Trauma Biomechanics

Accidental injury in traffic and sports

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2 Methods in Trauma Biomechanics

Work in trauma biomechanics is subjected to a number of limitations which are less stringent or even totally absent in other fields of the technical and life sciences. First of all, experiments involving loading situations with humans which are prone to cause injury are excluded. Second, animal models are of limited use because of the difficulty to scale trauma events reliably from animals up or down to humans. Questionable representativeness with respect to human biomechanics in spite of some similarity, furthermore, cost and above all ethical considerations along with public awareness limit however such experiments to special circumstances today.

Accordingly, methods applied in trauma biomechanics are to a great extent indirect and include mainly approaches based on

- statistics, field studies, databases (2.1)
- basic concepts of biomechanics (2.2)
- injury criteria, injury scales and injury risk (2.3)
- accident reconstruction (2.4)
- experimental models (2.5)
- impact tests performed in the laboratory (2.6)
- numerical simulation (2.7)

2.1 Statistics, field studies, databases

Epidemiology is of fundamental importance in trauma biomechanics and it represents also the oldest methodological approach. The identification of injury risks and the analysis of causative factors are largely based on epidemiological evidence which in turn stimulates the development of intervention strategies as well as of technical and legal countermeasures with the aim of accident prevention and injury reduction. Whether such countermeasures are indeed effective can again only be decided on the basis

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of statistical surveys which often require long-term studies. Hence, when working in the field of trauma biomechanics, in particular towards issues related to injury mitigation and prevention, the acquisition and in-depth analysis of real world accident data is an indispensable prerequisite and research tool.

The collection, classification and interpretation of accident data have to be subjected to a careful assessment with respect to the sampling process in that in most cases the available data set is not exhaustive but is limited to a selected sample. One should always be aware of the fact that major limitations on the applicability of the results of any statistical evaluation are already incorporated in decisions on how and what data are collected. In contrast to fully controlled laboratory experiments, uncertainties arise for example due to the fact that many important parameters in real accident situations are not monitored and may exhibit a large variability. In addition, the memory of those involved in an accident or acting as witnesses may be inaccurate about the details or influenced by legal or insurance related considerations. Other factors such as the current composition of the vehicle fleet in case of traffic accidents, the price of gasoline, changes of legislation, adaptation of rules in contact sports, or changes with respect to insurance coverage of workplace accidents have to be considered when attempting to analyse the influence and effectiveness of newly introduced safety measures. A sound statistical evaluation may also fail because of an insufficient number of cases available for a representative analysis.

With respect to methodology, two types of accident data bases or injury surveillance systems can be distinguished, viz., general accident collections involving a large, possibly complete coverage of accidental events on the one hand, and in-depth studies of selected cases on the other. General large-scale accident files are typically collected by the police, other government bodies or insurance companies and are presented in annual accident statistics. They usually contain a large number of cases but only limited information per case. In turn, in-depth case analyses are performed by specialised teams which attempt to recover as much detail as possible of each case under scrutiny - which somewhat cynically can be regarded as an involuntary experiment - on the basis of investigation of the accident scene, workplace or household locations and installations, vehicles, sports accessories, furthermore, police reports, witness depositions, interviews, medical records, weather reports, video coverage of sports events and on-site reconstruction with original vehicles or installations. Numerical simulation is then often applied to elucidate loading conditions and to relate them with injury patterns. Needless to say that such investigations are associated with a high expense and only a limited number of cases can be evaluated in this fashion. Representativeness is a particularly critical aspect in this approach.

Insurance companies often have larger collections than governmental bodies because accidents are reported to insurance companies for financial reasons while more reluctance is present with respect to involving the police, in particular in case of self-accidents without the involvement of a second party. Yet, insurance data are often not accessible, and if so, biased or not detailed enough. For example, insurance companies tend to quantify vehicle damage more in terms of repair cost than in terms of the biomechanically more important deformation energy.

Cases included in large-scale data collections are moreover often not collected and analysed by specialists in accidentology and may contain significant errors and be selected according to criteria which are not applied uniformly. Accordingly, the results obtained from different data bases are often difficult to compare due to differences in the data collection schemes. Even within one specific data base type, e.g. police records, differences in basic definitions, data set volume or privacy policies may vary considerably from source to source. Whether e.g. an elderly patient who dies in a hospital from pneumonia two weeks after a severe traffic accident is indeed a traffic accident victim and included in the statistics or not may depend simply on the reporting practice of the hospital.

In most industrialized countries, accidents associated with traffic, workplace, household and sports fall within the competence of different government agencies, foundations, private institutions, sports associations, insurance companies, etc. with little mutual interaction. Reporting and investigation practises may differ along with injury prevention strategies such that comparisons between various types of injury-producing circumstances have to be made with great care. Uniform statistics are mostly available from small countries like Switzerland where the Swiss Council for Accident Prevention (bfu) provides a comprehensive coverage of accident data.

The largest systematic collections and statistics on traffic accidents are provided by the US National Highway Traffic Safety Administration (NHTSA). They include general data with respect to vehicles, crashworthiness and trends (National Automotive Sampling System, NASS) as well as information on traffic fatalities in the Fatal Accident Reporting System (FARS). An overview over these activities can e.g. be found in Compton (2002). Similar, although sometimes less systematic information is available from most other countries worldwide. Work place safety issues are comprehensively addressed in the statistics of the US Occupational Safety & Health Administration (OSHA). In most industrialized countries, furthermore, workplace accidents are covered by government controlled insurance organisations. General statistics are regularly available from such sources.

The situation with respect to sports accidents and injuries is somewhat different. Sports activities are largely voluntary and leisure-based (with the exception of mandatory participation in schools), are mostly covered by special insurance programs (in particular when competitive events or contact sports are involved), and product liability is highly diverse and selective (e.g., trampolines, diving boards in swimming pools, American football helmets, ski bindings). Specific, let alone general statistics involving comprehensive coverage over years, e.g. to analyse trends are largely missing. General awareness with respect to sports injuries has only recently increased. The Olympic Committee established in 1990 a Medical Commission and Library involving a Special Collection of Sports Medicine and Sports Science where the injury problem is partially included. While the Fédération Internationale de Football Association (FIFA) releases no systematic information with respect to soccer accidents and injuries, the Fédération Internationale de Ski (FIS) and the Oslo Sports Trauma Research Centre NSS announced in 2006 that they have agreed to develop an Injury Surveillance System (ISS) for the FIS disciplines of alpine skiing, cross-country skiing, ski jumping, nordic combined, freestyle skiing and snowboarding.

In-depth case studies are made by specialised teams, usually with a specific aim or involving a limited geographical area. In order to be useful, such efforts have to be maintained over years and a sufficiently large number of cases has to be collected observing uniform procedures. Most projects of this type which are documented in the literature are performed in connection with traffic accidents. For example, a team working at the Medical University Hannover (Germany) has been collecting data of collisions occurring in the area of the city of Hannover over many years. Since 1999, an additional research team also collects data in the city area of Dresden, the data of the two sites is combined in the GIDAS data base (www.gidas.org). Because the data was collected systematically and following a uniform protocol for a long time, it is for instance possible to analyse factors related to changes in vehicle design.

An other example is the data base on whiplash associated disorders causing a sick leave of more than four weeks duration which is hosted by AGU Zurich (Switzerland, http://www.agu.ch). The collection includes cases from the entire country of Switzerland. Due to the large amount of available data, specific topics concerning technical, medical as well as biomechanical aspects of soft tissue neck injuries can be addressed [e.g.

Schmitt et al. 2003]. Yet other in-depth investigations are made by vehicle manufacturers where specialised teams investigate cases in which vehicles of their own production are involved in order to assess the effectiveness of safety measures and identify needs for improvements. Some of these latter accident data bases also include cases where vehicle damage occurred, but no injury was recorded. Such data are particularly helpful for statistical analysis, as they offer the possibility of well-defined control groups, which are not necessarily available in other types of data bases.

Having recognized that the adequate supply of road accident and injury records is perceived to be important for the selection, implementation and evaluation of road safety measures, several approaches such as for example the European STAIRS project (Standardisation of Accident and Injury Registration Systems, 1997-1999), that are aimed at harmonising accident data collections in order to allow more comprehensive and comparable studies, are under development. The EC integrated project SafetyNet, completed in 2008, has incorporated various European data bases of interest in the context of traffic safety (www.erso.eu).

Little such efforts are underway for workplace, household or sports injuries which in view of increasing globalization and international mobility may cause, among other, problems with liability and insurance coverage.

2.2 Basic concepts of biomechanics

In what follows, a number of basic mechanical concepts which are of importance in trauma biomechanics are reviewed. In general mechanics, a distinction is made between rigid body mechanics and continuum mechanics. In real applications, both formulations are associated with assumptions and approximations such that their applicability, validity and limitations have to be carefully assessed in each problem to be approached, in particular, when applications in biomechanics are considered.

The aim of mechanics consists of a quantitative description of the effects that forces exert on the motion and deformation of bodies, in case of biomechanics, primarily living objects. To this end, mass, time, position are the fundamental independent quantities as function of which all other mechanical quantities are expressed.

Rigid body mechanics: Basic quantities are mass m, time t, position $\vec{r}(t)$, associated quantities are moment of inertia I, angular velocity $\vec{\omega}(t)$. The position vector $\vec{r}(t)$ denotes the location of the centre of mass of a rigid body as function of time. Further quantities derived thereof are the velocity of the centre of mass $\vec{v}(t) = \frac{d}{dt}\vec{r}(t)$, furthermore the acceleration $\vec{a}(t) = \frac{d^2}{dt^2}\vec{r}(t)$. The linear motion of the rigid body is described by Newton's second law of motion:

$$m \cdot \vec{a}(t) = \sum_i \vec{F}_i(t) \tag{2.1}$$

whereby the sum extends over all forces $\vec{F}_i(t)$ acting on the body. The spatial orientation of the body, in turn, is obtained from the angular momentum equation,

$$I \cdot \frac{d}{dt}\vec{\omega}(t) = \sum_i \vec{M}_i(t) \tag{2.2}$$

with the angular acceleration $\frac{d}{dt}\vec{\omega}(t)$ and the sum over all moments $\vec{M}_i(t)$ acting on the body. Because of the solidification principle, these equations also hold for deformable bodies, however, the centre of mass is not at a constant location with respect to the contour of the body in such cases. Variational principles, which can be derived within the framework of Newtonian mechanics, lead to Lagrange or Hamiltonian formulations which may be useful depending on the application under consideration.

