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Human Body Models for Crash Safety Analysis of Reclining Posture Occupants: Applicability and Adaptation

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ABSTRACT

With the advancement of aviation, the low-altitude economy, and autonomous driving technologies, occupant postures are progressively evolving from traditional seated positions to reclining configurations. However, existing human body models and evaluation methods, developed based on seated postures, are not directly applicable to the analysis and assessment of occupant injuries in reclining postures. This paper focuses on the applicability and adaptability of human body models for crash safety analysis of occupants in reclining postures. It reviews the modeling characteristics, advantages, and limitations of common human body models. The suitability of these models for reclining postures is analyzed in terms of geometric configuration, joint range of motion, and biomechanical response. Furthermore, the study explores model types suitable for reclining postures, examines the fundamental reasons why existing models are difficult to apply directly to crash risk analysis of reclining occupants, and proposes targeted model adjustment strategies to more realistically simulate body configuration and dynamic responses in reclining postures. The results provide methodological guidance for enhancing the fidelity and reliability of crash simulations involving reclining postures, contributing to the development of more inclusive occupant protection systems and promoting safety design for multi-posture intelligent cabin environments.

Keywords: Human body models, Reclining posture, Occupant safety, Crash biomechanics, Model adaptation

INTRODUCTION

With the increasing emphasis on comfort and functionality in modern cabin environments, occupant postures are gradually expanding from the traditional upright seated position to reclining postures. In the field of civil aviation, the demand for long-haul direct flights continues to grow (Wang, 2021); however, passengers often experience physical fatigue and muscle soreness during extended flights (Ma, 2024). To resolve the conflict between passenger comfort and airline economic interests, aircraft sleeper berth designs predominantly featuring reclining postures have regained favor within the aviation industry (Kuo, 2022). Within the scope of the low-altitude economy, electric Vertical Take-Off and Landing (eVTOL) aircraft

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hold significant application potential for special missions such as medical rescue and emergency transport (Li, 2024). Such mission scenarios typically require eVTOLs to accommodate occupants in reclining postures, further expanding the application boundaries of reclining postures in aviation environments. In the field of autonomous vehicles, the widespread adoption of highly automated driving functions is also poised to fundamentally transform future occupant seating positions, with the traditional upright seated posture expected to be replaced by more relaxed reclining postures (Schaefer, 2021). Furthermore, reclining postures hold substantial practical significance in typical scenarios such as railway sleeper berths (Yang, 2025).

However, compared to the traditional safety systems for upright postures, which have been validated over long periods, this fundamental shift in occupant posture substantially alters occupant kinematic responses, load transmission paths, and injury mechanisms during collisions or emergency conditions. Existing human body models and evaluation methods, developed based on standard seated postures, may not be directly applicable to crash safety research for reclining posture occupants, thereby posing new challenges for occupant safety assessment.

Due to the high risks and ethical constraints associated with human subject testing, as well as the scarcity of real-world accident data, human body models (including digital dummy models and biomechanical human models) have become indispensable research tools. These models can accurately replicate occupant dynamic behavior during collisions within virtual environments and assess injury risks under various conditions, providing essential data for the optimization of restraint systems and cabin designs.

This paper focuses on the applicability and adaptation of human body models for crash safety analysis of reclining posture occupants. It reviews modeling methods suitable for ergonomic and crash safety analysis in reclining postures, with particular attention to multi-body and finite element models, such as THUMS and GHBMC. These models provide high-fidelity mechanical representations of humans across ages and body types, simulating dynamic responses and injury risks of the head, neck, thorax, abdomen, and lower extremities under complex collision scenarios. However, traditional physical dummies and their digital counterparts were developed based on standard seated postures in terms of geometric configuration, joint range of motion, and biomechanical response, limiting their direct application to reclining postures.

Building on this overview, this paper systematically examines the applicability, advantages, and limitations of existing human body models in reclining scenarios. It explores model types more suitable for reclining postures and elaborates on strategies for adapting key parameters to more realistically simulate body configuration and mechanical responses in reclining postures. By consolidating these modeling approaches, this study aims to provide methodological guidance and technical insights to enhance the fidelity and reliability of reclining posture simulations, thereby supporting future occupant safety analysis and cabin design.

The findings highlight essential considerations for extending human body model applications beyond standard seated conditions and provide methodological and theoretical guidance to enhance the fidelity and robustness of crash safety and ergonomic simulations in reclining postures. This work contributes to the development of more inclusive, posture-adaptive occupant protection frameworks and the design of safer, multi-posture cabin environments.

