The Biomechanics of Head Injury in Vehicle Collision

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By

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Cambridge
Scholars
Publishing

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This book first published 2026

Cambridge Scholars Publishing

Lady Stephenson Library, Newcastle upon Tyne, NE6 2PA, UK

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN: 978-1-0364-6974-0
ISBN (Ebook): 978-1-0364-6975-7

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FOREWORD

Head injury is the solitary, persistent constant that connects every violent aspect of modern life: the motorway at twilight, the Saturday football field, and the far-off blast area of an improvised explosive device. Wherever kinetic energy is abruptly redirected into human tissue, the same pressing questions resurface. How much force reached the intracranial cavity? Which microscopic blood vessels tore first? And—most poignantly—why does one victim escape unscathed while another never wakes up? This book, “The Biomechanics of Head Injury in Vehicle Collision”, is written for every engineer, clinician, regulator, and bereaved parent who has ever posed those questions and been informed that the answers are “too complicated” or “still under investigation.”

The volume arrives at a critical juncture. Road-traffic collisions still claim the lives of over one million people each year. In Europe alone, so-called “minor” whiplash injuries already cost society five to ten billion euros annually, and military physicians now report that blast-related traumatic brain injury has become the signature injury of contemporary conflict. Against this backdrop, the rate of discovery has accelerated beyond the ability of any single discipline to fully absorb it. High-resolution CT and MRI now enable us to delineate every cranial suture and air sinus. Biofidelic dummies can flex through twenty-four cervical vertebrae. Finite-element models can determine intracranial pressure within kilopascals. Yet the transition from laboratory findings to real-world protection remains tenuous. Our aim is thus two-fold: to condense the past seven decades of experimental and computational knowledge into a coherent biomechanical framework, and to translate that framework into practical prevention strategies.

We start, in “Chapter One: Methods in Injury Biomechanics”, by establishing the non-negotiable ethical boundary: no experiment that deliberately causes harm to a living human is acceptable. From this stringent premise, we examine the six mainstays of indirect investigation—epidemiology, injury criteria, accident reconstruction, cadaveric and animal surrogates, laboratory impact rigs, and numerical simulation—each exemplified by cautionary anecdotes about how one un-calibrated dummy or an unnoticed sampling bias once steered an entire regulatory system astray. The chapter concludes with a methodological manifesto: transparency regarding data origin, modesty in extrapolation, and unceasing validation against the complex diversity of real-world crashes.

"Chapter Two: Head Injuries" metaphorically opens the skull as if it were an archaeological site. The reader is guided, layer by layer, through the scalp, bone, meninges, and brain, learning why a five-millimetre scalp thickness can double the duration of an impact pulse and why bridging veins are the vulnerable point of the dura. Based on this anatomical map, we categorize every imaginable type of lesion—open versus closed, focal versus diffuse, coup versus contre-coup—before translating them into the forensic concise terms of the Abbreviated Injury Scale. Cadaveric impact data bring back the Wayne State Tolerance Curve and its modern counterparts (HIC, HPC, 3 ms, GAMBIT), with each being revealed for what it measures and what it overlooks. A final foray into the sports domain demonstrates that a boxer's punch and a soccer header follow the same mechanical principles as a dashboard impact.

If Chapter Two dissects the real head, "Chapter Three: Development of a Finite Element Head Model for the Study of Impact Head Injury" constructs its digital counterpart. Beginning with 460 CT slices and 1659-pixel MRI matrices, we orchestrate a segmentation process akin to a ballet—thresholding bone, growing regions for sinuses, trimming stray vessels, and reconciling CT and MRI coordinates to within 0.12 mm. Two models are created: Model 1 (skull + brain) and Model 2 (skull + grey/white matter + CSF + soft tissue). Both are meshed at 1.35 mm and calibrated to a total mass of 4.7 kg. Material properties are assigned from the broad range of data in the literature—linear viscoelastic for the brain, hydrostatic for the CSF cavities, and nearly incompressible for the aerogel inserts. Validation against three cadaveric impacts results in peak intracranial pressure and brain-displacement errors of less than fifteen percent—a figure that is both a cause for celebration and a note of caution.

"Chapter Four: Validation of the New 3D Finite Element Head Model" transforms the windshield into a biomechanical perspective. A thirteen-segment rigid-body pedestrian model is launched towards a sedan moving at 60 km/h. High-speed video frames are substituted with time-stamped images of limb trajectories, head accelerations, and the harsh calculation where HIC > 1000. We analyze the “contact–post-flight flip–fall to glide” sequence, uncover why anti-lock braking counterintuitively increases the head-injury risk at 55 km/h, and conclude with a colour-coded map of pedestrian HIC across impact speeds from 20 to 60 km/h—an implicit case for 30 km/h urban speed limits.