Continuum mechanics: Basic quantities are field-oriented, viz., density $\rho(\vec{r}, t)$, time t, velocity field $\vec{v}(\vec{r}, t)$. The density $\rho(\vec{r}, t)$ as well as the velocity field $\vec{v}(\vec{r}, t)$ refer to a specific, fixed location $\vec{r}$ in space (this approach is often denoted as Euler representation of the continuum). The equation of motion reads (the independent variables are omitted for brevity)

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \left[\vec{v}, \vec{\nabla}\right] \cdot (\rho\vec{v}) = \vec{k} + \left[\vec{\nabla}, \hat{\sigma}\right] \tag{2.3}$$

where $\vec{k}(\vec{r}, t)$ denotes field forces, e.g., gravity, while the stress tensor $\hat{\sigma}(\vec{r}, t)$ describes the internal state of loading (i.e., forces per unit area as normal and shear stresses) of the continuum and includes in addition forces which are due to external contact. $\vec{\nabla}$ is the Nabla operator and vectorial quantities in brackets separated by comma denote a scalar product. The angular momentum relation requires that the stress tensor $\hat{\sigma}$ be symmetric. Conservation of mass furthermore yields the continuity equation

$$\frac{\partial}{\partial t}\rho + \left[\vec{\nabla}, (\rho\vec{v})\right] = 0 \tag{2.4}$$

These equations are non-linear and the velocity field can be obtained as a solution providing that the mechanical characteristics of the continuum in the form of a constitutive equation (see below) are introduced (a textbook on continuum mechanics is, e.g., Liu 2002).

In order to proceed, a distinction between a solid and a fluid continuum has to be made. In case of a solid, the velocity field follows readily from the displacements that the particles making up the continuum undergo as function of time. A wide variety of constitutive equations relating the displacements (or the deformations of the continuum resulting thereof) to the stress state can be found in the literature. For fluids, in turn, the stress tensor can be formulated in terms of the velocity field and its gradients.

While rigid body models are characterised by a finite number of degrees of freedom associated with a set of ordinary differential equations, in continuum mechanics partial differential equations prevail and the number of degrees of freedom is infinite. For numerical treatment, the partial differential equations have to be approximated in special formulations involving in particular discretisation, of which the finite element approximation is most often used in trauma biomechanics (see section 2.7).

Constitutive Properties of Biological Tissues: Stress-strain characteristics of solid biological tissues are typically non-linear, anisotropic and visco-elastic. The non-linearity is mainly due to the large tissue deformations that are observed in biomechanics, the anisotropy to the fibrous character of biological tissues and the visco-elasticity to the internal friction inherent in the fibre-extracellular matrix composition. There are furthermore active elements (muscle fibres) whose tone influences the mechanical properties. In tests made under ex vivo conditions, the state of muscle activation has to be taken into account (muscle fibres can be activated chemically, e.g., by Barium compounds). Likewise, embalming of cadavers changes their mechanical behaviour. For biological fluids, non-Newtonian characteristics may be important (for a comprehensive treatment of constitutive properties in biomechanics see Holzapfel and Ogden, 2006).

A distinction is often made in biomechanics between "soft" and "hard" tissues. In order to specify this difference more quantitatively, the non-linear, anisotropic, partly active (muscles) properties of biological tissues have to be characterized by a simplified linear approximation. Under uniaxial loading of a long and thin specimen, a piecewise linear stress-strain relation in the form of Hooke's law can be adapted and a local modulus of elasticity or Young's modulus E can be defined. For "soft" tissues, E varies typically between some 10 and 10^5 kPa, whereas the values for "hard" tissues are on the order of several GPa.

While there are numerous kinds of soft tissues, hard tissue in humans appears essentially in the form of calcified tissue, in particular bone. Thereby, the calcium is contained in hydroxyapatite crystals [$Ca_5 (PO_4)_3 OH$] which are embedded in a collageneous matrix. Aside from the integrity and mechanical loading capacity of bones, a physiological calcium balance is eminently important for the overall homeostasis of the human body in that calcium is essential for many physiological processes, among them, the action of muscles, the transmission of nerve signals or the coagulation of blood. As such, calcium is by far the most abundant bone mineral material ("calcium reservoir"), others, e.g., phosphor, being much less concentrated. Therefore, the terms "calcification" and "mineralization" of bone are often used synonymously. Not surprisingly, bone mineral density (BMD) has been found to be a significant determinant with respect to fracture risk [Beason et al., 2003]. Low calcium content in bones, as in the case of osteoporosis, increases the risk of bone fracture and lowers injury tolerance.

Essential constituents of soft tissues from a biomechanics' point of view are elastin, collagen, and smooth muscle fibres. Modulus of elasticity (again under the simplified approximation of a piecewise linearised treatment of uniaxial loading) elastin (a globular, highly extensible polypeptide) has a Young's modulus of 10^2 - 10^3 kPa, collagen (a stiff three-fold triple helix molecule) a Young's modulus of up to 10^5 kPa, while smooth muscle fibres cover a wide range of stiffness characteristics between elastin and collagen depending on the state of activation. The anatomy of the organs consisting of soft tissue is mostly determined by their physiological function, therefore, according to the great variety of physiological functions, the composition of soft tissues varies greatly and so does their mechanical behaviour under load.

Bone, in turn, is less variable, although it exists in various forms: Cortical bone makes up the shaft (metaphysis) of the long bones as well as the outer layer of other bones while trabecular or cancellous bone is located mostly in the medullary canal of long bones, particularly in regions close to joints (epiphysis) as well as in the spine and in bones whose primary task is not to support loads (e.g., skull, iliac crest).

Since injury is basically associated with deformations beyond yield, linear approximations of the mechanical behaviour are generally questionable and great care has to be exercised when such procedures are applied. In reality, prior to irreversible, injurious tissue destruction, a mostly non-destructive, non-linear visco-elastic deformation behaviour sets in, followed by a plastic deformation phase. In soft tissues, plasticity is mainly due to an in general reversible rearrangement of tissue fibres. In the case of hard tissues, the processes underlying plastic deformation are less clear, they can however be visualized experimentally (Figure 2.1). It has in fact been estimated that peak stresses in bone may significantly be reduced due to plasticity [Stitzel et al., 2003].

Age dependence of constitutive properties is prominent. While soft tissues in young children are highly deformable, with increasing age,

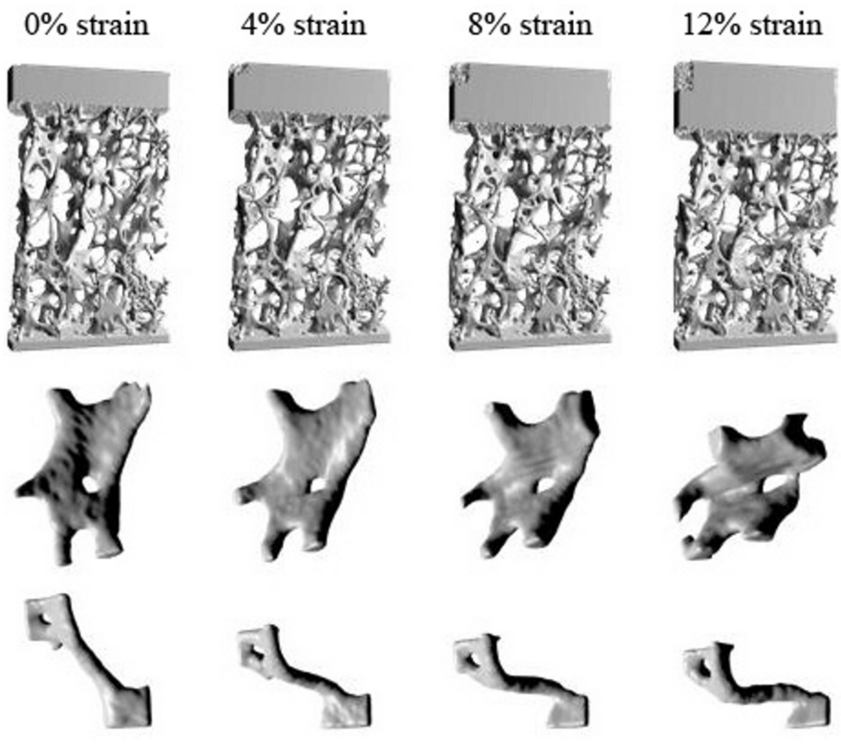


Fig. 2.1 Image-guided failure assessment of human spine samples with the aid of micro-CT (edge length of cross section 4 mm). The upper row exhibits a compressed specimen, imaged in steps of 4% strain. The middle and lower rows show that the typical constituents of trabecular bone, viz., plates and rods, respectively, can undergo large plastic deformation before ultimate failure. Since the basic material of bone, i.e., hydroxyapatite crystals in a collageneous matrix is the same also in cortical bone (although the microstructure is quite different), local plastic deformation may also occur in cortical bone sections under load [From: R. Müller et al., Functional Microimaging at the Interface of Bone Mechanics and Biology, in: Holzapfel and Ogden, op. cit.].

stiffening sets in. This effect is mainly due to decreasing water content and increasing fibre cross-linking. While the total body water during adolescence amounts up to 70% body weight, it decreases down to almost 50% in old age. The younger a child, furthermore, the more bendable a bone is because of the gradual development of mineralisation. Accordingly, fractures denoted as "greenstick" fractures are observed in children in contrast to adults where fractures tend to exhibit a more brittle appearance.

Two major failure criteria are often applied in general mechanics in that it is assumed that failure sets in if a limit value of one of the following parameters is exceeded:

- Absorbed energy (von Mises criterion, applied in trauma biomechanics, e.g., in the thorax).
- Shear stress (criterion according to Tresca, usually not applied in trauma biomechanics).

In trauma biomechanics, in addition, the following quantities are used for the formulation of failure criteria, i.e., onset of injury (see next paragraph), viz.

- Acceleration (applied, e.g., in head injury).
- Deformation (applied, e.g., for the assessment of bone fractures.)

2.3 Injury criteria, injury scales and injury risk

Injury criteria are important tools to assess the severity of accidental loading and the risk of sustaining injury thereof. By definition, an injury criterion correlates a function of physical parameters (e.g., acceleration, force) with a probability of a certain body region to be injured in a specific fashion (e.g., concussion, fracture). Injury criteria are generally derived from experimental studies in combination with empirical evidence, and their formulation and validation requires an extensive stepwise extrapolation procedure, since, as mentioned above, experiments on living humans at traumatic levels are excluded.

First, in addition to the concept of "injury criterion", two further expressions have to be introduced, viz., “damage criterion” and “protection criterion”. While an injury criterion is intended to describe the property with respect to injury tolerance of living tissue, a damage criterion normally relates to post mortem test objects as surrogate for the living human. In both cases, a threshold value for the exposure to a quantity calculated from physical parameters is established above which, i.e., if the exposure exceeds the threshold, the test tissue in question is injured with respect to its anatomical or physiological structure in a specific fashion in more than 50% of all experiments made or accidental exposures under comparable conditions. A protection criterion is obtained when postulating a threshold value on the basis of measurements performed with an anthropomorphic test device (see section 2.6.1) as a human surrogate. In the latter case, the relation to human injury tolerance levels is mainly derived from empirical investigations. It is thereby assumed that a healthy middle-aged adult does on average not sustain injuries of the kind addressed by the particular criterion if he or she is exposed to loading conditions which are comparable to the ones defined in the protection criterion. The actual risk of injury can then be estimated with a risk function which relates the probability to be injured to the criterion developed (i.e. the underlying mechanical properties measured). A threshold value is defined such that given a certain loading scenario, represented by a certain value for the criterion, the risk of sustaining injury does not exceed a percentage of 50%. Depending on the type of injury, this threshold may also be selected at a lower value of e.g. 20%.