MAINSTREAM HUMAN BODY MODELS

Overview and Application Background

With the deep application of simulation technology in crash safety, Human Body Models (HBMs) have become core tools for evaluating occupant crash responses and injury risks. Commonly used models in crash safety research include digital standardized dummy models (DMs) and human models (HMs) developed based on biomechanical experimental data. DMs, characterized by standardization, repeatability, and sensor integration, enable systematic acquisition of mechanical responses of various occupant body regions during collisions. HM data are primarily derived from Post-Mortem Human Surrogate (PMHS) tests or volunteer studies, focusing on injury mechanism analysis and determination of human tolerance limits (Wang, 2021).

Currently, a wide variety of digital human body models exist. Based on differences in modeling methods, levels of detail, and application scenarios, they can be categorized into three main types: kinematic models, multi-body dynamics models, and finite element models. These models exhibit significant differences in fidelity, computational efficiency, and applicability. For instance, compared with rigid multi-body models, finite element models can simulate geometry and material properties of various tissues and possess greater degrees of freedom, albeit at higher computational cost. Therefore, suitability of a human body model must be carefully considered for specific research questions.

Kinematic Human Body Models

Kinematic models, characterized by relatively low modeling complexity, are commonly employed for ergonomic assessment. These models consider only kinematic variables and evaluate reach envelopes, field of view, and comfort by introducing joint angle limits. Typical representatives include the RAMSIS and JACK models. By establishing anthropometric databases, these models enable ergonomic analysis tailored to specific ages, genders, and populations. RAMSIS can also simulate human postures and movements based on pre-recorded posture data and assess the level of discomfort associated with these postures. Models of this type are more frequently used to evaluate human-product interaction during the early design phase (Fahse, 2023).

Multi-Body Dynamics Human Body Models

Multi-body dynamics human body models are numerical representations of the human body constructed based on the theory of multi-body system dynamics. This class of models abstracts the human skeletal system into rigid body segments connected by kinematic joints, each possessing simplified geometry and concentrated mass properties that reflect the overall inertial characteristics of major anatomical structures (such as the head, thorax, pelvis, and extremities). The connections between rigid body segments are mathematically described using ideal kinematic joints (e.g., spherical joints, revolute joints, universal joints) to simulate kinematic constraints of human joints. Force elements represent the effects of muscles, ligaments, and soft tissues on the skeletal system, while contact algorithms compute interaction forces between the human body and the external environment (e.g., seat, seatbelt, airbag).

Considerable variation exists among different multi-body models, ranging from simplified models driven by joint torques with contact treated as rigid constraints, to high-fidelity models actuated by hundreds of lumped-parameter muscles approximating contact forces through flexible contact bodies. Common multi-body models include the following:

OpenSim is an open-source software system that enables users to simulate the motion of various musculoskeletal models. It provides functionalities such as forward/inverse kinematics, forward/inverse dynamics, and optimal control, allowing both the analysis of complex experimental data and the synthesis of physics-based human motion predictions. It is commonly employed to estimate muscle forces and joint contact loads from experimental recordings.

AnyBody offers dynamics and kinematics functionalities similar to OpenSim, but focuses specifically on solving inverse problems—namely, estimating muscle forces and joint loads based on experimental motion capture data. Its musculoskeletal models are exceptionally detailed, incorporating hundreds of muscles and sophisticated joint representations.

IPS IMMA (Intelligently Moving Manikin) is a multi-body model focused on ergonomic assessment, frequently used to evaluate human actions in production environments and ergonomic issues related to seated reaching tasks. The IMMA model simulates human motion through a series of optimized static postures; users are only required to define grasp points and gaze targets without the need to adjust joint angles. This model can also be applied to reach envelope analysis and assemblability evaluations.

EMMA (Ergo-dynamic Moving Manikin) is a multi-body model that integrates an optimal control solver with a cost function to synthesize human motion. Movements in EMMA are driven either by Hill-type muscles or by joint actuators acting directly on the joints, generating motion by minimizing a cost function that includes terms such as the sum of squared control signals, system kinetic energy, and movement execution time.

Madymo is a simulation system combining multi-body dynamics and finite element methods, featuring full-scale, multi-directional multi-body models. These models possess numerous input parameters (including geometry, mechanical/structural properties, contact characteristics, and initial conditions) and provide kinematic outputs. Its Active Human Body Models (AHBMs) are designed to simulate muscle-induced human motion during the pre-crash phase. Two distinctive features of this model are its posture stabilization control system and the anatomically detailed active musculature of the cervical region (Tierney, 2019). The head-neck controller is capable of simulating reflex responses across different frequency bandwidths, incorporating both conduction delays and frequency-dependent gains.