“Chapter Five: Modal and Dynamic Responses of the Human Head-Neck Complex for Impact Applications” initiates the head's vibration in modal analysis. A 483,711-node finite-element (FE) model, fixed at the C7-T1 junction, is examined for natural frequencies ranging from 0 to 360 Hz. The first mode, at 35.25 Hz, manifests as a composed nod. At 221 Hz, the entire cervical column twists into an S-shaped configuration, suggesting distress. Lesser-known modes emerge, such as the 62 Hz “flipping” of the nasal cartilage and the 150 Hz “mastication” of the mandible. Damping studies reveal a harsh trade-off: a damping ratio $\zeta = 0.2$ reduces injury metrics by thirty percent but increases higher modal frequencies by eight percent, highlighting that comfort and safety are biomechanical opponents.

“Chapter Six: Biomechanical Study of the Facial Impact on Pedestrian Traumatic Brain Injury” subjects nine typical facial impacts—nasal tip, lateral cartilage, maxilla, zygoma, mandible, teeth—to a velocity of 10 m/s. Meanwhile, a “high-speed camera” of finite elements captures pressure, stress, and strain at 0.1 ms intervals. Animated stress fronts speed along the nasal septum, bounce off the sphenoid sinus, and converge at the foramen magnum. Von Mises maps forecast a Le Fort I fracture from a 203 MPa blow to the maxilla. Shear-strain contours signal the potential for diffuse axonal injury following an apparently harmless lateral zygoma impact. A concluding table correlates each fracture pattern with its most likely intracranial consequence, serving as a valuable guide for emergency-room radiologists.

“Chapter Seven: Whiplash Injury” starts with a regret: soft-tissue neck injury is the most prevalent automotive trauma, yet its mechanism remains “not fully comprehended.” Microscopic anatomical exploration—uncovertebral joints, zygapophyseal capsules, viscoelastic discs—leads to volunteer sled tests and cineradiography, which expose the well-known S-shaped deformation during rear-end impact and its inverted form during rebound. Injury criteria NIC, N_{km}, N_{ij} are examined in light of real-world crash-recorder data; $NIC_{max} > 20$ m²/s² and $N_{km} > 0.8$ indicate a fifty-percent risk of chronic symptoms. The chapter concludes with a compilation of anti-whiplash seats—WHIPS, SAHR, WipGARD—each a testament to the biomechanical implications of regulatory perseverance.

“Chapter Eight: Brain Dynamic Responses due to Wave Propagation” shifts the setting from the road to the battlefield. A 1 atm blast wave explodes 30 cm in front of a helmeted head; the ensuing 3 ms are simulated using Coupled Eulerian-Lagrangian finite elements. Intracranial-pressure histories indicate a 122 kPa frontal peak without a faceshield, which decreases to 110 kPa with a five-layer polycarbonate-aerogel laminate. Skull-stress maps show a 4.4 MPa spike at the front point, dropping to 2.7 MPa when the visor is added. Parametric variations of aerogel thickness and layering identify an optimal configuration: two 0.6 mm aerogel layers embedded in polycarbonate reduce peak ICP by thirty percent while maintaining optical clarity. A final note: none of the configurations surpasses the 235 kPa serious-injury threshold, but the margin is worryingly narrow.

We conclude in “Chapter Nine: Conclusions and Recommendations” by weaving every thread into a single prevention-focused tapestry. Model 1 and Model 2, having been validated and cross-correlated, are made available as open-source tools. A prioritized list of countermeasures is presented: active head-restraints for rear-end impacts, compliant bonnet leading edges for pedestrian safety, graded polycarbonate-aerogel faceshields for blast protection, and—most contentiously—mandatory 30 km/h urban speed limits. A final research plan advocates for the integration of cervical muscles, the determination of sex-and age-specific material properties, and blast simulations in complex urban geometries. The closing sentence is an appeal, resonating with the start of this foreword: “The skull is ancient; the brain is irreplaceable; the time for complacency has passed.”

We recommend this volume to engineers aiming to create safer vehicles, to clinicians tasked with interpreting ambiguous scans, to policymakers who need to balance cost and compassion, and to every citizen who has ever fastened a seat belt, adjusted a helmet strap, or merely pondered what occurs inside the head in that split-second when the world suddenly comes to a violent halt.

—The Author

Prof. Dr. Bin Yang, Nanjing Institute of Technology, Jiangsu, China

PREFACE

Every year, over 15 million people are injured and 1.25 million killed in traffic on the world's roads. Traumatic brain injuries (TBI) impose a significant burden on society globally. For instance, in the US, approximately 1.4 million people suffer from TBI annually, and it is estimated that one-fifth of hospitalized patients are unable to return to work. In the UK, TBI accounts for 15-20% of deaths among people aged 5 to 35 years. Similar findings were revealed in studies carried out in France and China.

To gain a better understanding of crash-induced injuries, which is essential for designing injury countermeasures, several experimental and numerical approaches have been employed. Experimental approaches have sought to reproduce crash-induced injuries in laboratory settings through Post Mortem Human Subjects (PMHS) impact tests. Nevertheless, it is difficult to understand the injury mechanisms and develop accurate Injury Criteria from the data obtained in these tests because of the inherent variability in PMHS anthropometry and material properties.