However, the definitions of injury, damage, and protection criteria are often not clearly differentiated and thus the term injury criterion is widely used for any index meant to quantify impact or accidental loading severity. Protection criteria, in turn, are determined in internationally standardised test procedures, mostly for use in automotive laboratories. These procedures are listed in section 2.6. In the chapters 3 to 8 specific injury criteria for each body region are presented.

Scales to classify the type of an injury are based on medical diagnosis and were developed for injuries sustained in traffic accidents. The most widely used such scale is the Abbreviated Injury Scale (AIS), which was first developed in 1971 as a system to define the severity of injuries throughout the body and which is regularly revised and up-dated by the Association for the Advancement of Automotive Medicine (AAAM). The AIS is a standardised system for categorising the type and severity of injuries arising from vehicular crashes (Table 2.1) and is oriented towards the survivability of an

Table 2.1 The AIS classification.

AIS code	injury
0	non-injured
1	minor
2	moderate
3	serious
4	severe
5	critical
6	untreatable

injury, i.e., each category represents a certain threat-to-life associated with an injury. Thus, AIS is an anatomically based, global severity scoring system that classifies each injury in every body region by assigning a code which ranges from AIS0 to AIS6. Higher AIS levels indicate an increased threat-to-life. AIS0 means "non-injured" and AIS6 "currently untreatable/ maximum injury".

As a result, the AIS severity score is a single, time independent value for each injury and every body region. The severity is described regarding its importance to the whole body, assuming that the described injury occurs to an otherwise healthy adult. However, it has to be noted that the AIS considers only the injury and not its consequences. Clinical complexity, cost of surgical treatment and long-term sequelae are in particular not taken into account. Hence, severe impairments such as loss of eyesight or life-threatening complications due to nosocomial infections occurring in a hospital are not coded as severe injuries, because they do not represent an initial threat-to-life.

Moreover, the AIS is not a linear scale in the sense that the difference between AIS1 and AIS2 is comparable to the one between AIS5 and AIS6. It does therefore not make sense to calculate average AIS codes (AIS 3.7, e.g., is a meaningless number). To describe an overall injury severity for one person with multiple injuries, the maximum AIS (MAIS) is used. The MAIS represents the highest AIS code sustained by one person on any part of the body, even if the person in question sustained several injuries of the same severity level at different body parts. If, for example, a car occupant sustained AIS2 injuries on the head and the legs but no injuries classified higher, the MAIS will still be MAIS2.

To account for a better representation of patients with multiple injuries, the Injury Severity Score (ISS) was introduced which is regularly updated like the AIS scale [latest version: AAAM, 2005]. The ISS distinguishes six different body regions: head/neck, face, chest, abdomen, extremities including pelvis, external (i.e. burns, lacerations, abrasions, contusions independent of their location on the body surface). For each of these regions the highest AIS code is determined. Then the ISS is calculated by the sum of the squares of the AIS codes of the three most severely injured body regions. Thus the minimum ISS is 0 and the maximum ISS is 75 (i.e. three AIS5 injuries). If an AIS6 injury is recorded, the ISS is automatically assigned to 75. ISS values higher than 15 are regarded as major trauma. Several studies have shown that the ISS correlates quite well with several measurement systems such as mortality [e.g. Baker and O'Neill 1976] or long-term impairment [e.g. Campbell et al. 1994].

In addition to the AIS, other scales are used to specify injuries of particular body regions in more detail. The Quebec Task Force [Spitzer et al. 1995], for example, established a scaling scheme to categorise soft tissue neck injuries (see chapter 4). A classification scheme for head injuries often seen in emergency medical reports is the Glasgow Coma Scale (GCS) [Teasdale and Jennett, 1974]. GCS aims at describing the state of consciousness and some neurological signs (e.g. reflexes) of the injured person after a traumatic incident, and may thus allow the inclusion/ exclusion of potential injury mechanisms. The scale ranges from 3 (deep coma) to 15 (fully awake).

Further scales address impairment, disability and societal loss through ratings of the long-term consequences of the injury by assigning an economic value. An example is the Injury Cost Scale ICS [Zeidler et al. 1989], by which the average costs for an injury is determined taking into account the costs for medical treatment and rehabilitation, loss of income and disability. Further economic scales are the Injury Priority Rating IPR [Carsten and Day 1988] and the HARM concept [Malliaris et al. 1985] applied by the US government. One of the most crucial problems in trauma biomechanics is the assessment of the relationship between injury severity and a mechanical load which causes this injury, i.e. to find a relationship that allows assigning probabilities which describe the likeliness that a certain mechanical load (e.g. determined by an injury criterion) will cause a particular injury. This is important because without such correlations, it is useless trying to interpret any results obtained, for instance, in crash tests. Hence, it is necessary to perform well-equipped laboratory experiments using human surrogates to determine the biomechanical response and corresponding injury tolerance levels and consequently establish so-called injury risk functions.

For the determination of injury risk curves basic statistical methods are applied of which the maximum likelihood method, the cumulative frequency distributions, and the Weibull distribution are most often used. In chapter 3, an example with respect to head injury is presented. For in-depth information however with respect to the application of statistical methods to the often complex and difficult analysis of accident and injury data the reader is referred to statistical text books. Great care has to be exercised in such analyses; among the various problems which may arise when transforming experimental results to (real world) injury risk functions, are

- a small number of tests performed,
- differences in the biomechanical response between the human surrogates used in testing (e.g. cadavers) and living humans,
- anthropometric differences between the test subjects and the real world population at risk,

- a large spread of data due to different test conditions used by different researchers,
- a large number of possible injury mechanisms and injuries that might occur.

Basically the same limitations apply when using data from accident statistics instead of experimental results to fit injury risk curves. Nonetheless, decades of trauma biomechanics' research have provided a sufficiently large number of sources that allow establishing a number of well-founded relationships that link mechanical loads to injury probability - at least for certain injuries and injury mechanisms, respectively. However, work is this area is by far not finished and revisions of existing criteria on the basis of new findings are not uncommon.

2.4 Accident reconstruction

The reconstruction of accidents is an indispensable procedure in the field of trauma biomechanics because relations between loading and injury under physiological conditions manifest themselves only in real-life accidents. Likewise, accident reconstructions are often required for forensic purposes likewise in criminal and in civil cases.

The reconstruction of an accident consists of the mathematical analysis of the event in question on the basis of the laws of classical mechanics as outlined in section 2.2. Other than laboratory experiments, however, accidents in everyday life occur under largely uncontrolled and unmonitored conditions. Depending on the extent, quality and accuracy of the available documentation, therefore, the specialist in accident reconstruction has to apply assumptions and approximations at quite different levels of complexity. While an accident in a skiing competition may be covered by various video recordings or the traces in a traffic accident may accurately be documented by the police, a fall from a ladder during household activities is hardly documented. All information is of importance in a reconstruction process. Much as in a puzzle, various sources of information have to be combined in order to produce a reliable and conclusive account of the events; this may include facts as different as the sequence of traffic lights in a vehicle-pedestrian impact and the bending stiffness of a pole in case of a sports incident. A scrutiny of the accident scene is always indispensable. Experience from formerly performed tests under laboratory conditions or the results from well documented "comparable" accidents may furthermore be of help. Of paramount importance is often the collaboration with the medical forensic expert in that injury patterns may provide useful clues for the purpose of accident reconstruction; for example, from the particular appearance of street dirt under the skin, the direction of a fall can be deduced.

Missing documentation or missing visible evidence may pose problems in accident reconstruction. In case of vehicle collisions, uncertainties might arise e.g. if due to anti-locking systems no skid marks are produced. Furthermore, reconstruction becomes more difficult when no or only marginal vehicle deformation occurs. In order to reduce the repair cost, modern vehicles are designed such that in collisions of low intensity nearly no damage is caused (or at least it is not visible from the outside and therefore often mistaken as not existing by laymen). However, missing visible damage does neither mean that there was no collision at all nor that the energy transmitted might not have been sufficient to cause injury to the occupant.

Within the framework of a rigid body approximation (equations 2.1, 2.2) for the description of an impact event, empirical investigations and laboratory experiments have shown that the acceleration of the centre of mass experienced by a body limb under the influence of impact forces is an important parameter to assess the severity of an impact. In many practical cases, the modulus of the acceleration $\vec{a}(t)$ is thereby often related to the acceleration due to gravity, g (1g = 9.81 m/s^2), because we are constantly exposed to gravity such that we can relate a given acceleration level to everyday experience. Yet, the acceleration which a body undergoes during the course of an accident varies with time, such that the quantities "peak acceleration" and "mean acceleration" along with the corresponding intervals in time should always be clearly distinguished in order to prevent misunderstandings.

Reconstruction techniques have mostly been developed systematically for traffic accidents. In such cases, a number of specific parameters relating to an involved vehicle have found to be useful for an assessment of the loading situation of occupants.

- The collision or impact velocity of a vehicle is probably the parameter most frequently quoted in the public. In accident reconstruction, the travelling speed or, more accurately, the speed before the beginning of any braking action, is sometimes of importance when investigating whether or under which circumstances a collision could have been avoided, or whether a speed limit was exceeded.
- The collision-induced velocity change (delta-v) of the vehicle under consideration is, however, in most cases more useful for describing the collision severity where the effects of the collision on the occupants are

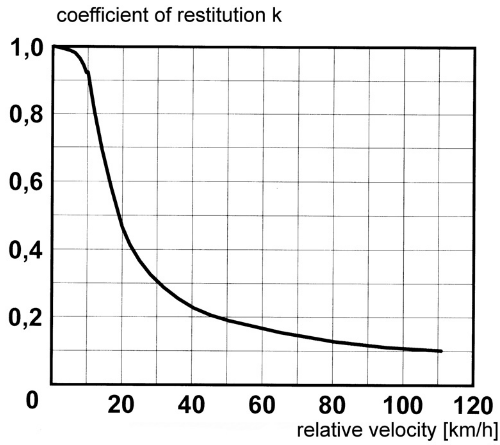


Fig. 2.2 Schematic representation of the relation between the coefficient of restitution and the relative velocity for a frontal impact on a rigid barrier for a passenger car [adapted from Appel et al. 2002]. Newer cars will generally exhibit higher coefficients of restitution in the low-speed range than shown in this figure.

concerned. The delta-v corresponds approximately to the integral of the translational vehicle deceleration over the collision time for collisions which are characterised by a single impact without significant rotation of the vehicle. Yet, in complex collision situations (roll over, fall over the roadside, etc.) delta-v may not be a well defined parameter.

