8 Injury biomechanics

Introduction

Biomechanics is the application of principles of mechanics to biological systems, including the response of human tissue and bones to mechanical loads. Injury biomechanics extends this to consider loading to failure, that is to understand injury mechanisms. During traffic crashes, the human body is subjected to large mechanical forces. A deeper understanding of these forces is essential for developing restraint systems in vehicles and wearable protective devices for users.

Learning outcomes

After studying this module, the students should be able to:

- remember the basics of the human structure and commonly injured body parts
- converse in terms of mechanical properties of the human body
- explain injury scales and concepts around injury risks for various road user groups
- explain collision patterns, injury mechanisms and thresholds, and energy absorption strategies
- explain the role of restraints and protective equipment

Key messages to learners

- Biomechanics applies mechanical principles to biological systems. *Impact biomechanics* specifically focuses on the body's response to high-rate loading events. It analyses key parameters like forces, accelerations, pressures, internal stresses, and strains. Determining human tolerance limits to these mechanical inputs is essential for identifying specific injury mechanisms and developing effective protective strategies. Impact biomechanics provides the knowledge base to design vehicles and safety systems that manage crash energy and limit occupant loading to acceptable tolerance levels.

- There are several metrics to systematically classify injuries. Most common is the Abbreviated Injury Scale (AIS). AIS codes an injury anatomically by body region, type, and severity. Severity is graded on a scale from 1 (minor) to 6 (currently untreatable/maximal), based primarily on the *threat to life* associated with the injury. For individuals with multiple injuries, the Maximum AIS (MAIS) identifies the single most life-threatening injury, while scores like the Injury Severity Score (ISS) provide an overall trauma score reflecting combined effects.

- Injury risk curves are used to describe the probability to sustain a specific injury as a function of the physical loading. On a macro-level (e.g. in decisions on an appropriate speed limit for a certain road type) relations between collision speed and probability of a severe injury/fatality are frequently used. On a micro-level (e.g. in design and optimization of passive safety features like seatbelts, airbags, and head restrainers) much more injury-specific criteria used, for example Neck Injury Criterion (acceleration of the head in relation to the first thoracic vertebra, a predictor of whiplash neck injuries in rear-end collisions).

- Mitigation strategies aim to reduce injury risk by managing impact energy and controlling body kinematics. For car occupants, this involves: (*i*) *external* energy management via deformable vehicle structures (e.g. crumple zones) absorbing crash energy, and (*ii*) *internal* control of the occupant's motion and force distribution using restraint systems like seatbelts (often with pre-tensioners and load limiters) and airbags.

- For more exposed road users like powered two-wheeler (PTW) riders, helmets are crucial protective devices. They mitigate head injury by absorbing impact energy, offering a smooth external surface to reduce 'gripping' (positive engagement), distributing loads over a larger area, and preventing direct skull contact. Protection other vulnerable road users (VRUs), such as pedestrians and cyclists, in collisions with motor vehicles presents distinct challenges often addressed through specific vehicle design considerations (e.g. front-end geometry and stiffness, and external airbags).

- Understanding impact biomechanics and developing countermeasures relies on a multi-faceted approach integrating several methodologies:

  - **Real-world data analysis.** In-depth crash investigation databases provide essential context on real-world accident scenarios, injury patterns, and the effectiveness of safety systems.

  - **Crash reconstruction**. Analysing physical evidence and vehicle data allows for reconstruction of crash dynamics, determining parameters like velocity change (ΔV) and impact forces.

  - **Computational modelling.** Multibody Dynamics (MBD) models simulate overall kinematics of a crash. More sophisticated computer models, particularly Finite Element (FE) Human Body Models (HBMs), enable detailed analysis of internal tissue-level responses (stresses, strains) under impact.

  - **Experimental testing.** Physical tests using Post-Mortem Human Subjects (PMHS), human volunteers (for low-severity, non-injurious tests), and Anthropomorphic Test Devices (ATDs, crash test dummies) generate fundamental biomechanical response data, validate computational models, and evaluate the performance of protective equipment. These methods are complementary and iterative. Experimental testing is the primary method to develop injury risk curves.

Learning activities

Exercise 1

Apply basic biomechanics principles to predict injury patterns for given scenarios:

- identify primary impact phases (e.g. car impact, ground impact)

- list likely injured body regions and explain why (based on kinematics and load)

- suggest one or more biomechanical parameters that could be measured (e.g. head acceleration, chest compression)

- propose one protective measure (helmet, vehicle front-end design, speed reduction).

Discuss your results.

Scenario A. Car-to-pedestrian impact at 40 km/h, frontal geometry typical of a sedan.

Scenario B. A powered two-wheeler rider falls sideways at 50 km/h without any protective gear.

