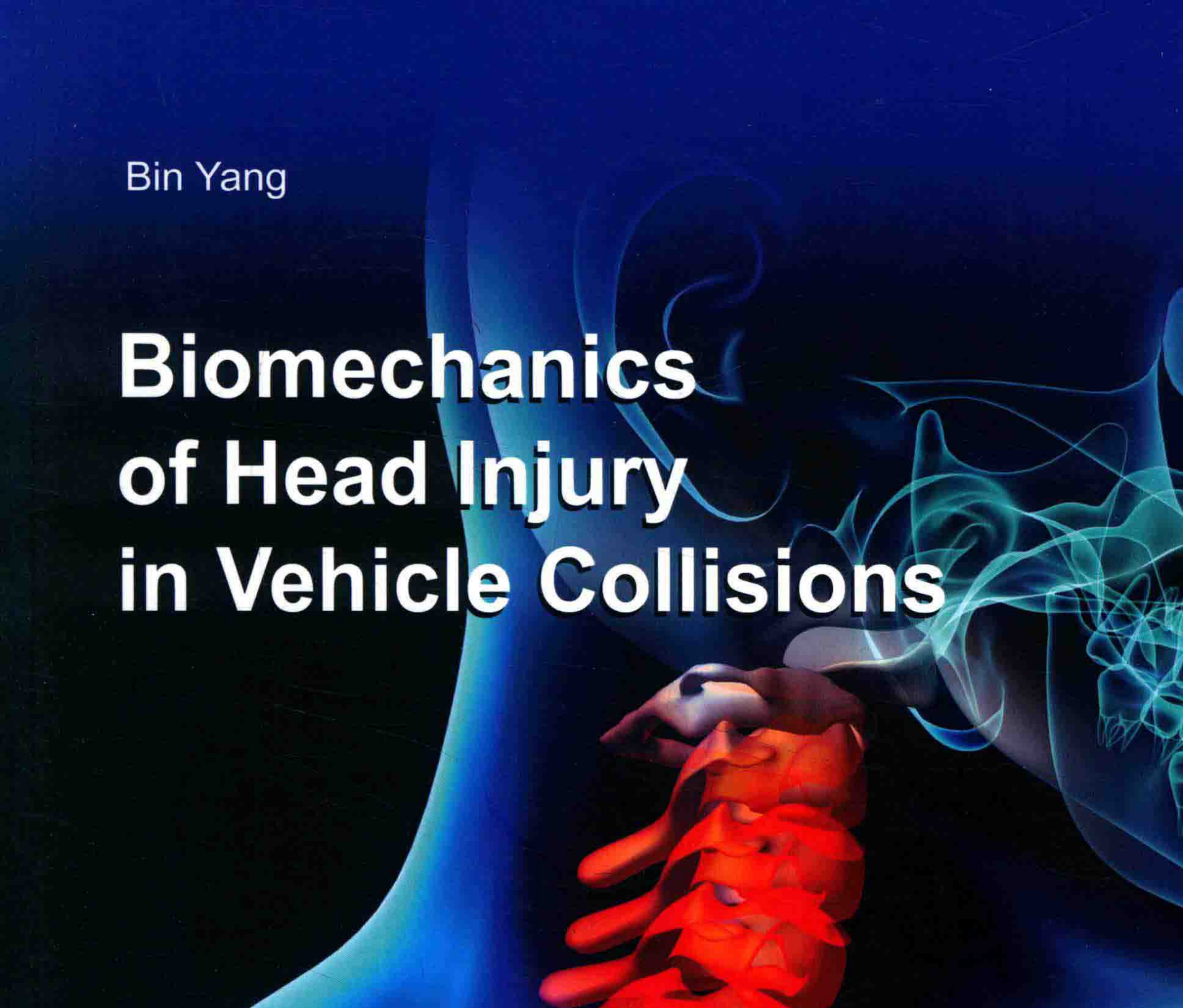
Bin Yang

Biomechanics of Head Injury in Vehicle Collisions



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Biomechanics of Head Injury in Vehicle Collisions