- The energy equivalent speed (EES) characterises the amount of energy needed to deform a vehicle. In fact, the EES represents the impact velocity into a rigid barrier that would have been necessary to cause the same permanent deformation as observed in the real world accident. The EES is given in [km/h] and can be obtained for many vehicle types from so-called EES catalogues. These catalogues are established on the basis of crash tests conducted under well-defined test conditions.
- A further parameter used to describe impact conditions is the vehicle overlap. This is the extent to which the vehicle and the collision partner (e.g. another vehicle or a barrier in a crash test) overlap. The overlap is generally presented as the percentage of the total width of the vehicle under consideration covered by the opposing vehicle (or wall).
- From basic mechanics, the principles of elastic and plastic impact and the accompanying coefficient of restitution (k-factor) are used to characterise the elastic and plastic (i.e. permanent) components of the deformation suffered in the impact. Figure 2.2. shows, as an example, the dependency of the coefficient of restitution on the impact velocity (against a rigid wall). The k-factor heavily depends on the design of the

car front structure, in particular the bumpers and underlying absorbers for low-energy collisions. Due to the requirements for no or little damage cost in these collisions, bumpers have been designed to be stiffer and more elastic, thus, for newer cars, higher coefficients of restitution must be assumed in the low-speed area. Furthermore, some impact absorber concepts involve designs or materials whose deformation recovers slowly after an impact. Since this restitution does not occur during the impact itself, the vehicle deforms in a fully plastic way although the accident investigator may not find any deformation after the collision.

Today, most traffic accident reconstructions are performed with facilitating computer programmes such as Carat [IBB 2002], PC-Crash [DSD 2000] or EDCRASH [EDC 2006] which are thoroughly validated and whose application procedures are well defined. These programmes mainly employ rigid body dynamics (equations 2.1, 2.2). Using such programmes, two methods can be distinguished in principle: "forward" and "backward" calculation. In the first case, the kinematics before the collision are assumed, i.e. initial directions of motion, velocities etc. are assigned to the collision partners. Then, the actual collision and the final positions of the collision partners after the collision are determined by integration of the rigid body equations taking into account tire and collision forces. Finally, the positions and traces that were recorded on the actual accident scene are compared with the results of the calculation. In an iterative process, the input parameters are adjusted and the procedure is repeated until a satisfactory match between the results obtained in the calculation and the available accident data is reached. The backward calculation method starts by investigating the final positions of the collision partners. Next, the motions after the impact are reconciled with the traces found (e.g. skid marks) giving the positions at impact, again utilizing rigid body approximations. Eventually, the initial parameters that lead to the determined course are obtained. Graphics are finally used to give a visual account of the reconstructed accident.

Because of the large mass ratio car occupant/vehicle, the influence of car occupants, likewise of other objects which are not rigidly connected with the vehicle can be taken into account in an approximate fashion. This is not the case in motorcycle or bicycle accidents, where the programmes mentioned above can only be applied under restricted conditions and the results have to be interpreted carefully.

Collision phases, not only in traffic accidents, are usually associated with deformation processes for which the application of approximations based on continuum mechanics (equations 2.3 and 2.4 and associated constitutive relations) are required. Because of liability issues mostly, car manufacturers are reluctant to publish the finite element models which they use to assess the crashworthiness of their vehicles. Various types of simplification are therefore made in general purpose reconstruction programmes. One way is to assume a segmented stiffness distribution of the vehicle's front, and then to integrate the equations of motion of the two vehicles over the collision duration. Another way, often employed in European reconstruction programmes, is to assume the collision duration to be infinitely short (in comparison to the pre- and post-crash motion of the vehicles) and to calculate only the transfer of the (linear and rotational) momentum from one vehicle to the other. The EES values mentioned above may, for both approaches, be used as control values to obtain not only conservation of momentum, but also the energy balance over the collision.

Once a vehicle motion is reconstructed, the motion of the occupants or of an impacted external victim (pedestrian, two-wheeler) during impact can be estimated, again using rigid body models. Furthermore, indications with respect to the occupant loading can be obtained. Further extrapolations, in particular concerning injuries, however require expertise beyond the classical (mechanical) accident reconstruction. The same holds true for accidents occurring at the workplace, household or in sports. Given appropriate circumstances and a careful adaptation to the situation in question, traffic accident reconstruction models and computer programmes can also be utilised in other accidents. For the purpose of injury analysis, the subsequent application of a finite element model of the human body may yield useful clues.

Finally, accidents are sometimes reconstructed by a one-to-one reproduction on location or in the laboratory with the original installations, vehicles, sports accessories, etc. This procedure is particularly important in non-traffic related accidents as well as in the course of legal procedures where large claims justifying the often considerable expense of such tests are involved.

2.5 Experimental models

All mechanical characteristics relating to the behaviour in time of the human body, of a part of it, of an organ or tissue when it is subjected to dynamic mechanical loading is subsumed under the term "biomechanical response". The head-neck kinematics as observed in a rugby scrummage or the force-deflection characteristics of the chest due to a frontal vehicle impact are examples for the biomechanical response of the human body. Besides such mechanical changes, the biomechanical response can also lead to physiological changes like neck pain, oedema of the lung or aberrations of the ECG.

A thorough knowledge of the biomechanical response is indispensable for the development of measures for injury prevention and mitigation. Since accident situations as such are highly dynamic by their nature, relevant tests to investigate the biomechanical response of the human body have generally to be conducted under corresponding loading conditions. Nevertheless, whenever extrapolations to dynamic conditions are possible, quasi-static tests are made because of the much simpler installations needed for such tests.

The analysis of the biomechanical response of the human body is not only crucial for an understanding of injury mechanisms, but it is also needed for the definition and verification of injury tolerance thresholds. An important aspect thereby is the biological variability. In particular, age-related changes are prominent. For a reliable measurement of an injury risk function, a large amount of experimental data is therefore required. As biological material for testing purposes is not readily available, a careful examination of statistics is of primary importance. Response data may also be restricted by the impossibility to install instrumentation at the desired location,. Bearing in mind that many of the relevant studies represent pioneering work in trauma biomechanics research dating back to the 1940s, some of these shortcomings can be explained with the lack of adequate measurement instrumentation and the lack of knowledge at that time. In the chapters dealing with the biomechanical response of the different body regions these problems are discussed in more detail. Furthermore, section 2.6.1 is devoted to the utilisation of human surrogates (dummies) used in impact testing where the response data obtained from the surrogate have to be interpreted in light of biological verisimilitude.

In the following, experimental models used to determine the biomechanical response of the human body are briefly discussed. Five different models can thereby be distinguished, viz., human volunteers, human cadavers, animals, mechanical human surrogates and mathematical models.

Volunteer experiments are, for obvious reasons, restricted to the low severity range only, i.e. well below any level thought to be possibly injurious. The pain threshold is often taken as the upper limit up to which mechanical loads are applied. Advantages related to volunteer tests are first of all the use of the "correct" anatomy and physiological state. Moreover, the influence of the muscle tone can be studied and effects like the bracing prior to a collision can be considered. However, the cohorts used for volunteer tests are usually not statistically representative for the population at risk. Particularly, females, children and the elderly are strongly under-represented in the available volunteer data. Difficulties also arise with the instrumentation as load cells can often not be brought to the location of interest (e.g. the centre of gravity of the head or the first thoracic vertebra), even a rigid external fixation is difficult to obtain because of the skin. Advances in high-speed video camera technology along with sophisticated mathematical post-processing have considerably contributed to the improvement of such results. Even cineradiography has sometimes been used to monitor the response of the skeleton to impact, e.g. by Ono and Kaneoka 1997 to investigate the motion of the vertebrae of the cervical spine. As the number of subjects tested in this fashion is particularly small, questions of scaling to other groups of humans as well as to a higher impact severity are all the more critical.

Human cadavers (usually denoted as post mortem human subjects (PMHS) or post mortem test objects (PMTO)) are the second type of model used to determine human biomechanical response. Despite the great anatomical similarity to the living human (a PMTO may to some extent be compared with a sleeping human), several influencing factors have to be considered. First, the age of the PMHS is often high. Age-related degeneration is therefore often prevalent in the cadaver cohort available for a test series. For example, in case of osteoporosis, fracture is observed too frequently. Second, the lack of pressure in the lungs and the blood vessels, the absence of muscle tone, as well as differences due to preparation techniques used (i.e. embalmed vs. non-embalmed cadavers) significantly influence the biomechanical response. Fresh cadavers, however, were shown to be good models for the detection of fractures, vessel ruptures and lacerations. Nonetheless, physiological responses (e.g. the neck pain or ECG aberrations) cannot be addressed with such models. For the investigation of the response of a single body part only, for instance of the leg (see chapter 7), isolated cadaver parts are used. Here the connection to the rest of the body has to be mimicked in the test set-up in an appropriate way.

Animal models have a limited significance for human trauma biomechanics. Nevertheless, anaesthetised animals offer the only possibility to investigate physiological reactions to severe mechanical loading. Animal experiments also allow a comparison between living and dead tissue and thus give important input to the proper interpretation of cadaver tests. However, due to differences in anatomy and physiology, the possibilities of scaling the results obtained, particularly with respect to injury thresholds, are limited.

Further models used in trauma biomechanics include mechanical human surrogates, i.e. anthropomorphic test devices (ATDs) as well as mathematical (computational) models. Because of their importance (e.g., all regulations on vehicle occupant safety are formulated in terms of measurements made on ATDs), these models are discussed in separate sections below.

The objective of impact testing in the laboratory consists of a realistic simulation of accident scenarios and of the determination of the mechanical loading that a human victim possibly sustains in such an accident. Most laboratory test set-ups are thereby made for vehicle crash testing mostly because of the comprehensive regulatory coverage of vehicle safety. In the automotive industry, extensive usage of crash facilities is made for the assessment of restraint systems as well as for the development of new measures in passive safety to reduce the number and severity of injuries sustained in automotive accidents. Yet, laboratory tests are also used to certify football helmets or ski bindings, etc.

Real world accident scenarios are manifold. Thus, only selected impact conditions which are thought to be of relevance are simulated in crash testing. Bearing in mind the need of repeatability and comparability of test results along with the cost and time related to crash testing, several standards were developed that define the exact test protocols, the evaluation process, as well as the protection criteria to be derived thereof. In section 2.6 such standardised test procedures are described in detail.

Three different categories of automotive crash tests can be distinguished, viz., full scale tests, sled tests, and component tests (Figure 2.3). The basic principles with respect to laboratory practise, evaluation of results and documentation also apply to non-automotive testing and certification procedures as, for example, the closing force of elevator doors or the strength of nets used by the fire brigade.