Possible answer:

Scenario	Impact phases	Injured body regions	Measured parameters	Suggested protective measures
A	(*i*) pedestrian is hit by the car front (*ii*) pedestrian moves upwards on the bonnet, and the head hits the front windshield pillar (*iii*) pedestrian falls down and hit the ground with the upper body, head, and pelvic region (*iv*) pedestrian could be run over by the car	knee/thigh, head, shoulders, pelvic region, thorax	Knee ligament extension Bone strain Head acceleration Head Injury Criteria	less rigid and lower material of the front bumper 'smoother' shape of the car frontal part allowing to glide upwards external airbag lifting the bonnet and covering the rigid windshield pillars automatic pedestrian detection and braking to reduce the collision speed braking to a full stop after first impact
B	(*i*) rider hits ground (*ii*) bike falls on the rider (*iii*) rider separates from the bike and slides/hit an object on the side of the road	extremities—foot and ankle, hand and arm head injuries pelvic (during the last phase) thorax (during the last phase)	Bone strain Frangible bones (bones breakage) Head Injury Criteria	helmet protecting clothing with low friction/abrasion resistance (padded or armour) enforcement to have only one passenger (better balance and control) gloves boots

Assessment quiz

The assessment quiz can be used as a part of the examination, or as another form of learning activities (e.g. students take the quiz in class individually and then discuss the results with the teacher).

Question 1

Which is the primary focus of injury biomechanics?

    a.   Chronic musculoskeletal disorders (incorrect)

    b.   Application of mechanical principles to understand injury mechanisms under high-rate loading (correct)

    c.   Structural integrity of vehicle components (incorrect)

    d.   Classification of injuries for insurance purposes (incorrect)

Question 2

What does the Abbreviated Injury Scale (AIS) primarily indicate?

    a.   The cost of treatment for an injury (incorrect)

    b.   The probability of long-term disability due to an injury (incorrect)

    c.   The threat to life associated with an injury (correct)

    d.   The energy absorbed by the body during the impact (incorrect)

Question 3

Which of the following is false about key function of a motorcycle helmet in impact biomechanics?

    a.   Eliminating rotational acceleration (incorrect)

    b.   Reducing head acceleration and distributing impact forces (incorrect)

    c.   Eliminating all head injuries in crashes (correct)

    d.   Increasing stiffness to prevent skull deformation (incorrect)

Question 4

Which injury criterion is widely used to assess head injury risk in crash testing?

    a.   Head Injury Indicator (HII) (incorrect)

    b.   Head Injury Criterion (HIC) (correct)

    c.   Neck Injury Criterion (NIC) (incorrect)

    d.   Neck Injury Index (NII) (incorrect)

Question 5

Which modelling approach is best suited for analysing local tissue-level stresses in the brain during impact?

    a.   Multi-body dynamics (MBD) (incorrect)

    e.   Finite Element (FE) modelling (correct)

    b.   Anthropomorphic Test Device (ATD) testing (incorrect)

    c.   Epidemiological analysis (incorrect)

Recommended reading for students

- Schmitt, K.-U., Cronin, D. S., III, B. M., Callaghan, J. P., & Muser, M. H. (2025). *Trauma biomechanics: an introduction to injury biomechanics* (6th ed.). Springer. https://doi.org/10.1007/978-3-032-00357-7

Recommended (additional) reading for teacher

- Carroll, J., Gidion, F., Rizzi, M., & Lubbe, N. (2022). *Do motorcyclist injuries depend on motorcycle and crash types? An analysis based on the German in-depth accident study*. International Motorcycle Conference (IFZ), Cologne, Germany. https://www.ifz.de/wordpress/wp-content/uploads/2022/10/Do-motorcyclist-injuries-depend-on-motorcycle-and-crash-types-presentation-IFZ-3-October-2022.pdf

- Ding, C., Rizzi, M., Strandroth, J., Sander, U., & Lubbe, N. (2019). Motorcyclist injury risk as a function of real-life crash speed and other contributing factors. *Accident Analysis & Prevention*, 123, 374–386. https://doi.org/10.1016/j.aap.2018.12.010

- Fredriksson, R., Rosén, E., & Kullgren, A. (2010). Priorities of pedestrian protection—A real-life study of severe injuries and car sources. *Accident Analysis & Prevention*, 42(6), 1672–1681. https://doi.org/10.1016/j.aap.2010.04.006

- Nordin, M., & Frankel, V. H. (2021). Basic biomechanics of the musculoskeletal system (5th ed.). Wolters Kluwer.

- Puthan, P., Lubbe, N., Shaikh, J., Sui, B., & Davidsson, J. (2021). Defining crash configurations for Powered Two-Wheelers: Comparing ISO 13232 to recent in-depth crash data from Germany, India and China. *Accident Analysis & Prevention*, 151, 105957. https://doi.org/10.1016/j.aap.2020.105957

- Yoganandan, N., Nahum, A. M., & Melvin, J. W. (Eds.). (2015). Accidental injury: biomechanics and *prevention* (3rd ed.). Springer. https://doi.org/10.1007/978-1-4939-1732-7.

Prepared by expert

In case you have specific questions, need a discussion partner, or just want feedback on your lecture materials, you may reach out the author(s) of this module. Please, put 'AfroSAFE curriculum' in the email subject.

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