical and geometric properties of human biological materials. Once developed there will be the need to validate the models and methods are urgently needed to enable validation without the use of live human beings

Areas for further knowledge

1. The development of suitable models and their use in research and development is a rapidly changing field. A primary set of issues concerns the procedures for evaluation, validation and acceptance of a model since, in general, it is possible to tune any model to one specific test condition. Minimum standards are needed to determine the suitability of a model for research or engineering purposes. While it is desirable to develop a range of humanoid models, it is also desirable that there should be greater coordination to avoid unnecessary duplication of research.

2. While models do offer the opportunity to introduce any particular set of human physical characteristics, there is currently no available mechanism to manage this process in a systematic way. Stochastic techniques do offer potential but their further development is needed before they can be used to represent the range of human population variation.

3. As simulation capabilities improve, there is an increasing need for more detailed and more accurate information on the properties of human biological material and structures. There is a need for further experimental data of sufficient detail, gathered under relevant loading conditions, that can be used both as a reference for model validation and for improved reproduction of injuries. These data should include the simulation of muscle response.

4. Even at the current stage of development, there is the potential to use human numerical models to improve biomechanical knowledge, especially of child injury risk. Because it is extremely difficult to obtain experimental information on the biomechanical properties of children, research in this area should be fostered. In addition, improved scaling techniques are needed to obtain better representations of children.

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SECTION 13:
DUMMIES

Introduction and state of knowledge

The crash performance of motor vehicles and their safety features is evaluated through tests defined in automotive safety standards. In these standards, road crashes are simulated by well-defined laboratory experiments. Such tests are similarly defined for aircraft crashes. For obvious reasons, it is impossible to perform such experiments with real human beings. Therefore, approval tests in accordance with these standards are carried out with anthropomorphic test devices (ATDs) known as crash dummies. These surrogates have similar characteristics as human beings and are fitted with special instrumentation that enables injuries to be assessed. Mathematical models are also used, as an alternative to these mechanical models, to represent the human body in crash performance analyses, but mathematical models of the human body are not specified yet in a regulatory environment.

A number of the current automotive safety standards have been developed on different continents and make use of rather different crash dummy designs although the crash situations are very similar. For several reasons, including economics, global harmonisation of such safety standards is important.

Crash dummies normally consist of a metal or plastic skeleton, including joints, covered by a simulated flesh-like plastic or foam. They are constructed such that dimensions, masses and mass distributions, and therefore the kinematics in a crash, replicate the human. The dummy is fitted with instrumentation to measure accelerations, forces and deflections during the test that correlate with injury criteria for human beings. Repeatability of dummy response in identical tests is fundamental.

Design requirements for crash dummies include, among others, repeatability, durability, anthropometry and biofidelity, where biofidelity (i.e., achieving realistic human-like response) is probably the most difficult part of the design of a dummy. Mechanical characteristics, such as the stiffness of the dummy at the points at which it is struck and where it is likely to strike the vehicle, should be similar to those of similar parts of the human body. This means that the dummy should inflict damage on the vehicle and interact with restraint systems similar to that found from human impacts in real-world crashes or from human cadavers in crash tests. Similarly, the dummy should deform where struck in a representative manner. If the detailed dummy response is not realistic, the impact measurements at those points on the dummy will not be correct and the dummy will guide the vehicle design in the wrong direction. Van Ratingen (2004) provides an overview of the current status in the field of crash dummies.

There is a great need for physical test tools that are better able to represent the human body in a crash environment than the current generation of crash test dummies. As vehicles become more sophisticated and better able to protect their occupants in a range of crash situations, tools are needed that can assess the level of protection offered in all of these situations. The dummies currently in use are optimised for impacts in only one direction (front or side), but with crash conditions other than purely front or side increasingly coming to the forefront of safety discussions, there is a need for dummies that are omni-directional. It is notable that recent advanced dummies such as THOR (Rangarajan and

Shams, 2002) and WorldSID (Cesari et al., 2001) have been partly evaluated under oblique impact conditions.

The current dummies are also generally quite limited in their biofidelity, not only in terms of the kinematics of some joint complexes (for instance, the shoulder and neck), but also in terms of their mass distribution and properties of the soft tissues. The structure of crash dummies should become more human-like, with soft tissue and skeletal structures having geometries and densities increasingly similar to the human equivalent.