In full scale impact tests, a vehicle impacts an obstacle or another vehicle or is impacted by a moveable object (e.g. a barrier as used in side impact tests). Anthropomorphic test devices (i.e. crash test dummies) represent occupants located in the vehicle under consideration, and the kinematics and the mechanical loadings of the dummy are recorded during impact. Full scale crash tests have the advantage that the actual vehicle properties, e.g. the deformation characteristics, are inherent in the results. These properties influence the acceleration response of the vehicle and consequently the loading of the occupants. In addition to passive safety issues, full scale tests also provide information about the repair costs to be faced after a collision and are therefore performed by insurance companies with respect to the

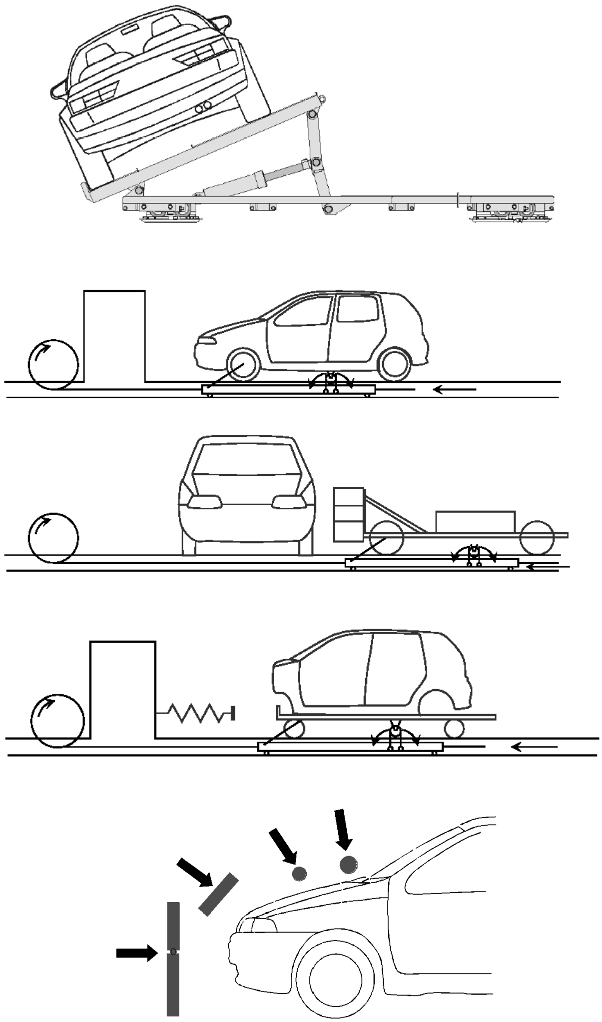


Fig. 2.3 Different methods of crash testing. From top to bottom: full scale testing (rollover test, frontal and lateral impact), sled testing and different impactors used in pedestrian safety testing of the front of a car.

rating of the insurance premium. Full scale tests are also used for non-biomechanical purposes, e.g. to check the fuel system integrity or the braking system.

While in full scale tests the interaction between the restraint systems and the deformation characteristics is investigated, sled tests are primarily used to analyse the isolated behaviour of restraint systems or vehicle components (e.g. a front seat). For this purpose, parts of the vehicle or the components of interest are mounted on a sled. The sled is accelerated or decelerated, respectively, in a controlled manner without damaging the test rig. Consequently, the sled including parts of the rig can be re-used, thereby significantly reducing the associated cost. The disadvantages of this type of test are, among other, the restriction that the vehicle loading may only be unidirectional, and that the vehicle acceleration pulse must be established by a prior full-scale test or, in prototyping, by e.g. computer simulations.

Component tests form a third type of testing. Here, in quasi-static as well as dynamic tests various aspects concerning single parts of the car body may be investigated. In quasi-static tension tests, for instance, the strength of the seat belt attachment points is examined. Furthermore, using devices such as the free motion head form (FMH) the compliance and the energy dissipation properties of the vehicle interior are assessed. The FMH is a head form mounted on a propelling device such that it can be projected onto the vehicle structure in question under different angles. Using other dummy parts (e.g. lower and upper limb surrogates and head forms simulating children and adult heads), pedestrian safety is assessed by evaluating the deformation properties of the vehicle front. As opposed to e.g. full scale tests, component tests offer the advantage that the point of impact of e.g. a head impactor on the bonnet may be specified with millimetre-accuracy. Thus, along with the fact that the cost of component tests is an order of magnitude lower, a large number of impact points may be assessed.

2.6 Standardised test procedures

All new car models are required to pass numerous tests related to occupant safety before they may be brought into circulation. These tests often differ in different regions of the world; the most important regional standards are those of the U.S. and of the European Community. In Europe, the corresponding procedures are laid down in the regulations of the UN Economic Commission for Europe (ECE). ECE R94, for example, describes the test procedure for frontal impact protection, while in ECE R95 the side impact test is defined. These regulations have been incorporated in the EC directives, where e.g. 96/27/EC contains ECE R95 and 96/79/EC includes ECE R94. For the sake of simplicity, we will refer to the older ECE Rxx designation in the following chapters. In the United States, the Federal Motor Vehicle Safety Standards (FMVSS) are incorporated in the Federal Register 49 CFR part 571. Since most car makers aim to sell their cars on a global market, the differing safety standards in different parts of the world constitute a considerable problem. International harmonisation of tests and the international recognition of test results obtained in a certified laboratory are important aspects in worldwide trade. To this end, numerous bilateral trade agreements between countries, furthermore free trade initiatives, UN, US and EU ("Cassis de Dijon" principle) activities were made or are under way. Therefore, the UN/ECE/WP.29 has been designated to develop harmonised regulations, called GTR (Global Technical Regulations).

Where aircraft crashes are concerned, the U.S. Federal Aviation Administration has laid down some crash tests procedures in the FAR (Federal Aviation Regulations) parts, these are largely identical to the JAR parts valid in Europe by the Joint Aviation Authorities of Europe. In addition, instruments, machines, installations, sports accessories, etc. which are in daily use are subjected to a myriad of regulations, guidelines and recommendations made by government bodies, manufacturers, insurance companies, sports associations and consumer organisations. In different countries, quite different regulations and practises can be found. A general overview can hardly be made. In Europe, however, most safety requirements are tested in conjunction with product liability and constitute a part of a product certification process (CE mark).

As can be seen in Tables 2.2 and 2.3, the ECE regulations and the FMVSS are quite similar and include many corresponding regulations. However, differences arise for the types of dummies requested, the test conditions prescribed or the evaluation of the tests (Figure 2.4).

Furthermore, different threshold values for occupant loading apply in some cases. The requirements stated in both the ECE regulations and FMVSS are also often adapted in other countries and therefore can be considered the most powerful safety regulations worldwide. For complete and up-to-date information the reader is advised to consult the corresponding internet sites, as these regulations might be amended after publication of this book.

Tables 2.4 and 2.5 summarise the requirements for occupant protection as defined in ECE R94 and FMVSS 208 for frontal impact and in ECE R95 and FMVSS 214 for lateral impact.

More details on the protection criteria mentioned and their threshold values are given in chapters 3 to 8 for the respective parts of the human body. It has to be noted that neither the ECE nor the FMVSS include regulations concerning occupant safety in low speed rear-end collisions although these occur frequently and cause eminent health problems and

Table 2.2 ECE regulations (for details see http://www.unece.org).

regulation	collision type	impact velocity	test conditions	comments
R94	frontal	56 km/h	40% overlap, deformable barrier	2 Hybrid III dummies
R12	frontal	48..53 km/h	rigid wall	concerning deformation of the steering assembly
R33	frontal	48..53 km/h	rigid wall	concerning stability of passenger compartment
R12	frontal	24 km/h	impactor test	determining force on body block impactor
R95	side	50 km/h	moveable, deformable barrier, 90° angle	1 EuroSID at driver position
R32..34	rear-end	35..38 km/h	moveable, rigid barrier (mass: 1100 kg)	integrity of the petrol system
R42	minor collisions	2.5, 4 km/h	pendulum	checking safety in operation only
R44	child restraint systems (CRS)	50 km/h	sled tests	different dummies used depending on CRS
R16	seats	-	static	recliner moment, deformation
R17	seats	-	sled tests, 20 g	seat anchorage to vehicle body, head restraint geometry
R14	belts	-	static	e.g. deformation

Table 2.3 FMVSS regulations (for details see http://www.nhtsa.dot.gov).

regulation	collision type	impact velocity	test conditions	comments
571.208 (latest version phase 2)	frontal	25 mph	100% overlap, 0 - 30° rigid barrier	2 unbelted Hybrid III dummies (50% male)
		35 mph	100% overlap, 0° rigid barrier	2 belted Hybrid III dummies (50% male)
		25 mph	100% overlap, 0° rigid barrier (max. 5° oblique)	2 unbelted Hybrid III dummies (5% female)
		35 mph	100% overlap, 0° rigid barrier (max. 5° oblique)	2 belted Hybrid III dummies (5% female)
		25 mph	40% overlap, 0° deformable barrier	2 belted Hybrid III dummies (5% female)
		-	various configurations, firing of airbags	various dummies in OOP situations
571.204	frontal	30 mph	100% overlap, rigid barrier	steering assembly rearward displacement
571.212	frontal	30 mph	100% overlap, rigid barrier	concerning the mounting of the windscreen
571.203	frontal	15 mph	impactor test	determining force on body block impactor

Table 2.3 ctd. FMVSS regulations (for details see http://www.nhtsa.dot.gov).

regulation	collision type	impact velocity	test conditions	comments
571.203	frontal	15 mph	impactor test	determining force on body block impactor
571.214	side	33.5 mph	moveable, deformable barrier, oblique impact	2 SID dummies used
571.301+ 303	rear-end, front, side	30 mph	moveable, rigid barrier (mass: 1800 kg)	fuel system integrity
581	minor collisions	2.5 mph (rear), 5 mph (front)	pendulum/barrier	checking safety in operation only
571.213	child restraint systems (CRS)	30 mph	sled tests	different dummies used depending on CRS
571.210	seats	-	static tests	e.g. deformation
571.209	seat belts	-	static tests	e.g. deformation

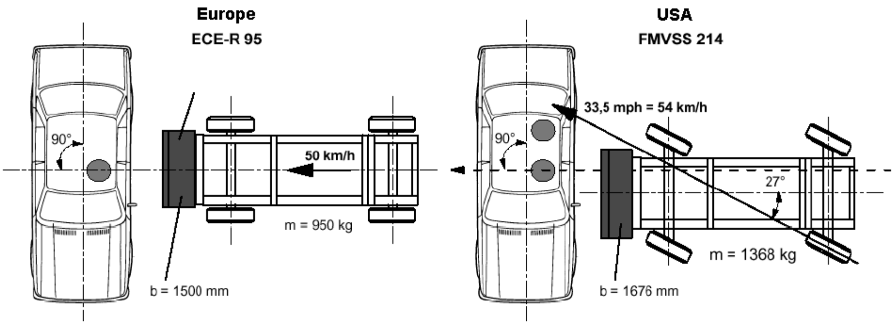


Fig. 2.4 Different test conditions for lateral impact are required by the ECE (left) and the FMVSS (right).