With the recent rapid progress in computational technology, human finite-element (FE) models of the head and neck are now the most sophisticated numerical models available. These models can offer the general kinematics of the brain and compute detailed stress/strain distributions, which can be linked to the risk of injuries. The field of trauma biomechanics, also known as injury biomechanics, applies the principles of mechanics to study the response and tolerance levels of biological tissues under extreme loading conditions. By comprehending the mechanical factors that affect the function and structure of human tissues, countermeasures can be devised to mitigate or even prevent such injuries.

This book, *The Biomechanics of Head Injury in Vehicle Collision*, surveys a wide range of topics in head-neck injury biomechanics, covering the anatomy and injury mechanisms in traffic accidents. The objective of our study is to develop a more biofidelic finite-element (FE) human head and neck model by directly reconstructing the geometry from the medical scan data of a 50th percentile male volunteer. Such an FE head and neck model should replicate the irregular anatomical features of the head and neck, be validated against a comprehensive set of head-impact data, and be applicable in diverse impact scenarios to predict facial, skull, and intracranial responses. Consequently, it is advisable to incorporate only those anatomical structures that will improve the accuracy of these analyses.

It is the first collection I know of that lists regional injury reference values. Although the book is designed as an introduction for medical doctors, scholars, and engineers who are new to the field of injury biomechanics related to traffic safety, it provides ample references for those wanting to conduct further research. Even experienced researchers will find it valuable as a reference for grasping the biomechanical background of each proposed injury mechanism. As more people become informed about and understand this subject, it will, someday, lead to better mitigation and prevention of automotive-related injuries. I really like this book and believe you will too.

—The Author

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ACKNOWLEDGEMENTS

I would like to express my profound and sincere gratitude for the financial support from the National Natural Science Foundation of China (Grant No. 12372079), the Natural Science Foundation of Jiangsu Province, China (Grant Nos. BK20201470 and BK20220687), and the Fund of Nanjing Institute of Technology (Grant No. CKJB202205). On behalf of all team members, I thank all the institutions and individuals who have supported and shown concern for this program.

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CHAPTER ONE

METHODS IN INJURY BIOMECHANICS

Work in injury biomechanics is subject to a number of limitations that are less stringent or even completely absent in other fields of the technical and life sciences. First of all, experiments involving loading situations with humans that are likely to cause injury are excluded. Second, animal models have limited utility because it is difficult to scale trauma events reliably from animals to humans, either up or down. In earlier years, a number of experiments related to seat belts were nonetheless conducted using pigs, as their thoraxes resemble the human thorax mechanically to some degree. Similarly, monkeys were subjected to impact to study head motion and neck dynamics. Additionally, anaesthetized animals provide a model for investigating physiological reactions at high mechanical exposure levels. However, despite some similarities, the questionable representativeness with respect to human biomechanics, along with cost, and above all, ethical considerations and public awareness, limit 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 (1.1)
- injury criteria, injury scales and injury risk (1.2)
- basic mechanical concepts and accident reconstruction (1.3)
- experimental models (1.4)
- impact tests performed in the laboratory (1.5)
- anthropomorphic test devices (1.6)
- numerical simulation (1.7)

Statistics, Field Studies, Databases

Epidemiology is of fundamental importance in trauma-biomechanics; it also represents the oldest methodological approach. The identification of injury risks and the analysis of causative factors are largely based on epidemiologic evidence. This evidence, in turn, stimulates the development of intervention strategies, as well as technical and legal countermeasures, with the aim of accident prevention and injury reduction. Whether such countermeasures are truly effective can only be determined based on statistical surveys, which often necessitate long-term studies. Thus, when working in the field of trauma-biomechanics, especially regarding issues related to injury mitigation and prevention, the acquisition and in-depth analysis of real-world accident data are indispensable prerequisites and research tools.

The collection, classification, and interpretation of accident data must be carefully assessed in relation to the sampling process. In most cases, the available data set is not comprehensive but limited to a selected sample. One should always bear in mind that significant limitations on the applicability of the results of any statistical evaluation are already inherent in decisions regarding how and what data to collect. Unlike fully controlled laboratory experiments, uncertainties occur. For instance, many crucial parameters in real-accident situations are not monitored and can vary widely. Additionally, the memories of those involved in an accident or serving as witnesses may be inaccurate regarding details or influenced by legal or insurance-related concerns. When attempting to analyze the impact of newly introduced safety measures, other factors must also be considered. These include the current composition of the vehicle fleet in traffic accidents, the price of gasoline, changes in legislation, modifications to rules in contact sports, or alterations in insurance coverage for workplace accidents. A reliable statistical evaluation may also be compromised due to an insufficient number of cases for a representative analysis.

Regarding methodology, two types of accident databases or injury surveillance systems can be differentiated: general accident collections, which may involve extensive, perhaps comprehensive, coverage of accidental events on one hand, and in-depth studies of selected cases on the other. General large-scale accident files are typically gathered by the police, other government agencies, or insurance companies and are presented in annual accident statistics. These usually contain a large number of cases but only limited information per case. Conversely, in-depth case analyses are carried out by specialized teams. These teams strive to obtain as much detail as possible for each case under examination-which, somewhat cynically, can be seen as an involuntary experiment. They do this based on an investigation of the accident scene, workplace or household locations and installations, vehicles, sports accessories. Additionally, they rely on police reports, witness depositions, interviews, medical records, weather reports, video coverage of sports events, and on-site reconstruction using original vehicles or installations. Numerical simulation is often then employed to clarify loading conditions and relate them to injury patterns. It goes without saying that such investigations are costly, and only a limited number of cases can be evaluated in this way. Representativeness is a particularly crucial aspect of this approach.