Crash dummies should represent the human frame in terms of selected size and corresponding mass and mass distribution. The dummy should interact correctly with the vehicle seat and the safety belt system. Moreover, the dummy should sit in the seat in a human-like manner. In automotive tests, a mid-sized (50th percentile) adult male dummy is most frequently used. Occasionally, two other sizes are used in vehicle crash tests, a 95th percentile (large) male and a 5th percentile (small) female. In addition, there are also several crash dummies representing various sized children, but the level of biofidelity of these dummies is even more of concern than for adult dummies due to the lack of suitable biomechanical data.

With the advent of active safety technologies, it will not only be the mechanical properties of a dummy during a crash that need to be addressed, but also the radar and thermal signatures will need to be replicated as well as the response of the human body before the crash (pre-crash phase) (EPSN 2004).

Future milestones are expected to include:

- 2005-2010 - development of a new generation of advanced, more biofidelic dummies (e.g., THOR, WorldSID, “whiplash”, rollover and child dummies)
- 2010 and beyond - development of a family of next generation, general- purpose dummies. These dummies will be:
    - omni-directional
    - based on the human anatomy and material properties
    - applicable to all impact directions and including motorcyclists and pedestrians
    - able to replicate pre-crash characteristics (thermal and radar signatures)
    - able to represent bracing (muscle tension)
    - equipped with advanced instrumentation to monitor 3D occupant kinematics, occupant loading and injury response.

Areas for further knowledge

1. New biomechanical (biofidelity) data especially for the elderly population and for children are fundamental.

2. Materials able to simulate the human body in a more realistic way are needed.

3. Knowledge of human body response in pre-crash conditions and how that response can be simulated must be developed.

4. The applicability of current dummies to advanced restraints needs investigation.

5. The interaction of crash dummies with sensors (occupant monitoring) is a fertile field for research.

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SECTION 14:
ACCIDENT DATA
Introduction and state of knowledge

The prevention of injuries to road users requires detailed field accident data to direct and support many aspects of countermeasure development. Most fundamentally, basic data are required to identify the types of injuries occurring and the circumstances of injury so as to prioritise the areas where new technologies or injury mitigation approaches are needed. In so doing it will also give direction to other areas of crash research to ensure work is directed towards the areas of maximum casualty reduction. At a more detailed level, in-depth data can give insights into the causation of injuries where living tissues are known to have substantially different properties from dead tissues, for example, the brain. Additionally, there are areas where it is not possible to conduct the conventional processes of experimental biomechanics research, such as injuries to children, where detailed real-world data provide the only possibility to quantify injury risk.

In general, the collection of road accident data is poor when compared to other transport modes. Typically the only information is recorded in a police report where the main purpose is normally the attribution of blame. In many countries even some that are highly motorised, road crashes are underreported and even fatal crashes only receive a superficial investigation. Although some territories such as the US (NASS), Europe (SafetyNet, Pendant), UK (CCIS, OTS) and Germany (GIDAS) have a coordinated range of crash injury databases, most do not and there are major obstacles to building an accurate and detailed picture of crash injury patterns. Developing statistical and conceptual links between existing databases can open new opportunities for crash injury analysis, augmenting special accident data sets.

Often crash injury databases are constructed so as to be representative of the wider crash population. While there are strengths to these systems, they often do not address the issues relating to the most recent aspects of vehicle design or the more life-threatening and impairing injuries. Thus, more selective databases can often provide more useful information.

Specific application areas include:

Injured populations

- identification of populations at risk
- assessment of risk and exposure for particular crash conditions
- generalisation from crash samples to populations

Countermeasure development

- prioritisation of injury types based on threat to life, impairment and wider costs to society
- identification of injury causation mechanisms (e.g., parts of the vehicle that contribute to injury)
- evaluation of specific loading conditions related to specific injuries
- assessment and feedback of countermeasure effectiveness

Biomechanics research

- anatomical description of injuries and loading conditions to direct more detailed experimental research
- validation of humanoid and dummy models
- validation of experimentally-derived injury risk curves
- development of injury risk curves for specific population groups and/or injuries (children, soft tissue injuries)

Crashworthiness development

- evaluation of loading conditions on vehicles
- assessment of vehicle response such as crush, intrusion, energy absorption, effectiveness of load paths
- quantification of loading conditions against injury outcome (real-world injury risk curves)
- validation of vehicle FE models under a wide range of crash conditions

Exposure data

Exposure data describe the frequency that road users are exposed to a particular condition. At the level of injury prevention, exposure data are needed to describe:

- pre-crash occupant sitting posture
- pre-crash loading conditions (e.g., bracing).