（汽车碰撞头部损伤生物力学）

Bin Yang（羊　玢）

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Preface

Every year, more than 15 000 000 people are injured and 1 250 000 people are killed for life on the world's roads. Traumatic brain injury (TBI) is a great burden for the society worldwide, e.g. in the US, there are about 1.4 million people who sustained TBI each year and estimated one fifth of the hospitalized persons cannot return to work. In the UK, TBI accounts for 15% to 20% of deaths between the age of 5 and 35. The same indication was shown in studies made in France and China. To develop a better understanding of crash-induced injuries required in designing injury countermeasure, several experimental and numerical approaches have been used. Experimental approaches have been tried to replicate crash-induced injuries in lab conditions using Post Mortem Human Subjects (PMHS) impact tests. However, understanding the injury mechanisms and development of accurate injury criteria using this test data is challenging due to inherent variation in terms of PMHS anthropometry and material properties. With recent rapid increases in computational technology, the human finite element (FE) models of the head and neck are currently the most sophisticated numerical models, which can provide general kinematics of the brain and calculate the detailed stress/strain distributions which can be correlated with the risk of injuries. The field of trauma biomechanics, or injury biomechanics, uses the principles of mechanics to study the response and tolerance level of biological tissues under extreme loading conditions. Through an understanding of mechanical factors that influence the function and structure of human tissues, countermeasures can be developed to alleviate or even eliminate such injuries.

This book, Biomechanics of Head Injury in Vehicle Collisions, surveys a wide variety of topics in head-neck injury biomechanics including anatomy and injury mechanism during the traffic accidents. The objective of our study is to develop a more biofidelic FE human head and neck model using the geometry directly reconstructed from the medical scan data of a 50th percentile male volunteer. Such an FE head and neck model should mimic irregular anatomical features of the head and neck, is validated against a full spectrum of head impact data, and can be used in a wide variety of impact scenarios to predict facial, skull, and intracranial responses. It is therefore desirable to only include those anatomical structures that will enhance the accuracy of such analyses. It is the first collection I am aware of that lists regional injury reference values. Although the book is meant to be an introduction for medical doctors, scholars and engineers who are beginners in the field of injury biomechanics involved traffic safety, sufficient references are provided for those who wish to conduct further research, and even established researchers will find it useful as a reference for finding the biomechanical background of each proposed injury mechanism. As more people become aware of and understand this subject, it will someday lead to better mitigation and prevention of automotive related injuries. I like this book very much and believe that you will find the same.

Bin Yang

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Chapter 1 Methods in Injury Biomechanics

Work in injury 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. A number of experiments in connection with seat belts were nevertheless made in earlier years with pigs (Verriest et al., 1981) since their thorax resembles the human thorax mechanically to some extent; likewise, monkeys were subjected to impact in order to study head motion and neck dynamics. Anaesthetised animals provide moreover a model to investigate physiological reactions at high mechanical exposure levels. 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:

(1) Statistics, field studies, databases.

(2) Injury criteria, injury scales and injury risk.

(3) Basic mechanical concepts and accident reconstruction.

(4) Experimental models.

(5) Impact tests performed in the laboratory.

(6) Numerical simulation.

1.1 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 epidemiologic 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 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 circumstance 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 analyze the influence 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 specialized 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 yes, not detailed or biased.

Cases included in large-scale data collections are moreover often not collected and analyzed 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. Similar, although sometimes less systematic information is available from most other countries worldwide(Gennarelli et al., 2005).

Work place safety issues are comprehensively addressed in the statistics of the US Occupational Safety and Health Administration (OSHA). In most industrialized countries, furthermore, workplace accidents are covered by government controlled insurance organizations. 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 analyze trends are largely missing. General awareness with respect to sports injuries has only recently increased (Gennarelli, 2001). 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 specialized 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. Because the data have been gathered systematically and following a uniform protocol for a long time, it is for instance possible to analyze factors related to changes in vehicle design. Another 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. 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. Yet other in-depth investigations are made by vehicle manufacturers where specialized 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 (Standardization of Accident and Injury Registration Systems, 1997 to 1999), that are aimed at harmonizing accident data collections in order to allow more comprehensive and comparable studies, are under development. 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.

1.2 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 criteria 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 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 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%.

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 standard test procedures, mostly for use in automotive laboratories, which have been defined and established internationally.

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. The AIS is a standardized system for categorizing the type and severity of injuries arising from vehicular crashes (Table 1-1) and is oriented towards the survivability of an 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".

Table 1-1 The AIS classification

AIS code	Injury
0	Non-injured
1	Minor
2	Moderate
3	Serious
4	Severe
5	Critical
6	Untreatable

As a result, the AIS severity score is a single, time independent value for each injury and everybody 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 blindness or life-threatening complications due to nosocomial infections occurring in a hospital are not coded as severe injury, 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. The ISS distinguishes six different body regions: head/neck, face, chest, abdomen, extremities including pelvis, external (i.e. burns, lacerations, abrasions, and 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 categories soft tissue neck injuries. 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) (Zeiler 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.