Insurance companies often possess larger collections compared to governmental bodies. This is because accidents are reported to insurance companies for financial motives, while there is more hesitation when it comes to involving the police, especially in cases of self-accidents that do not involve a second party. However, insurance data are frequently inaccessible. And even if they are accessible, the data may not be detailed or could be biased.

Moreover, the cases included in large-scale data collections are often not gathered and analyzed by accidentology specialists. As a result, these cases may contain significant errors and be selected according to non-uniformly applied criteria. Consequently, it is often difficult to compare the results obtained from different databases because of variations in data-collection schemes. Even within a particular type of database, such as police records, there can be substantial differences in basic definitions, data-set volume, or privacy policies from one source to another. For example, whether an elderly patient who dies in a hospital from pneumonia two weeks after a severe traffic accident is considered a traffic-accident victim and included in the statistics may simply depend on the hospital's reporting practice.

In most industrialized countries, accidents related to traffic, the workplace, households, and sports fall under the purview of different government agencies, foundations, private institutions, sports associations, insurance companies, etc., with limited interaction among them. Reporting and investigation practices, as well as injury-prevention strategies, can vary. Thus, comparisons between various injury-causing situations must be made with great caution. Uniform statistics are generally more likely to be available from smaller countries such as Switzerland. There, the Swiss Council for Accident Prevention offers 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). These include general data regarding 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 of these activities can be found, for example, in Compton. Similarly, although sometimes less systematically presented, information is available from most other countries around the world.

Work-place safety issues are comprehensively dealt with in the statistics of the US Occupational Safety & Health Administration (OSHA). Additionally, in most industrialized countries, workplace accidents are insured by government-controlled insurance organizations. General statistics are regularly accessible from these sources.

The situation regarding sports accidents and injuries is somewhat distinct. Sports activities are predominantly voluntary and leisure-oriented (except for mandatory participation in schools). They are mostly insured by special insurance programs, especially when competitive events or contact sports are concerned. Product liability in sports is highly diverse and selective; for example, it applies to trampolines, diving boards in swimming pools, American football helmets, and ski bindings. Specific, not to mention general, statistics providing comprehensive coverage over several years, such as those needed to analyze trends, are largely lacking. General awareness of sports injuries has only recently grown. The Olympic Committee established a Medical Commission and Library in 1990, which includes a Special Collection of Sports Medicine and Sports Science, where the injury problem is partly addressed. While the Fédération Internationale de Football Association (FIFA) does not release systematic information about soccer accidents and injuries, the Fédération Internationale de Ski (FIS) and the Oslo Sports Trauma Research Centre NSS announced in 2006 that they had 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 conducted by specialized teams, typically with a specific objective or within a limited geographical area. To be valuable, these efforts must be sustained over several years, and a sufficiently large number of cases must be collected while adhering to uniform procedures. Most of the projects of this kind that are documented in the literature are related to traffic accidents. For example, a team at the Medical University of Hannover (Germany) has been gathering data on collisions in the Hannover city area for many years. Since the data have been systematically collected following a consistent protocol for an extended period, it is possible, for instance, to analyze factors related to changes in vehicle design. Another example is the database on whiplash-associated disorders that result in sick leave lasting more than four weeks, which is maintained by AGU Zurich. The collection encompasses cases from the entire country of Switzerland. Thanks to the large volume of available data, specific topics regarding the technical, medical, and biomechanical aspects of soft-tissue neck injuries can be explored. Vehicle manufacturers also carry out in-depth investigations. Specialized teams within these companies examine cases involving their own vehicles to evaluate the effectiveness of safety measures and identify areas for improvement. Some of these accident databases even include cases where vehicle damage occurred but no injury was reported. Such data are especially useful for statistical analysis as they provide the opportunity to establish well-defined control groups, which may not be available in other types of databases.

Having recognized that an adequate supply of road accident and injury records is considered important for the selection, implementation, and evaluation of road safety measures, several approaches, such as the European STAIRS project (Standardization of Accident and Injury Registration Systems, 1997-1999), are being developed. These approaches aim to harmonize accident data collections to enable more comprehensive and comparable studies. However, few such efforts are being made for workplace, household, or sports injuries. Given the increasing globalization and international mobility, this may lead to problems, among others, with liability and insurance coverage.

Injury Criteria, Injury Scales and Injury Risk

Injury criteria are vital tools for assessing the severity of accidental loading and the associated risk of sustaining an injury. By definition, an injury criterion links a function of physical parameters (such as acceleration or force) to the probability of a particular body region being injured in a specific way (for example, suffering a concussion or a fracture). Injury criteria are typically derived from experimental studies combined with empirical evidence. Their formulation and validation demand an extensive, step-by-step extrapolation process, as, as previously noted, experiments on living humans at traumatic levels are not permitted.