Field accident data, a basic tool in crash research, are used to identify priorities, to provide feedback on the effectiveness of new countermeasures and to describe crashes and injuries and their circumstances to support new interventions. A classification of data types is given in Table 1 although in practise there is a continuum with no real boundary between the levels. Typically national level data are gathered by the police and are used to follow trends over time and to make international and regional comparisons. Examples are the EU CARE and the US General Estimates System (GES) databases. The development and assessment of countermeasures, whether they address crash or injury prevention, requires more detailed data that are most often gathered using specialist investigations. These studies may sometimes address just a single research question but more commonly are observational, extending over several years, due to the magnitude of the research infrastructure that has to be installed.

Table 1: Types of accident data

Increasing numbers ↑ (upward, left side) / Increasing detail ↓ (downward, right side)

Level	Main Source of Data	Functions
Base Level (low detail, many cases)	National accident data	• Priorities • Trends • Progress to targets
Intermediate level	Specialist police reports Insurance reports	• Identification of blame • Reconstruction of pre-crash events
In-Depth level (high detail, few cases)	Special investigations	• Accident causation • Injury causation • Basic research • Engineering feedback • Technical standards
Specialist	Research studies	• Specific research questions
Exposure data	National level surveys	• Estimation of risk • Comparison between countries

This review addresses the issues concerned with injury prevention and associated biomechanics and crashworthiness research. It does not address the types of crash injury data needed for national road safety policies or the developing field of crash avoidance. Nevertheless, a key feature of a robust road and vehicle safety policy is the availability of a range of coordinated databases that together provide both a broad and a detailed knowledge of crash and injury causation.

Crash Investigation Tools: In-depth crash investigation has been conducted for several decades and many of the tools that are currently used are refinements of early systems. Injury assessment scales provide anatomical descriptions of the injuries and some quantification of the threat to life. Crash reconstruction methods determine impact speeds and location of applied forces. Observational methods are still used to assess occupant kinematics based on contact locations. However, while other areas of crash research--experimental biomechanics, vehicle and human simulation--have taken advantage of technology development and are now able to investigate at a much more detailed level, crash investigation has changed much less and there is now a need to develop new tools to match the level of engineering activity elsewhere.

Areas for further knowledge

1. A representative, in-depth observational study investigating injuries, their causes and the effectiveness of countermeasures should be undertaken. This should be a long-term study, conducted as part of national casualty reduction policies and automotive manufacturing. Key features include the continued assessment of the casualty reduction effects of legislation and new technologies and continued comparison of biomechanics research priorities against the incidence of real-world injuries.

2. Event Data Recorder technologies ("black boxes") should routinely provide

3. improved engineering information about the crash phase (e.g., crash pulse, airbag deployment, seat belt use, pre-crash conditions).

4. Continued research on the causation of child injuries in crashes supported by detailed reconstructions to evaluate child injury risk curves should be a priority.

5. Information on post-crash events, rescue and treatment should be improved and made readily available for research purposes.

6. While emphasis should continue on increasing seat belt use, research into the prevention of injuries to unrestrained occupants has a role.

7. The real-world performance of anti-whiplash seats should be evaluated. Neck injuries sustained in such seats should be compared with current injury criteria, such as the NIC and the Nkm.

8. Continued research into injury causation of pedestrians and motorcyclists should be supported.

9. Detailed crashworthiness research into the interactions between vehicles and roadside objects is an important study area.

10. New technologies to gather and store information on pre-crash occupant sitting posture, possibly coupled with simulation methods, should be developed.

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GIDAS, German In-depth Accident Study, Medical University of Hanover, 2005.

SafetyNet, The European Road Safety Observatory, DG-TREN European Commission, 2004.