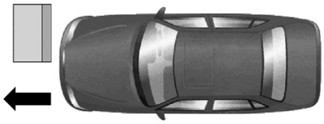
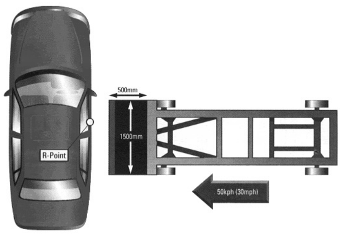
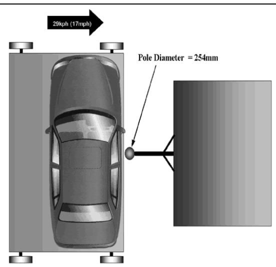
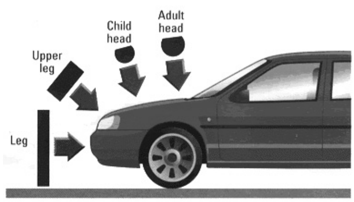
Table 2.4 Frontal impact threshold values.

	FMVSS 208	ECE R94
dummies	Hybrid III 50% male, 5% female	2 Hybrid III 50% male
head	HIC 15 < 700	HPC < 1000 a3ms< 80 g
neck	Nij <= 1.0, {-4.17kN < Fz < 4.0kN} (Hybrid III 50% male) {-2.62 kN < Fz < 2.52 kN} (Hybrid III 5% female)	Mext<57 Nm
thorax	a3ms <= 60 g, deflection < = 63 mm (Hybrid III 50% male)/ deflection <= 52 mm (Hybrid III 5% female)	deflection < 50 mm VC < 1.0
femur	axial force < 10 kN	not exceeding defined force corridor
knee		deflection < 15 mm
tibia		axial force < 8 kN TI < =1.3

Table 2.5 Side impact threshold values.

	FMVSS 214	ECE R95
dummies	ES-2, SIDIIs	1 EuroSID
head	HIC 36 < 1000 (both dummy types)	HPC < 1000
thorax	A max < 82 g (both dummy types) d max < 42 mm (ES-2)	VC < 1.0
abdomen	F < 2.5 kN (ES-2)	internal force < 2.5 kN
pelvis	F < 5.1 kN (SIDIIs) / F < 6 kN (ES-2)	pubic force < 6 kN

Table 2.6 Test conditions applied by the Euro-NCAP [http://www.euroncap.com]. Note: impact is performed on the driver side, i.e. the illustrations show a right-hand drive vehicle.

impact	test conditions	
frontal impact	64 km/h, deformable barrier, 40% overlap plus knee-mapping sled test, where applicable 2 Hybrid III in driver and passenger seats, TNO P1/2 and P3 dummies in CRS in rear seats	
side impact	50 km/h, Trolley fitted with a deformable front is towed into the driver's side of the car ES-2 in driver seat, TNO P1/2 and P3 dummies in CRS in rear seats	
pole test (head protection)	29 km/h, car is propelled sideways into a rigid pole ES-2 in driver seat	
rear impact (whiplash protection)	3 sled tests with driver seat using Low, Medium, and High Severity pulse BioRID in driver seat	
pedestrian impact	40 km/h or variable impactor speed, various impacts on front structure upper legform, legform, adult and child head impactors	

associated cost. To fill this gap, a new test procedure was developed by AGU Zurich in collaboration with Autoliv GmbH Germany, GDV Munich and the University of Graz [Muser et al. 1999]. A modified version of this procedure has been incorporated into an ISO standard by ISO/TC22/SC10.

In addition to the crash tests required by governmental regulations, consumer tests are performed. As legislation provides a minimum statutory standard of safety for new cars only, and because the results from the governmental tests are not necessarily published, it is the aim of consumer tests to encourage car manufacturers to exceed these minimum requirements and make the results of these consumer tests publicly available. Thus, consumers can obtain reliable and accurate comparative information regarding the safety performance of individual car models.

In Europe, dummies have been used in consumer tests to determine the occupant loading even before regulations demanded such tests. Thus, the public was made aware of the importance of passive safety issues. Moreover, consumer tests are characterised by ranking systems which are intended to give the consumers the possibility to assess and compare the occupant protection potential of different vehicle types. Such rating schemes often include dummy symbols with coloured body regions ranging from green (i.e. low loading) to red, and final star ratings where the number of stars correlates with the total number of credits gained in the assessment. This total number of credits cannot only be obtained from vehicle performance during the crash tests, but credits are also given for safety features concerning prevention or driver education (e.g. an acoustic "fasten seat belt" reminder or an electronic stability control (ESC) will influence the final grade positively in EuroNCAP tests).

To date, the most important consumer tests are the so-called New Car Assessment Programs (NCAP). NCAP testing is performed in Europe (EuroNCAP), Australia, Japan and the US. The test conditions and ranking systems differ for different NCAP agencies. Table 2.6 lists the tests performed by EuroNCAP. It should be noted that in the US and e.g. Australia, NCAP tests were performed by government agencies long before non-government institutions like EuroNCAP came into play.

It should also be borne in mind that consumer test ratings do not necessarily reflect the biomechanical performance of a car in a crash in an absolute way, but rather relative to the other cars tested under the same conditions. Threshold levels or rating scales are normally selected such that e.g. a certain percentage of cars in a test series will be rated 'good' and another percentage will be rated 'bad', even if, in a hypothetical case, all cars of a series would exhibit biomechanically sub-critical results.

2.6.1 Anthropomorphic test devices

Standardised tests required the usage of well defined and validated test objects. An anthropomorphic test device (ATD) is a mechanical model of the human body that is used as a human surrogate in crash testing. ATDs are in particular designed such that mechanical loading parameters can be measured at impact levels which would be injurious for a living human. To this end, a dummy is made of steel or aluminium (e.g. skeleton), polymers (joint surfaces, skin) and foam (flesh) and is equipped with several accelerometers and load cells to record acceleration, force or deformation. To date various types of ATDs - commonly called crash test dummies - are available whereas each ATD is designed for one specific type of impact only.

In automotive engineering, ATDs are used in the homologation tests required for new vehicles, and in safety device testing to evaluate the occupant protection potential. To a somewhat smaller extent, dummies are also used in the aircraft industry for similar purposes. Historically, the first dummies were developed for the use in aviation, to test parachutes and ejection seats.

Test devices and especially devices embodied in official regulations are expected to fulfil a given set of requirements:

- Anthropometry and biofidelity. An ATD should on the one hand represent a human in terms of size, mass, mass distribution, moments of inertia and (sitting) posture and on the other hand display a human-like biomechanical response to impact. The 50th percentile adult male of which the underlying anthropometric data were established in the 1960s from the US population (standing height: 1.75 m, total weight: 78.2 kg) is the most commonly used dummy in automotive crash testing. Other dummy types include the 5th percentile female (h: 1.51 m, w: 49.1 kg) and the 95th percentile male (h: 1.87 m, w: 101.2 kg). 3, 6 and 10 year old child dummies are furthermore available. The biofidelity is assessed on the basis of cadaver and volunteer studies.
- Instrumentation. The crash test dummy should be sensitive to and allow the measurement of parameters that are related to the injury or the injury mechanism to be examined.
- Repeatability and durability. It should be borne in mind that a dummy must continue to record data for later evaluation even if a critical threshold is exceeded during the test, i.e. it should not or only rarely be damaged.

Repeatability (performing the same test repeatedly with the same dummy) and reproducibility (comparing results obtained under the same test

Table 2.7 Dummies available and their field of application.

application	anthropomorphic test devices
frontal impact	Hybrid III family, THOR
lateral impact	EuroSID, EuroSID2, SID, SID-HIII, SID IIs, BioSID, WorldSID
rear-end impact	BioRID, RID2
pedestrian	POLAR
children	P0, P3/4, P3, P6, P10, Q-dummies, CRABI
belt	TNO-10
impactor	free motion head impactor, head/hip/leg impactor for pedestrian impact

conditions with different dummies) require that an ATD be calibrated regularly. Moreover, practical considerations play an important role in dummy design. Dummies should be robust enough to withstand a high number of tests (even with overload) and they should allow easy handling (up to 102 kg!) and adjustment of the posture.

Currently, over 20 different dummy types are available of which not all are, however, included in government regulations. Table 2.7 gives an overview of available ATDs.

The Hybrid III family of dummies consists of a 3-year-old, 6-year-old, 10-year-old, small adult female (5th percentile), mid-sized adult male (50th percentile) and large adult male (95th percentile). These dummies are designed for use in frontal impact tests. The Hybrid III 50th percentile male dummy (Figure 2.5) is the most widely used crash test dummy for the evaluation of automotive restraint systems in frontal crash testing. The dummy is defined in the US Federal Motor Vehicle Safety Standards (FMVSS, contained in the US Federal Register) as well as in the European directives. The skull and skull cap of the Hybrid III 50th percentile male dummy are made of cast aluminium parts with removable vinyl skins. The neck is a segmented rubber and aluminium construction with a centre cable. It accurately simulates the human dynamic moment/rotation flexion and extension response in situations involving high neck loading. The rib cage, in turn, is represented by six high-strength steel ribs with polymer based damping material to simulate human chest force-deflection characteristics.

Fig. 2.5 50th percentile male Hybrid III dummy [Denton ATD Inc.].

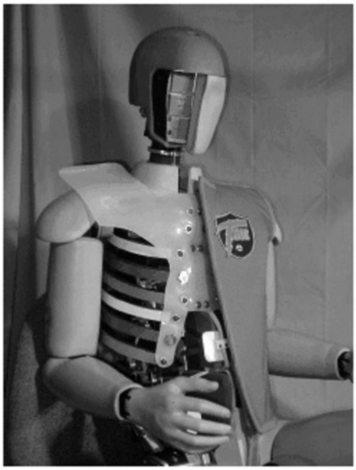


Fig. 2.6 The THOR dummy [Gesac Inc.].

Each rib unit comprises left and right anatomical ribs in one continuous part which is open at the sternum and anchored to the back of the thoracic spine. A sternum assembly connects to the front of the ribs and includes a slider for the chest deflection rotary potentiometer. The angle between the neck and upper torso is determined by the construction of the neck bracket, in which a six-axis lower neck transducer can be incorporated. A two-piece aluminium clavicle and clavicle link assemblies have cast integral scapulae to interface with shoulder belts. A curved cylindrical rubber lumbar spine mount provides human-like slouch of a seated person and mounts to the pelvis through an optional three axis lumbar load cell. The pelvis is made of a vinyl skin/urethane foam moulded over an aluminium casting in the seated position. The ball-jointed femur attachments carry bump stops to reproduce the upper leg to hip moment/rotation characteristics. While the femur, tibia and ankle can be instrumented to predict bone fracture, the knee is designed to evaluate tibia to femur ligament injury. The foot and ankle simulates heel compression and ankle range of motion.