First, apart from the concept of "injury criterion," two additional criteria need to be introduced: the damage criterion and the protection criterion. An injury criterion is designed to describe the injury-tolerance property of living tissue. In contrast, a damage criterion pertains to post-mortem test objects, which serve as surrogates for living humans. In both cases, a threshold value is set for the exposure to a quantity calculated from physical parameters. If the exposure exceeds this threshold, in more than 50% of all experiments or accidental exposures under comparable conditions, the test tissue will be injured in a specific way with respect to its anatomical or physiological structure. A protection criterion is established by postulating a threshold value based on measurements made with an anthropomorphic test device as a human surrogate. In this case, the connection to human injury-tolerance levels is primarily derived from empirical research. It is assumed that, on average, a healthy middle-aged adult will not sustain the types of injuries addressed by the specific criterion when exposed to loading conditions similar to those defined in the protection criterion. The actual risk of injury can then be estimated using a risk function that relates the probability of being injured to the developed criterion (i.e., the underlying measured mechanical properties). A threshold value is defined so that, for a given loading scenario, represented by a particular value of the criterion, the risk of sustaining an injury does not exceed 50%.

However, the definitions of injury, damage, and protection criteria are frequently not clearly distinguished. As a result, the term “injury criterion” is commonly used for any index intended to quantify the severity of impact or accidental loading. Protection criteria, on the other hand, are determined through standard test procedures. These are mainly designed for use in automotive laboratories and have been defined and established on an international scale.

Scales for classifying the type of an injury are founded on medical diagnosis and were devised for injuries incurred in traffic accidents. The most extensively utilized scale of this kind is the Abbreviated Injury Scale (AIS). First developed in 1971 as a system to define the severity of injuries across the body, it is regularly revised and updated by the Association for the Advancement of Automotive Medicine. The AIS is a standardized system for categorizing the type and severity of injuries resulting from vehicular crashes (Table 1-1). It is centered around the survivability of an injury; that is, each category represents a particular threat-to-life associated with an injury. Consequently, the AIS is an anatomically-based, global severity scoring system. It classifies each injury in every body region by assigning a code that ranges from AIS0 to AIS6. Higher AIS levels signify an increased threat-to-life. AIS0 denotes "non-injured," and AIS6 means "currently untreatable/maximum injury."

As a result, the AIS severity score is a single, time-independent value for each injury and each body region. The severity is described in terms of its significance to the entire body, assuming that the described injury befalls an otherwise healthy adult. However, it should be noted that the AIS takes into account only the injury itself and not its consequences. Specifically, clinical complexity, the cost of surgical treatment, and long-term sequelae are not considered. Thus, severe impairments such as blindness or life-threatening complications resulting from nosocomial infections that occur in a hospital are not coded as severe injuries because they do not pose an initial threat-to-life.

Table 1-1 The AIS classification

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

Moreover, the AIS is not a linear scale; that is, the difference between AIS1 and AIS2 is not comparable to that between AIS5 and AIS6. Consequently, calculating average AIS codes (such as AIS 3.7, which is a meaningless number) is not sensible. To describe the overall injury severity of a person with multiple injuries, the maximum AIS (MAIS) is employed. The MAIS represents the highest AIS code a person has sustained anywhere on the body, even if the person has several injuries of the same severity level in different body parts. For instance, if a car occupant has AIS2 injuries to the head and legs and no higher-classified injuries, the MAIS will be MAIS2.

To better represent patients with multiple injuries, the Injury Severity Score (ISS) was introduced. Like the AIS scale, it is regularly updated. The ISS differentiates six distinct body regions: head/neck, face, chest, abdomen, extremities including pelvis, and external (i.e., burns, lacerations, abrasions, and contusions regardless of their location on the body surface). For each of these regions, the highest AIS code is identified. The ISS is calculated as the sum of the squares of the AIS codes of the three most severely injured body regions. So, the minimum ISS is 0, and the maximum ISS is 75 (i.e., from three AIS5 injuries). If an AIS6 injury is noted, the ISS is automatically set to 75. ISS values greater than 15 are considered major trauma. Several studies have demonstrated that the ISS correlates fairly well with various measurement systems, such as mortality or long-term impairment.

In addition to the AIS, other scales are utilized to detail injuries of specific body regions more precisely. The Quebec Task Force, for instance, developed a scaling system to categorize soft-tissue neck injuries. Moreover, there are scales that deal with impairment, disability, and societal loss by assigning an economic value to rate the long-term consequences of an injury. One such example is the Injury Cost Scale (ICS), which determines the average costs of an injury, considering expenses for medical treatment, rehabilitation, income loss, and disability. Other economic scales include the Injury Priority Rating (IPR) and the HARM concept employed by the US government.

One of the most critical problems in trauma-biomechanics is assessing the relationship between injury severity and the mechanical load that causes the injury. That is, finding a relationship that enables the assignment of probabilities indicating the likelihood that a specific mechanical load (e.g., determined by an injury criterion) will result in a particular injury. This is of utmost importance because, without such correlations, attempting to interpret results from, for example, crash tests is rather futile. Therefore, it is essential to conduct well-equipped laboratory experiments using human surrogates to determine the biomechanical response and corresponding injury-tolerance levels, and subsequently establish so-called injury-risk functions.

