Accident Analysis and Prevention 80 (2015) 7–17

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

The tolerance of the human body to automobile collision impact – a systematic review of injury biomechanics research, 1990–2009

Jason L. Forman [a,*], Francisco J. Lopez-Valdes [b], Sonia Duprey [c], Dipan Bose [d], Eduardo del Pozo de Dios [e], Damien Subit [f], Tim Gillispie [a], Jeff R. Crandall [a], Maria Segui-Gomez [g]

[a] University of Virginia Center for Applied Biomechanics, 4040 Lewis and Clark Dr., Charlottesville, VA 22911, USA
[b] University of Zaragoza, Zaragoza, Spain
[c] Laboratoire de Biomécanique et Mécanique des Chocs, IFSTTAR, Lyon, France
[d] Global Road Safety Facility, World Bank Group, Washington D.C., USA
[e] Applus IDIADA Group, Spain
[f] LBM – Institut de Biomécanique Humaine Georges Charpak, Arts et Métiers ParisTech, Paris, France
[g] Director General for Traffic, Ministry of Interior, Spain

ARTICLE INFO

Article history:
Received 9 July 2014
Received in revised form 12 February 2015
Accepted 4 March 2015
Available online xxx

Keywords:
Automobiles
Biomechanics
Injuries
Prevention
Surveillance
Trauma

ABSTRACT

Road traffic injuries account for 1.3 million deaths per year world-wide. Mitigating both fatalities and injuries requires a detailed understanding of the tolerance of the human body to external load. To identify research priorities, it is necessary to periodically compare trends in injury tolerance research to the characteristics of injuries occurring in the field. This study sought to perform a systematic review on the last twenty years of experimental injury tolerance research, and to evaluate those results relative to available epidemiologic data. Four hundred and eight experimental injury tolerance studies from 1990–2009 were identified from a reference index of over 68,000 papers. Examined variables included the body regions, ages, and genders studied; and the experimental models used. Most (20%) of the publications studied injury to the spine. There has also been a substantial volume of biomechanical research focused on upper and lower extremity injury, thoracic injury, and injury to the elderly – although these injury types still occur with regularity in the field. In contrast, information on pediatric injury and physiological injury (especially in the central nervous system) remains lacking. Given their frequency of injury in the field, future efforts should also include improving our understanding of tolerances and protection of vulnerable road users (e.g., motorcyclists, pedestrians).

1. Introduction

Automobile collisions are the most common source of severe unintentional injury worldwide (Chandran et al., 2010). Every year, more than 1.3 million people die and 50 million people are severely injured in road traffic crashes (Peden et al., 2004). It is projected that by 2020, fatal and nonfatal road traffic injuries will increase by approximately 65 percent (Kopits and Cropper, 2003), and will be the sixth leading cause of death (Murray and Lopez, 1997) and the third leading cause of disability adjusted life years (DALYs) lost (Peden et al., 2004) world-wide. This projected increase in burden relates to an expansion of motorized transport, combined with shifts in road-user demographics to populations more susceptible to injury (e.g., pedestrians, the elderly). In response to this growing pandemic, the United Nations has declared 2011–2020 as the Decade for Action, with a goal of halving the number of world road traffic fatalities.

A critical component of the injury prevention effort is the understanding of injury tolerances. The human body can bear a certain amount of mechanical input – force, acceleration, compression, etc., – before a tissue failure or dysfunction occurs. This transition to a load that results in mechanical or functional tissue failure is known as the injury tolerance. In the automotive field, injury tolerance information informs engineers and

Abbreviations: DALYs, disability adjusted life years; GBD, global burden of disease; WAD, Whiplash Associated Disorder; PTW, powered two-wheeler.

* Corresponding author. Tel.: +1 434 296 7288; fax: +1 434 296 3453.
E-mail addresses: jlf3m@virginia.edu (J.L. Forman), fjlv@unizar.es (F.J. Lopez-Valdes), sonia.duprey@univ-lyon1.fr (S. Duprey), dipan.bose@gmail.com (D. Bose), EduardoDelPozo.DeDios@idiada.com (E. del Pozo de Dios), Damien.SUBIT@ensam.eu (D. Subit), tlg5a@virginia.edu (T. Gillispie), jrc2h@virginia.edu (J.R. Crandall), mariaseguigomez@gmail.com (M. Segui-Gomez).

http://dx.doi.org/10.1016/j.aap.2015.03.004
0001-4575/

designers on what body structures can be safely loaded, allows them to predict injury risk, dictates the design of vehicle safety features, and serves as the basis for regulations and assessment procedures for vehicle safety. Target scenarios and risk factors for intervention are often identified through epidemiology. When engineering solutions are indicated – for example, through improved vehicle restraints – injury biomechanics researchers work with policy makers, automobile manufacturers, and other stakeholders to identify strategies for intervention. Knowledge on injury tolerances provides insight into the causes of injuries in the field and provides performance targets for the evaluation of possible interventions prior to field implementation. Once implemented, the cycle renews with continuing epidemiology to observe the effectiveness of the interventions in reducing deaths or injuries, to identify opportunities for the further refinement of those intervention strategies, and to identify new research priorities. Injury tolerance information also allows the identification of differential intervention strategies based on specific road user characteristics, especially for at-risk populations (for example, the elderly (Kent et al., 2005a)).