A further frontal impact dummy called THOR (Test device for Human Occupant Restraint) (Figure 2.6) was developed in recent years. This dummy is also based on the anthropometry of the 50th percentile male. Compared to the design of the Hybrid III, all dummy components were improved except the arms, which are identical to those of the Hybrid III. The facial region of the dummy is, for example, instrumented with unidirectional load cells to asses the probability of facial skull fracture. Furthermore, the biofidelity and geometry of the rib cage was enhanced by the use of elliptical ribs and by improving instrumentation such that the dynamic three-dimensional compression of the rib cage can be determined at four distinct points. A new abdominal assembly was developed to allow for the measurement of belt intrusion and compressive displacement at the upper abdomen that might possibly result from an airbag. Changes to the pelvis and the lower limbs increased the sensing capabilities and in addition, the ankle joint was rendered more human-like.

The first side impact dummy (SID) was developed in the late 1970s at the University of Michigan. SID is based on the predecessor of the Hybrid III (the Hybrid II) with an adapted thorax, but without arms and shoulder structures. SID is also sized corresponding to the 50th percentile male and is used in US government-required side-impact testing of new cars (FMVSS 214). The dummy primarily allows a measurement of the injury risk to the head, chest and pelvis. To account for a better head-neck biofidelity, a SID dummy equipped with a Hybrid III head and neck is available (called SID-HIII). It is applied in compliance testing of side-impact head airbags. Additionally, the SID II, i.e. a side-impact dummy representing a 5th percentile female, became commercially available in 2000.

European lateral impact regulations (ECE R95) require the use of the Euro-SID1, the European side impact dummy. In Australian and Japanese regulations the Euro-SID1 is likewise prescribed. An updated version, today also accepted for homologation testing, is denoted as ES-2. The original Euro-SID, which was finalised in 1989 represents a 50th percentile adult male. Euro-SID basically consists of a metal and plastic skeleton, covered by flesh-simulating materials. The sitting height is 0.904 m. The total body mass is 72 kg. The dummy which has no lower arms is shown in Figure 2.7. While the head and the legs are that of the Hybrid III, the thorax was developed to analyse lateral impact. Three separate identical ribs covered with flesh-simulating foam are attached to a rigid steel spine box through a system consisting of a piston/cylinder assembly, springs and a damper (Figure 2.7). A special shoulder construction allows the arms to rotate realistically and expose the ribs to direct impacts. The pelvis is designed to allow for a measurement of the pubic symphysis force specified in ECE-R95. The dummy can be used for side impacts from its left- as well as from its right-hand side.

Further developments in side impact dummies include the Biofidelic Side Impact Test Dummy (BioSID) intended to improve the performance of the current US standard SID series. Although available since 1990, the

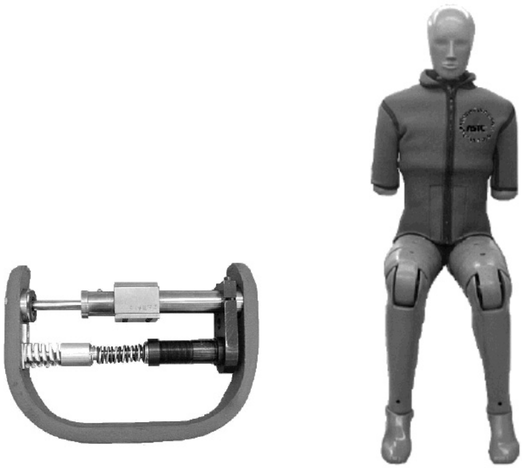


Fig. 2.7 Euro-SID and one of its spring-damper-elements used in the rib cage [Denton ATD Inc.].

BioSID was not yet included in FMVSS 214. BioSID has more sensors and a more biofidelic body than SID/Hybrid III, such that it allows the measurement of the thoracic, abdominal and pelvic injury potential as well as the rib deflection and other compression-based injury criteria. By rotating the upper torso by 180 degrees, the dummy can be converted from a left side to a right side impact dummy.

As the automotive industry becomes more global, a harmonised side-impact dummy, denoted as World-SID was developed by a worldwide consortium under the umbrella of the International Standardisation Organisation (ISO). In a comprehensive approach, a mid-sized male side impact dummy for improved assessment of injury risk to car occupants in

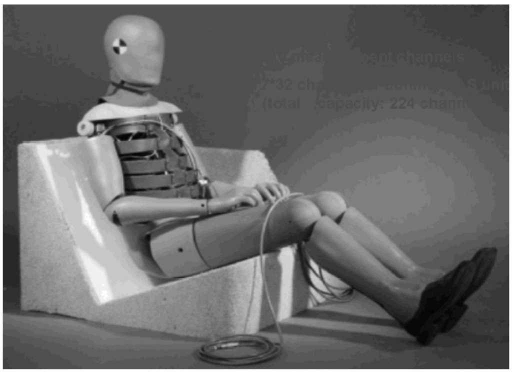
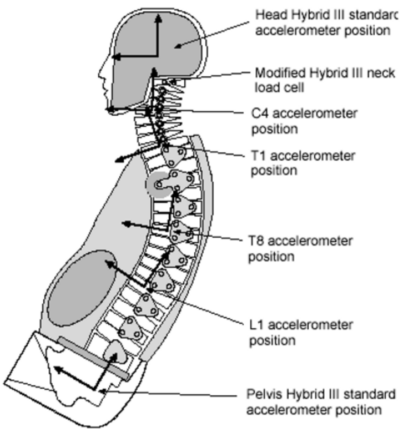


Fig. 2.8 The World-SID [ISO World SID Task Group].

lateral collisions was developed within the framework of the World-SID programme. Besides an improved biofidelity [e.g. Damm et al. 2006], the World-SID is intended to lead to a worldwide harmonisation in safety regulations and will in the future probably be incorporated in the Global Technical Regulation initiative (GTR) which was created to this end. A first prototype as well as 11 pre-production dummies were evaluated in various laboratories worldwide. The production design of the World-SID was released in March 2004 (Figure 2.8).

So far only dummies for frontal and lateral impact were presented. This is not surprising, as current occupant safety regulations are restricted to these impact directions. Because the assessment of occupant protection in other than frontal and lateral impacts, (rear-end impacts are most prominently absent), there was no need to develop suitable test devices. However, since injuries sustained in rear-end collisions, especially neck injuries sustained in low-speed rear-end collisions, constitute a major problem in road traffic (see chapter 4), the need emerged to develop anthropomorphic test devices that allow the investigation of these impact conditions.

To date, two different dummies for posterior impact are available, the BioRID and the RID2. Both are mid-sized male dummies have been developed in Europe for assessing the risk of "whiplash" injuries in low-speed rear-end impacts. The main feature of the biofidelic rear-end dummy (BioRID) is its fully segmented spine consisting of 24 segments. Each human spinal pivot point is reproduced. Due to such a detailed representation, a biofidelic spinal movement is observed (Figure 2.9). The rear impact dummy (RID2), in turn, is based on the THOR frontal impact



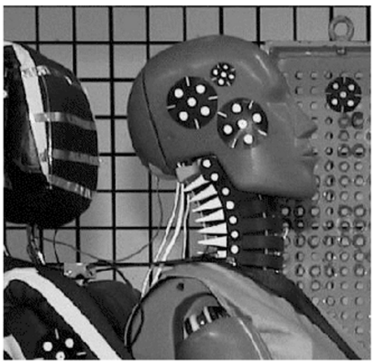


Fig. 2.9 The BioRID makes use of a fully segmented spine [Denton ATD Inc].

dummy. However, several modifications were made of which the new design of the neck, which consists of seven aluminium discs interspaced with rubber stops, and of the flexible thoracic and lumbar spine are most relevant in view of the analysis of the neck injury risk. Both the RID2 and the BioRID were developed and validated for pure rear-end impacts with a movement of the spine exclusively in the anterior-posterior plane. More recently, an improved neck for the RID2, called RID3D, was presented, allowing also oblique rear-end and even low speed frontal impacts to be analysed. Although these dummies offer the possibility for better investigation of the head-neck kinematics, difficulties in handling arise due to the increased flexibility of the spine. The seating procedure, for example, is quite an intricate task compared to a Hybrid III.

In addition to the dummies described above, several specially designed test devices exist. These test devices are generally used for one particular test purpose only.

- The TNO-10 dummy is a loading device for testing vehicle safety belts in a frontal crash situation. The dummy represents a 50th percentile male adult with respect to size and weight distribution. For reasons of simplicity the dummy has no lower arms and only one lower leg assembly combining the two human legs.
- The Child Restraint Air Bag Interaction dummy (CRABI) is used to evaluate air bag exposure to infants restrained in child safety seats that are placed in the front seat. CRABI dummies come in three sizes: six-month-old, 12-month-old and 18-month-old. Further child dummies like the Q-dummies, or infant dummies representing the newborn (P0) and the nine-month-old (P3/4) are available in addition to the child dummies of the Hybrid III family.
- The POLAR dummy (current version: POLAR II) has been designed to simulate more accurately the kinematics of the human body during car-pedestrian collisions. Standing 175 cm tall and weighing 75kg, the new dummy will help to gather more accurate data on injuries sustained by pedestrians.
- Test devices representing only parts of a dummy are used. The free motion head form (FMH) models a human adult head. Mounted on a propelling device, parts of the vehicle interior may be subjected to a simulated head impact. These tests are required by some safety regulations, e.g. FMVSS 201. Other impactors are used to test the behaviour of a car front with respect to pedestrian safety. These impactors, representing an adult head, a child head, an upper leg and a lower leg are, for example, used in the EC directives and the Euro-NCAP (New Car Assessment Programme) test scheme.

- A 50th percentile torso-shaped body block which is solely used to test the deformation characteristics of the steering assembly, is required for testing in e.g. ECE R12. Parts of ECE R12 have, however, been superseded under certain conditions by ECE R94 and are therefore not required any more in Europe.

Given the fact that a considerable variety of dummies exist which represent different levels of development and which apply in part to the same test conditions, efforts are being made to scale measured values in order to allow for comparisons. To this end, Injury Assessment Reference Values (IRAV) are determined which are dummy specific and can be used for scaling purposes [Mertz et al. 2003].

2.7 Numerical methods

Thanks to the continuous advancements in computer technology as well as in numerical methods, mathematical modelling has become gradually more detailed and more powerful. Today, computer simulations are an important tool in trauma biomechanics and are applied in all areas of safety engineering such as vehicle crashworthiness design and accident reconstruction; in addition, computer models are successfully used in human body modelling, addressing in particular biomechanical response and possible injury mechanisms.

The most widely used simulation techniques are the multi body system (MBS) approach based on rigid body dynamics (equations 2.1, 2.2) and the finite element (FE) method, a particular formulation of continuum mechanics (equations 2.3, 2.4). Multi body systems are sometimes also referred to as lumped mass models in that complex structures such as a human organ or a vehicle are condensed into one or more rigid units connected by mass-less elements like springs and dampers (see e.g. the Lobdell thorax model, chapter 5). Besides, the solidification principle of basic mechanics as well as St.Venant's principle of continuum mechanics are always in the background. Multi body systems and FE representations of subunits are furthermore often combined. Likewise, a multi body system can contain flexible subunits, e.g., a cantilever or a plate which can be approximated with models having only few degrees of freedom.