CARE, Community database on Accidents on the Roads in Europe – 2005, DG-TREN European Commission

Pendant, Pan-European coordinated Accident and Injury Database, 2003, DG-TREN, European Commission

SECTION 15: INJURY SCALES

Introduction and state of knowledge

Data systems on crashes and injuries are fundamental to the establishment of sound public policies, for monitoring trauma care and for identifying injury prevention and mitigation measures. The classification of injuries by type and severity, both in terms of their relative threat to life as well as the probability of resultant impairment or long-term disability, should be the cornerstone of every data system. Without standardised schemes for describing the nature and severity of both fatal and non-fatal injuries, the societal and financial burden of injury remains guesswork.

Injury classification systems provide the tools to document the frequency and severity of injuries by specific organ, anatomical structure and body region, hence facilitating the prioritisation of measures to prevent or mitigate injuries to the most vulnerable parts of the human frame. Further, injury classification systems provide a scientific basis for evaluating the effects of interventions and countermeasures on injury reduction, thus providing a basis for adopting optimal public policies.

Several tools currently exist that can contribute to the globalisation of injury scales.

Tissue Damage Assessment: The Abbreviated Injury Scale (AIS), first published in 1971 (Committee on Medical Aspects of Automotive Safety 1971), is the most widely used scheme for injury severity assessment. Currently in its sixth revision, the AIS (2005) is a dictionary of approximately 2,000 descriptions of individual injuries, mainly anatomically-based, written in currently acceptable medical terminology. While many of the injury descriptions are clinically-specific and require some knowledge of contemporary trauma language, the AIS is so structured that it can equally accommodate less detailed information, thus fostering compatibility across different data needs and uses. The bedrock of the AIS is its 6-point numerical severity ranking system (AIS 1=minor injury; AIS 6=injury currently untreatable) that has remained virtually unchanged for three decades. By its nature, the AIS can be used by both medical and non-medical researchers.

A number of derivative systems have evolved over the years for assessing overall injury severity in multiply-injured persons. These include the Maximum AIS, Injury Severity Score (Baker et al., 1974), New Injury Severity Score (Osler et al., 1997), Trauma Score, TRISS (combined Trauma Score and ISS) (Boyd et al., 1987) and ASCOT (A Severity Characterization of Trauma) (Champion et al., 1996). Some of these scales combine anatomical and physiological measures and, therefore, are used specifically in a clinical setting. However, several others, such as the MAIS and the ISS both of which have been in use since the 1970s, do not require any clinical basis for use and have been widely applied in both medical and non-medical settings. All of these derivative schemes are founded on the AIS.

Impairment and Disability: More recently, the development of an injury outcome scale has become a priority. While the topic is not new – scales date back to the 1980s (Hirsch and Eppinger, 1984, Gustafsson et al., 1985, Bull 1985) – there is still significant disparity on what criteria to use, although there seems to be agreement that any future impairment scale should be directly linked to the AIS. One such effort was the Injury Impairment Scale (IIS) (AAAM 1994). It was fashioned directly on the AIS severity code and assigned a value between 1 and 6 to each injury descriptor that was adjudged to have some residual impairment one year post injury. Several years later, the IIS was supplanted by the Functional Capacity Index (FCI), developed through a large collaborative effort in the US (MacKenzie et al., 1996). The FCI, also directly linked to the AIS, has been validated on one patient population and some revisions to the Index were subsequently proposed. It is anticipated that the FCI will be integrated into the AIS dictionary thus offering substantial opportunities to validate it as a research tool to assess the probability and severity of injury-related impairment.

ICDMAP: The International Classification of Diseases (ICD) is the most widely used hospital-based system in the world to characterize patient discharge diagnoses and for billing purposes for all hospital admissions for any cause. In the mid-1980s, a conversion scheme between the trauma-related sections of the ICD 9th edition, Clinical Modifications, and the AIS was developed to broaden the application of the AIS (MacKenzie 1989). The ICDMAP is a system that provides a summary severity measure, in effect, an approximation of severity, particularly useful for large administrative databases where detailed injury information is either not available or where limited resources would prohibit coding directly from the AIS. While the current ICDMAP does not offer the potential for linking with an impairment scale because of its lack of detail, it has utility in certain circumstances and could further promote the use of the AIS, albeit through a surrogate system. Work is underway to map AIS 2005 to both ICD9-CM and to ICD10-CM when the latter is released for general application.