Finite Element Human Body Models

Finite element human body models are high-fidelity numerical representations of the human body constructed based on continuum mechanics and finite element methods. Unlike multi-body dynamics models that simplify the human body into rigid segments and lumped-parameter elements, finite element models, through detailed mesh discretization of human geometry, can accurately reproduce the complex morphological characteristics and material nonlinearities of anatomical structures such as bones, muscles, ligaments, solid organs, and neurovascular tissues. Their core advantage lies in their high geometric and material fidelity, enabling accurate simulation of the geometric structure and damage mechanics of the musculoskeletal system, nervous system, and internal organs, as well as prediction of injury risks to bones, connective tissues, and internal organs.

THUMS was collaboratively developed by Toyota Motor Corporation and Toyota Central R&D Labs in the 1990s. It features highly accurate anatomical structural characteristics, complex material models, and exceptional biofidelity. This model not only accurately simulates injuries to various body regions during collisions but also provides stress and strain states of tissues such as the brain, internal organs, and ligaments, offering researchers enhanced criteria for injury determination. The model has been widely employed to study different types of collisions, including side impacts, thoracic injuries, abdominal injuries, brain injuries, and pelvic loading.

GHBMC was established in 2006 by North American automotive manufacturers and research institutions, aiming to maintain biofidelity and serve automotive crash simulations. These models encompass different age groups and are commonly used to simulate occupant head, abdomen, upper extremity, and lower extremity injuries occurring in real-world collision scenarios. The initial GHBMC 50th percentile male human body model was developed in 2011 based on the anthropometry of a 26-year-old male and has since been continuously expanded, now including a wide variety of human models such as males and females, children and adults, occupants and pedestrians, as well as simplified and detailed representations (Mokhtar AA , 2025).

The THUMS and GHBMC models exhibit distinct characteristics in crash safety research: THUMS can predict injuries and simulate biomechanical responses, demonstrating higher accuracy in head kinematic response and enabling assessment of vertebral fractures resulting from vehicle collisions. In contrast, GHBMC focuses on significant injury patterns in real-world crash scenarios and is frequently used for analysis of injuries to the human head, abdomen, upper extremities, and lower extremities. Its simplified versions can predict occupant kinematics in low-speed impacts.

Furthermore, active finite element models have advanced rapidly in recent years. The active THUMS model incorporates simplified 1D Hill-type muscles and an angle-based posture maintenance controller. The VIVA+ model provides a cervical spine posture controller incorporating vestibular and stretch reflexes. The GHBMC model now includes multiple stretch reflex controllers and a head-neck controller integrating both vestibular and stretch reflexes, among others.

Applicability and Characteristics of Human Body Models

These models exhibit distinct characteristics regarding applicability and features for crash safety research involving reclining occupants.

Kinematic models can rapidly assess an occupant's field of view, operational reach envelopes, and static comfort in reclining postures, providing ergonomic foundations for seatback angle design. However, due to their lack of dynamic response capability, they are challenging to apply for injury risk assessment under crash conditions. Multi-body models are suitable for system-level parametric studies requiring occupant response considerations and for pre-crash phase simulations. Compared to finite element models, multi-body models offer higher computational efficiency but cannot accurately predict tissue-level injuries. Finite element models serve as core tools for investigating injury mechanisms of reclining occupants and are applicable for crash phase analysis requiring precise prediction of tissue-level injuries.

Nevertheless, direct application of existing finite element models in reclining postures has limitations; their model geometry, joint ranges of motion, and soft tissue material properties are all calibrated based on standard seated postures, necessitating systematic postural adaptation adjustments.

CRASH INJURY MECHANISM DIFFERENCES IN RECLINING POSTURES

The transition of an occupant's posture from a standard seated to a reclining position induces systematic alterations in the mechanical response, load transfer pathways, and injury patterns during a collision. Consequently, directly applying existing human body models and evaluation methods developed based on seated postures may compromise the accuracy of injury risk assessments. Current research indicates the following significant differences in crash injuries between reclining and standard seated occupants:

Alteration of Head and Neck Injury Mechanisms. Due to the lowered initial head position in a reclining posture, both upward displacement and rotation of the head increase during a collision. Furthermore, head inertial loading in this posture may induce cervical spine injuries through the skull-cervical spine load transfer pathway and resulting whipping action (Liu, 2024).

Increased Risk of Thoracoabdominal Injury. The increased seatbelt angle in reclining postures reduces restraint effectiveness, concentrating loads on the thorax and abdomen and elevating the risk of rib fractures and internal organ injuries (Wang, 2025).

Changes in spinal loading patterns. In collisions involving a reclining posture, the cervical spine is subjected to tensile loading due to forward torso movement, and axial load on the spine increases significantly (Tusha, 2023). Concurrently, upward inertial movement of the occupant imposes a cranial-caudal impact on the spine, which may lead to vertebral compression fractures.