In a multi body system the various elements are connected by kinematic joints. The presence of the kinematic joints restricts the relative motion between adjacent bodies and hence reduces the degrees of freedom of the system. Different types of joints are available, for example translational,

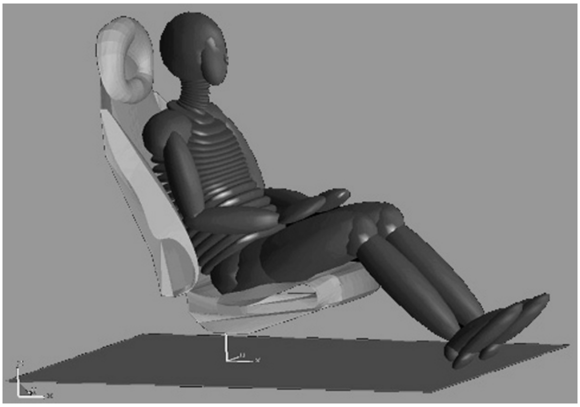


Fig. 2.10 MBS model showing a BioRID dummy seated [adapted from Schmitt et al. 2004].

revolute and spherical joints, of which each is characterised by a specific number of degrees of freedom. Additional kinematic constraints (e.g. spring/damper elements) can be applied. The rigid bodies themselves are characterised by their inertial properties and by the location of the above mentioned joints only. For the modelling of contact interactions (e.g. head-windscreen impact) and for visualisation purposes, geometrical shapes may be associated with rigid bodies. For the modelling of human body or dummy parts, ellipsoids are often used. Other geometrical primitives include planes and cylinders.

The behaviour of a MBS system is analysed by subjecting the system to external forces such as an acceleration field corresponding to a crash pulse or the forces associated with a fall from a window. This technique has proved its strength especially in whole body response modelling. Approximating the human body by various rigid bodies that are linked by joints and by assigning inertia and mass properties to those bodies, the gross human body kinematics during impact can be simulated. First models were presented already in the 1970s. To date, a wide range of extensively validated models is available. In particular, dummies are well suited to be modelled as a MBS, because the geometrical and mechanical properties (inertia, mass, joint properties) of the dummy components are clearly defined. Figure 2.10 illustrates an example of a MBS that includes a model of a BioRID. The example was established using the software MADYMO [TNO 2001] which is probably the most frequently used MBS programme for occupant safety problems.

In the finite element (FE) method, originally derived from Galerkin's

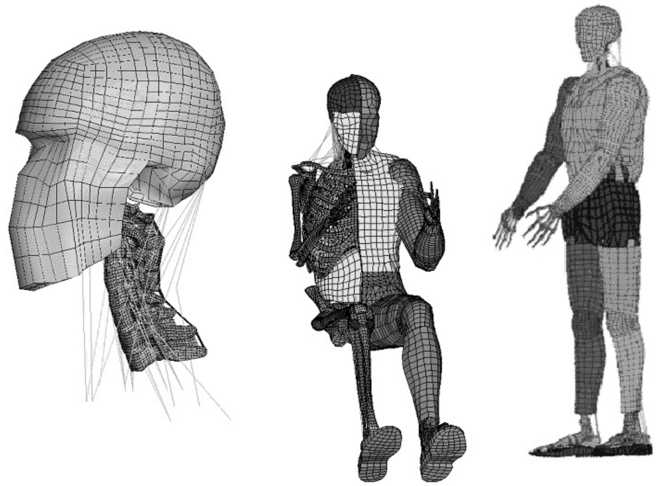


Fig. 2.11 The FE technique used in human body modelling. A detailed model of the head-neck complex on the left [adapted from Schmitt et al. 2002] and a whole body model on the right [adapted from Iwamoto et al. 2002].

theorem, a continuous system is reduced to a discrete numerical model consisting of well defined elements (e.g. hexahedrons, quadrilaterals, bars). Each element consists of a fixed number of nodes. The degree of freedom of the whole FE model is therefore restricted by the number of nodes. Depending on the boundary conditions applied and the geometry of the mesh, in particular for those elements that share common nodes, the degree of freedom of the whole FE model is given. A detailed description of the finite element method can be found, among other, in Bathe (2007) and Zienkiewicz (1994). However, it should be noted that the nature of the problems to be solved in trauma biomechanics (e.g. non-linear material behaviour, large deformations in short time intervals) require specialised approaches to the solution of the models. In general, FE programmes used in this field (PAM-CRASH [ESI 2001], LS-DYNA [Livermore 1999], or Radioss [Mecalog 2000]) are based on explicit time integration formulations. These formulations are based on the differential equations of motion of the nodes rather than on the equilibrium of inertial, field and contact forces (implicit formulation). This approach requires less calculation effort and easily lends itself for implementation in parallel computers. On the other hand, more care must be taken to control the numerical stability than in implicit formulations.

The FE method offers the possibility of detailed analysis of the response to impact of both the vehicle and the human body (Figure 2.11). For example, regarding the response of the head and brain, FE models offer the possibility to investigate the stress distribution in the brain during impact. Such results are important with respect to the understanding of diffuse brain injuries (see chapter 3), but can hardly be addressed in experiments. There are however promising approaches to apply e.g. the external loading conditions on the head as measured on an ATD in a crash test to a FE model of the head, thus allowing insight into complex damage mechanisms in the brain. Other complex biomechanical phenomena, for instance the influence of muscle activity or the interaction of fluid flow and the changing geometry of the surrounding tissue, can be approached by the FE method as well [e.g. Schmitt et al. 2002].

In summary, both the MBS and the FE technique offer their specific advantages and disadvantages in the field of crash simulations. The FE method allows for detailed studies of complex geometries and problems concerned with contact interactions. With respect to crash simulations, the study of local deformations and stress distributions are important advantages of this method. As such, this method can also be used for the analysis of injury mechanisms by modelling a specific part of the human body. However, a detailed representation of a complex geometry leads to an enormous number of elements and therefore a large number of unknowns to be calculated. In case of non-linear constitutive properties of the involved materials as well as large deformations, the enormous computational cost often associated with the FE method represents a major limitation. Parallel processing is suited to alleviate this problem. To date, large computer systems are able to handle FE models with millions of degrees of freedom (e.g. about 700’000 elements for simulations of compatibility tests with two cars modelled in detail), with computation times of several days. In contrast, its capability to represent complex kinematic connections efficiently makes the MBS approach particularly attractive. Additionally, computation times required are generally much shorter than for FE calculations since usually only a comparably small number of ordinary differential equations, though mostly stiff, are to be treated. Hence the MBSs are widely used as design tools as they are well suited for optimization studies involving many design parameters.

With respect to human body modelling, general problems arise that both techniques have to cope with. The choice of parameters to describe the material behaviour of the living human tissue requires the availability of experimental data with respect to the deformation characteristics of living tissues. Such data are hardly available, and, if so, often associated with a large uncertainty because of general biological variability on the one hand, and limitations of the particular experimental procedure chosen for the constitutive tests on the other. Furthermore, the validation of human body models, especially those intended for use in several different impact conditions, is crucial but remains a complex task.

To conclude, both methodologies can be reasonably used in the field of general impact and injury analysis. Depending on the purpose, either the best suited technique has to be chosen, or a combination of both methods can be considered. Such an integrated (or hybrid) approach is for instance realised in simulations of interactions of a car occupant and a deploying air bag. In this case an FE model is used to model the airbag while the human is represented by a MBS. Various other studies are presented where a MBS is used to model the gross motion while FE models are included for detailed analysis of single structures, for example, an ice hockey player crashing into a rink board. As of today, numerical models are included at basically all stages of the development process of safety devices.

Despite the widespread and rapidly increasing use of simulation techniques and their potential to reduce the number (and associated cost) of crash tests, numerical simulations are not yet included in the general vehicle safety standards. This can partly be attributed to the fact that general guidelines for simulations and especially for quality control are only emerging today, but would be required if crash simulations were embodied in safety regulations. The complexity of even moderate MBS simulation data sets makes it a difficult task for e.g. an external reviewer to efficiently validate simulation results, whereas the results of a real crash test is, in most cases, obvious.

2.8 Summary

Statistics and databases are tools to map the real-life situation with respect to accidents and injuries. They also allow for the analysis of trends, e.g. related to new vehicle designs or the use of safety gear in sports. In the automotive field STAIRS and GIDAS are important databases in Europe as are NASS and FARS in the US. The most prominent injury scaling system in trauma biomechanics is the Abbreviated Injury Scale (AIS). Injury risk curves relate the level of a given criterion to the risk of sustaining an injury. Accident reconstruction allows to investigate an accident in detail to reconstruct e.g. velocity changes (delta-v) and other parameters characterising the accident. The transfer of the parameters into biomechanical loadings of the persons involved, however, is much more complex.

To determine the biomechanical response, cadaver tests, animal models, or, where justifiable, volunteer tests are used. The data obtained allows investigating the injury risks and serves as important input for the development and validation of ATDs or computer models. Relatively simple multi- (or rigid-) body-systems (MBS) simulations, complex finite element (FE) models, or combinations thereof assume an increasingly important role in the design of e.g. safety devices and car structures.

Full-scale tests, sled tests and impactor tests are common experimental procedures in trauma biomechanics. Full scale tests are expensive, but necessitate fewer assumptions. Sled and impactor tests, on the other hand, allow for parameter variation studies due to their lower cost. For such tests various ATDs are available whereas usually an ATD is designed for a special impact type. The evaluation of standardized test procedures is prescribed in regulations such as ECE or FMVSS or by consumer tests (e.g. EuroNCAP).

2.9 Exercises

E2.1: A driver seat with integrated seat belts and a special device to prevent submarining (sliding of the pelvis underneath the lap belt in a frontal collision, see e.g. Figure 7.18) has been developed. Plan a test to verify the efficiency of this seat (test method, crash pulse / velocity, dummy type).

E2.2: Describe the various parameters used to describe the 'violence' of a collision. Which parameters are important for trauma-biomechanics?

E2.3: A free motion head form impacts a deformable surface, whose force-deformation characteristic is a) known b) not known (only the material properties and the geometry of the surface are known). Choose a numerical method to simulate this impact, give reasons for your choice.

P2.1: In Europe and the U.S. different crash test procedures are required for homologation of new cars. Also, consumer tests employ different crash test procedures. Discuss the effects of these disparities on the car maker and on the consumer.

P2.2: ATDs that are more biofidelic and offer more measurement possibilities than e.g. the Hybrid III or the Euro-SID have been available for quite some time now. Why are they neither specified in the relevant regulations nor used in consumer crash tests?

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