Cost of Injury: The economic and societal costs of injury among other disease and public health problems are enormous (Murray and Lopez, 1996, Peden et al, 2004). While there have been a number of attempts to develop an AIS-based cost model, the components of such efforts vary enormously. For example, a study conducted in the USA (Miller 1991) reporting on the costs of road traffic-related injuries included costs of emergency services, medical care, insurance administration and lost wages as well as other estimated costs based on a "quality of life" concept. The monetary costs of actual emergency and medical care will differ very significantly between the USA and India, for example. Even across the 25 countries of the European Union, there will be marked differences, say, between England and Poland. When considering the more subjective "quality of life" issues, the differences will be even wider.

Apropos biomechanics research, some work has been done using surrogate-based injury assessment functions (Kroell et al, 1974, Patrick 1974, Rouhana et al, 1990) linked to actual costs of AIS-based injuries toward development of a Biomechanical Injury Cost Model (Newman et al, 1992). It has been proposed that such a model would be an effective tool for predicting the effects in economic terms of slight changes in vehicle design and might allow more rational decisions regarding the tradeoffs between various potential injury scenarios. Clearly, the validity of such a model is wholly dependent on the accuracy and completeness of both the IAFs and the injury cost data.

A cost of injury scale, either for actual injuries or for laboratory research, does not currently exist. While certain universal criteria for establishing the burden of injury can likely be agreed, the global application of a cost of injury scale seems dubious at best. Economic and societal cost of injury will likely remain a country-specific and culture-specific exercise.

In the EU, US and elsewhere policy makers are increasingly using cost-benefit methods to determine the viability of injury prevention measures. These procedures rely on the availability of basic knowledge of the costs of injuries, casualties and accidents specific to that territory. Two basic approaches have been utilised – the human capital approach (e.g. Miller et al, (2001), Malliaris et al (1985) and the willingness to pay approach (e.g. Hopkin and Simpson (1995) Miller et al (2001)) Research utilising these tools has been used in a range of studies (e.g. Fildes et al (1996) and Welsh et al (2006). While the willingness to pay method is the preferred approach within the EU, there is still a need for improved scales with greater precision and differentiation between injuries.

Areas for further knowledge

1. The adoption of a global standard for injury severity assessment is fundamental both to institutionalise the importance of sound injury data and for international comparisons. The AIS has the longest history as a threat-to-life tissue damage scale and, in its current form, can accommodate quite different levels of injury detail to meet the needs, or limitations, of varying data systems. As such, it should become *the* international injury scale for detailed injury databases

2. A need exists for a Simple Injury Scale that can be used in the pre-hospital context to provide uniformity and clarity to the classification of trauma victims. An SIS also has application in countries where detailed injury information or resources to collect it are not readily available. Such a scale needs to be simpler than the Abbreviated Injury Scale, but compatible with it.

3. The need for medical examiner and autopsy reports on patients who die at the scene or who do not survive long enough to be assessed in hospital are imperative to understand injury types and mechanisms that contribute to fatalities.

4. Specific criteria to include in measuring long-term impairment and disability need to be agreed. This should include monitoring of the FCI, but should also include exploring alternative schemes linked to the AIS.

5. Existing willingness to pay injury cost scales should be refined to improve precision and international comparability

6. In-depth crash injury research as well as clinical studies have underscored the role of age and how it relates to injury severity. The very young and the very old are at greater risk of suffering a fatal injury for the same insult than is a healthy individual in the third or fourth decade of life. The need for specialised injury scales to address these age-related disparities should be investigated.

7. Police-reported injury information is, in many countries, the basis for defining a country's crash injury problem and for making comparisons between countries. National definitions of what is a "slight" or "serious" injury vary, however, from one country to another, thus making such national comparisons dubious. An agreed set of definitions across countries is fundamental and urgent.

8. To further exacerbate the data problem, significant disparities in defining injury severity exist between police-reported injury "statistics" and hospital-based injury data, resulting in serious underreporting by the police of non-fatal casualties at all levels of severity. Data linkage between police data and hospital data, at a minimum, should be pursued.

9. The establishment of an international protocol for injury severity assessment is necessary. This includes agreement on issues such as minimum data needs, sources of injury information, appropriate training of data collectors and certification of data systems.

10. The overall burden of injury is ill understood and oftentimes is country-specific. International criteria for establishing the cost of injury should be agreed and adopted.

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