For the determination of injury-risk curves, basic statistical methods are applied, with the maximum-likelihood method, cumulative-frequency distributions, and the Weibull distribution being the most commonly used. An example regarding head injury is presented. However, for in-depth information on applying statistical methods to the often complex and challenging analysis of accident and injury data, the reader is directed to statistical textbooks. Extreme caution must be exercised in such analyses.

Among the various issues that may occur when translating experimental results into (real-world) injury-risk functions, are

- the small number of tests performed,
- differences in the biomechanical response between the human surrogates used in testing (e.g. cadavers) and living humans, differences between the population of 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 hold when using data from accident statistics rather than experimental results to fit injury-risk curves. Nevertheless, decades of research in trauma-biomechanics have yielded a sufficiently large number of sources, enabling the establishment of several well-founded relationships that connect mechanical loads to injury probability, at least for certain injuries and injury mechanisms. However, work in this area is far from complete, and revisions of existing criteria based on new findings are not uncommon.

Basic Mechanical Concepts and Accident Reconstruction

The reconstruction of accidents is an indispensable procedure in the field of trauma-biomechanics. This is because the relationships between loading and injury under physiological conditions are only revealed in real-life accidents. Similarly, accident reconstructions are frequently necessary for forensic purposes, both in criminal and civil cases.

The reconstruction of an accident involves the mathematical analysis of the event based on the laws of classical mechanics. However, unlike laboratory experiments, everyday accidents occur under largely uncontrolled and unmonitored conditions. Depending on the extent, quality, and accuracy of the available documentation, the accident reconstruction specialist must apply assumptions and approximations at various levels of complexity. For instance, an accident in a skiing competition might be captured by multiple video recordings, and the traces of a traffic accident could be accurately documented by the police. In contrast, a fall from a ladder during household activities is rarely documented. All information is crucial in the reconstruction process. Similar to solving a puzzle, different sources of information need to be combined to create a reliable and conclusive account of the events. This can include diverse details such as the sequence of traffic lights in a vehicle-pedestrian impact and the bending stiffness of a pole in a sports incident. A thorough examination of the accident scene is always essential. Experience from previously conducted laboratory tests or the results of well-documented "comparable" accidents can also be helpful. Often, collaboration with a medical forensic expert is of utmost importance, as injury patterns can offer useful clues for accident reconstruction. For example, the direction of a fall can be inferred from the specific appearance of street dirt under the skin.

Missing documentation or visible evidence can present challenges in accident reconstruction. For instance, in vehicle collisions, uncertainties may surface when anti-locking systems prevent the formation of skid marks. Moreover, reconstruction is more arduous when there is little to no vehicle deformation. To cut down on repair costs, modern vehicles are engineered to incur minimal damage in low-intensity collisions (or at least the damage is not externally visible, often leading laypeople to wrongly assume no damage occurred). However, the absence of visible damage does not imply that no collision took place or that the transmitted energy was insufficient to injure the vehicle's occupants.

In what follows, a number of basic mechanical definitions are first revisited. A distinction must be made between rigid-body mechanics and continuum mechanics. (For a comprehensive theory of classical mechanics, including the formulations employed here, the reader is directed to textbooks.) Both approaches involve approximations that need to be carefully evaluated in each application, and they are widely utilized in trauma-biomechanics.

Rigid-body models are defined by a finite number of degrees of freedom, related to a set of ordinary differential equations. In contrast, in continuum mechanics, partial differential equations are dominant, and the number of degrees of freedom is infinite. For numerical analysis, these partial differential equations must be approximated using special formulations. Among these, the finite element (FE) approximation is most commonly employed in trauma-biomechanics.

Within the framework of a rigid-body approximation for describing an impact event, empirical studies and laboratory experiments have demonstrated that the acceleration of the center of mass that a body limb experiences under the influence of impact forces is a crucial parameter for assessing the severity of an impact. In numerous practical situations, the magnitude of this acceleration is frequently related to the acceleration due to gravity, g (1g=9.81 m/s^2), as we are continuously subjected to gravity, allowing us to relate a given acceleration value to our everyday experiences. However, the acceleration a body undergoes during an accident changes over time. Thus, the quantities “peak acceleration” and “mean acceleration,” along with their corresponding time intervals, should always be clearly differentiated to avoid misunderstandings.