It is pertinent to periodically review trends in injury tolerance research compared to injury frequencies, injury types, affected populations, and causation scenarios observed in the field. The last such review was performed by Viano et al. (1989) as a part of a treatise on the fundamentals of injury biomechanics. Several deficiencies in injury tolerance information were noted, including knowledge on functional injury to the central nervous system, structural spinal injury, functional injury to the heart and great vessels, lung injury, injury to the hollow abdominal organs, injury to the joints and long-bones of the extremities (other than the femur), and injury to the face and sensory organs. The only body structures for which "somewhat understood and verified" or "well known" injury tolerance information were available were the skull, the ribcage, the solid organs of the abdomen, and the femur. Children and adult females were identified as populations for which little information was available. There was also little mention of differential injury tolerances based on advanced age, body-type, or existing pathologies.

The goal of this study is to perform a systematic review of injury tolerance investigations in the 20 years following the review of Viano et al. (1989), and to compare trends therein to the road traffic injuries occurring in the field. To define the scope, this study focused on papers describing new injury tolerance information applicable to the motor-vehicle collision environment, derived from experimental studies with biological (not artificial or computational) models. A descriptive analysis was performed to study trends in the body regions, injury types, ages and genders studied, and the types of models used. Those results were then compared to the previous state of knowledge and to motor-vehicle injury trends observed in the epdidemiologic literature.

2. Method

2.1. Literature database

Papers were selected from a custom index of reference information (housed and maintained by the University of Virginia Center for Applied Biomechanics) for approximately 68,000 scholarly papers, reports, books, book chapters, and theses relating to injury biomechanics, biomedical engineering, automobile engineering, and automobile safety (referred to here as the Index). The Index spans from the year 1840 to the present, and is populated by monthly updates of 140 journals and conference proceedings for keywords related to injury biomechanics and automobile safety (e.g., 'traffic', 'biomechanics', 'safety', etc.). Index entries are stored in a searchable Access (Professional Edition 2003, Microsoft) database.

2.2. Paper selection criteria

This study targeted publications that included new experimental data describing injury tolerances with biological models. The inclusion criteria were as follows:

- Published between 1990 and 2009 (inclusive).
- Published in English.
- Included data recorded from experiments with biological models (e.g., human volunteers, cadavers, animals, or cell cultures).
- Included information on injuries or tissue failures that occurred during the experiments. This included either mechanical tissue failure (for example, breaking of an isolated bone segment or bone sample), or physiological injury (for example, mild traumatic brain injury in an animal model). Non-injury, living human, volunteer studies were included when they could be used for determining a lower-bound for the estimation of a tolerance for physiological injury. Non-injurious human cadaver studies were included only if they specifically sought to study injury tolerances, but happened to not cause injury in their experiments. Observational studies (studies observing real-life human exposures and resulting injuries in a non-laboratory setting) were included only if the observational subjects were instrumented or recorded to the extent that the mechanical inputs into the body could be reasonably deduced.
- Related to acute injury of mechanical origin in otherwise healthy tissue. This was not necessarily limited to papers specifically targeting the automotive environment because injury tolerance information from other fields (e.g., sports) can potentially be applied to the automotive environment. Papers relating to repetitive stress, injury in pathological tissue, injury in prosthetic interfaces, penetrating injury (e.g., gunshots and stabbing), blast injury, burns, and drowning were excluded.
- Included data not previously published. Review papers and papers describing amalgamations of previously-published data were excluded.

2.3. Query method

To facilitate categorization of papers by body region, the Index was queried with each of the body-region-specific search terms listed in Table 1. Queries were performed as an all-field search, returning entries based on search-term matches in the title, keywords, or abstract. Six reviewers were assigned one or two body regions each for which to perform queries and initial reviews. Once queried for each search term, the returned entries were reviewed to identify those possibly meeting the selection criteria. The resulting candidate papers were then obtained and reviewed in full to determine inclusion or exclusion in a provisional database.

2.4. Variables

Information to be extracted during the review process was operationalized in a dictionary that was used to develop a web-based extraction form used throughout the study. The reviewers were trained for consistency. The study leader reviewed all entries prior to closing the review process to check for repeat entries, missing values, and for consistency with the paper selection criteria.