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

- The collision or impact velocity of a vehicle is perhaps the parameter most commonly cited by the public. In accident reconstruction, the traveling speed, or more precisely, the speed prior to the onset of any braking action, is sometimes significant when examining whether a collision could have been avoided and under what circumstances.
- The collision-induced velocity change (delta-v) of the vehicle in question, however, is in most cases more valuable for depicting the collision severity when considering the effects of the collision on the vehicle's occupants. The delta-v approximately equals the integral of the translational vehicle deceleration over the collision time for collisions that involve a single impact and have no significant vehicle rotation. Nevertheless, in complex collision scenarios (such as roll-overs, falling off the roadside, etc.), delta-v may not be a well-defined parameter.
- The energy equivalent speed (EES) quantifies the amount of energy required to deform a vehicle. In essence, the EES is the impact velocity into a rigid barrier that would have been needed to produce the same permanent deformation as seen in an actual accident. The EES is expressed in [km/h] and can be found for many vehicle types in so-called EES catalogues. These catalogues are created based on crash tests carried out under well-defined test conditions.
- Another parameter employed to describe impact conditions is the vehicle overlap. This refers to the degree to which the vehicle and its collision partner (such as another vehicle or a barrier in a crash test) overlap. The overlap is typically expressed as the percentage of the total width of the vehicle in question that is covered by the

opposing vehicle (or wall). Basic technical definitions and accident reconstruction.

- From basic mechanics, the principles of elastic and plastic impact, along with the associated coefficient of restitution (k-factor), are utilized to characterize the elastic and plastic (i.e., permanent) components of the deformation incurred during an impact. Figure 1-1 shows, as an example, the dependence of the coefficient of restitution on the impact velocity (against a rigid wall).

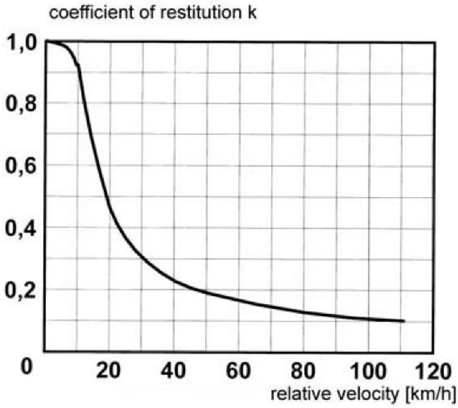

Figure 1-1: Schematic representation of the relation between the coefficient of restitution and the relative velocity for a frontal impact on a rigid barrier for a passenger car

Today, most traffic accident reconstructions are carried out with the aid of computer programs such as CARAT, PC-CRASH, or EDCRASH. These programs are thoroughly validated, and their application procedures are well-defined. Rigid-body dynamics are implemented within them. In principle, when using such programs, two methods can be distinguished: "forward" and "backward" calculation. In the forward calculation method, the kinematics before the collision are assumed. That is, 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 integrating the rigid-body equations, taking into account tire and collision forces. Finally, the positions and traces recorded at the actual accident scene are compared with the calculation results. In an iterative process, the input parameters are adjusted, and the procedure is repeated until a satisfactory match is achieved between the calculated results and the available accident data. The backward calculation method begins by examining the final positions of the collision partners. Next, the motions after the impact are made consistent with the traces found (e.g., skid marks), yielding the positions at impact, again using rigid-body approximations. Eventually, the initial parameters that led to the determined course are obtained. Graphics are finally employed to provide a visual representation of the reconstructed accident.

Due to the large mass ratio of car occupant to vehicle, the influence of car occupants, as well as that of other objects not rigidly attached to the vehicle, on the motion of the colliding vehicle can be approximated. However, this is not the case in motorcycle or bicycle accidents. The above-mentioned programs can only be applied under restricted conditions in such accidents, and the results must be interpreted with caution.

Collision phases, not just in traffic accidents, typically involve deformation processes that necessitate the application of approximations based on continuum mechanics. Primarily due to liability concerns, car manufacturers are hesitant to make the FE models they use to evaluate the crashworthiness of their vehicles publicly available. Consequently, various simplifications are made in general-purpose reconstruction programs. One approach is to assume a segmented stiffness distribution of the vehicle's front and then integrate the equations of motion of the two vehicles over the collision duration. Another method, commonly used in European reconstruction programs, is to assume that the collision duration is infinitely short (when compared to the pre- and post-crash motion of the vehicles) and calculate only the transfer of (linear and rotational) momentum from one vehicle to the other. For both of these approaches, the EES values mentioned earlier can be used as control values to ensure not only momentum conservation but also an energy balance over the collision.

Once the motion of a vehicle is reconstructed, the motion of the occupants or an impacted external victim (such as a pedestrian or two-wheeler rider) during the impact can be estimated, again by using rigid-body models. Additionally, information regarding the occupant loading can be obtained. However, further extrapolations, especially those related to injuries, demand expertise beyond classical (mechanical) accident reconstruction. The same is true for accidents that occur in the workplace, at home, or during sports. Given suitable conditions and a careful adjustment to the specific situation, traffic accident reconstruction models and computer programs can also be employed in other types of accidents. For the purpose of injury analysis, the subsequent application of a FE model of the human body may provide useful insights.

Finally, accidents are sometimes reconstructed through a one-to-one reproduction either on-site or in the laboratory, using the original installations, vehicles, sports equipment, etc. This approach is especially crucial in non-traffic accidents and during legal proceedings when substantial claims are at stake, justifying the often significant costs associated with such tests.

Experimental Models

All mechanical characteristics related to the time-dependent behavior of the human body, a body part, an organ, or tissue when subjected to dynamic mechanical loading are encompassed by the term "biomechanical response". Examples of the human body's biomechanical response include head-neck kinematics observed during a rugby scrummage and the force-deflection characteristics of the chest resulting from a frontal vehicle impact. In addition to these mechanical changes, the biomechanical response can also cause physiological changes such as neck pain, lung edema, or ECG abnormalities.

A comprehensive understanding of the biomechanical response is essential for the development of injury prevention and mitigation measures. Given that accident scenarios are inherently highly dynamic, relevant tests to study the human body's biomechanical response typically need to be carried out under corresponding loading conditions. However, whenever it is feasible to extrapolate to dynamic conditions, quasi-static tests are performed due to the significantly simpler equipment requirements for these tests.

The analysis of the human body's biomechanical response is not only vital for understanding injury mechanisms but also necessary for defining and verifying injury tolerance thresholds. An important factor here is biological variability; age-related changes, in particular, are significant. Thus, a large volume of experimental data is required for a reliable measurement of an injury risk function. Since biological material for testing is not easily accessible, a meticulous examination of statistics is of utmost importance. Response data can also be limited by the inability to place instrumentation at the desired location, the use of different test protocols by various research teams, and a small number of tests. Considering that many relevant studies are pioneering works in trauma-biomechanics research dating back to the 1940s, some of these drawbacks can be attributed to the lack of suitable measurement equipment and knowledge at that time. In the chapters addressing the biomechanical response of different body regions, these issues are discussed in greater detail. Additionally, section 1.5 focuses on the use of human surrogates (dummies) in impact testing, where the response data from the surrogate must be interpreted in terms of biological plausibility.

In what follows, the experimental models employed to determine the biomechanical response of the human body are briefly discussed. Five distinct models can be identified, namely human volunteers, human cadavers, animals, mechanical human surrogates, and mathematical models.

Volunteer experiments, for obvious reasons, are confined to the low-severity range only, well below any level suspected of potentially causing injury. The pain threshold is frequently regarded as the upper limit up to which mechanical loads are applied. The advantages of volunteer tests include, first and foremost, the use of the "correct" anatomy and physiological state. Additionally, the influence of muscle tone can be studied, and effects such as pre-collision bracing can be considered. However, the cohorts utilized for volunteer tests are typically not statistically representative of the at-risk population. Specifically, females, children, and the elderly are severely under-represented in the available volunteer data. Instrumentation also poses difficulties, as load cells often cannot be placed at the location of interest (such as the head's center of gravity or the first thoracic vertebra), and even achieving a rigid external fixation is challenging due to the skin. Advances in high-speed video camera technology, along with sophisticated mathematical analysis, have significantly contributed to improving such results. Ciné-radiography has sometimes been employed to monitor the skeleton's response to impact. For example, Ono and Kaneoka in 1997 used it to investigate the motion of cervical spine vertebrae. Since the number of subjects tested in this manner is particularly small, issues regarding scaling to other human groups and to other (more severe) impact severities are all the more crucial.

Human cadavers (usually referred to as post-mortem human subjects (PMHS) or post-mortem test objects (PMTO)) represent the second type of model used to determine the human biomechanical response. Despite their strong anatomical resemblance to living humans (a PMTO can, to some degree, be likened to a sleeping human), several influencing factors must be taken into account. Firstly, the age of PMHS is often advanced. As a result, age-related degeneration is commonly present in the cadaver cohort available for a test series. For example, in cases of osteoporosis, fractures are observed more frequently. Secondly, the lack of pressure in the lungs and blood vessels, the absence of muscle tone, and differences resulting from the preparation techniques employed (i.e., embalmed vs. non-embalmed cadavers) significantly affect the biomechanical response. However, fresh cadavers have been demonstrated to be good models for detecting fractures, vessel ruptures, and lacerations. Nevertheless, physiological responses (such as neck pain or ECG abnormalities) cannot be studied using these models. When investigating the response of only a single body part, such as the leg, isolated cadaver parts are utilized. In this case, the connection to the rest of the body must be appropriately simulated in the test setup.

Animal models have limited relevance in human trauma-biomechanics. Nonetheless, anaesthetized animals provide the sole means to study physiological reactions to severe mechanical loading. Animal experiments also enable a comparison between living and dead tissue, thereby offering crucial insights for the correct interpretation of cadaver tests. However, because of anatomical and physiological differences, the ability to scale the results obtained, especially regarding injury thresholds, is restricted.

Other models employed in trauma-biomechanics are mechanical human surrogates, namely anthropomorphic test devices (ATDs), and mathematical (computational) models. Due to their significance (for example, all vehicle occupant safety regulations are framed based on measurements taken from ATDs), these models will be discussed in separate sections hereinafter.

The objective of laboratory impact testing is to realistically simulate accident scenarios and determine the mechanical loading a human victim might endure in such an accident. Most laboratory test set-ups are designed for vehicle crash testing, largely due to the extensive regulatory framework covering vehicle safety. In the automotive industry, crash facilities are extensively utilized to assess restraint systems and develop new passive safety measures to reduce the number and severity of injuries in automotive accidents. However, laboratory tests are also employed to certify football helmets, ski bindings, and the like.

Real-world accident scenarios are diverse. Consequently, only certain impact conditions deemed relevant are simulated in crash testing.