Increased Risk of Submarining. Reclining occupants are prone to the “submarining phenomenon” during collisions. When an occupant is in a reclining posture, the pelvis rotates posteriorly, preventing the seatbelt from effectively restraining the hips. This increases the risk of the lap belt slipping off the iliac crests and exacerbates abdominal loading (Rawska, 2020).

Changes in Lower Extremity Injury Patterns. Postural changes also lead to increased axial loading on the lower extremities, potentially resulting in high-load fractures of the lower limb bones (Cristino, 2021).

Furthermore, a study investigating the effects of reclining occupant posture and restraint variations on submarining probability indicated that if model coordination with the target occupant’s anatomical structure and postural characteristics is not performed, using different versions of 50th percentile male finite element models for future vehicle safety ratings could lead to inconsistent ratings due to variability in submarining predictions (Brynskog, 2025). This finding reveals the potential risks of directly applying existing models for injury assessment of reclining occupants.

In summary, the injury patterns of reclining occupants exhibit characteristics in multiple body regions, including the head and neck, thorax and abdomen, spine, pelvis, and lower extremities, that are distinctly different from those of standard seated occupants. These differences originate from postural changes that alter initial positions, reconfigure load transfer pathways, and modify interaction modes with the restraint system. Therefore, directly applying human body models developed based on standard seated postures, along with their associated injury thresholds, for the safety assessment of reclining occupants may lead to underestimation or misjudgment of injury risks. This necessitates that researchers either systematically adapt existing models or develop human body models specifically designed for reclining posture analysis to ensure the accuracy and reliability of simulation results.

ADAPTATION STRATEGIES FOR HUMAN BODY MODELS IN RECLINING POSTURES

To address the limitations of existing seated-posture human body models in crash analysis for reclining configurations, this chapter presents adaptive strategies along two dimensions: posture reconstruction and parameter calibration.

Posture Reconstruction via Parametric Modeling

Posture reconstruction is the foundation for simulating reclining occupants in crash scenarios. As the baseline versions of mainstream human body models are predominantly developed based on standard seated or standing postures, simply converting these models to reclining postures through rigid rotation or basic mesh transformation fails to accurately replicate posture-dependent characteristics such as soft tissue settling and deformation under gravity, changes in spinal curvature, and pelvic rotation. Therefore, developing posture reconstruction methodologies specifically tailored for reclining configurations is essential for adapting existing models.

Parametric human body modeling provides an effective technical pathway for posture reconstruction. By establishing mathematical mapping relationships between human body geometry and a limited set of semantic parameters, this approach enables efficient and reproducible control over human body shape, allowing the description of highly complex human mesh models using only a few parameters (e.g., skeletal rotations, body habitus features).

To enhance the accuracy of semantic anthropometric parameters in representing human morphology and to simplify manual preprocessing required for mapping parameters to body shape, a method was proposed for generating three-dimensional human body models based on automatic mesh binding to anthropometric parameters (Li, 2023). First, 27 key anthropometric parameters were used to constrain the target human morphology; missing parameters were estimated through partial user input, thereby circumventing complex manual preprocessing procedures. Second, the XGBoost-RFECV algorithm was utilized to automatically identify the most relevant anthropometric parameters for each mesh region, establishing a correlation model between parameters and local geometric morphology. Finally, local mapping was performed to generate a three-dimensional human body model matching the target anthropometric measurements. Through iterative refinement of the anthropomorphic model, the local deformation effects were superior to those achieved by traditional methods, while adjustment of weight coefficients rendered the overall body shape of the human model more intuitively consistent with perceptual expectations.

Parameter Calibration for Dynamic Response

Postural changes not only affect the geometric configuration of the human body but also induce systematic alterations in mass distribution, joint stiffness, and soft tissue mechanical properties. Failure to calibrate these parameters may compromise the accuracy of injury prediction outcomes. The research team led by Antoine Muller proposed a method for correcting body segment inertial parameters (BSIP) based on rigid body kinematics. This approach utilizes motion capture systems and force platforms to optimize BSIP estimates by minimizing dynamic residuals in the equations of motion (Muller, 2017).

Calibration of joint stiffness and soft tissue material parameters is equally critical and cannot be overlooked. In reclining postures, the passive restraint characteristics of periarticular soft tissues change due to alterations in joint angles, and existing joint stiffness curves calibrated based on standard seated postures may not accurately reflect these changes. Similarly, the compressive behavior and gravitational settling effects of soft tissues such as the abdomen and buttocks in reclining postures necessitate recalibration of material model parameters.

CONCLUSION

Current mainstream human body models, including kinematic, multi-body dynamics, and finite element models, serve as essential tools for evaluating occupant crash responses and injury risks, each offering distinct trade-offs in fidelity, computational efficiency, and applicability. These models face limitations when applied to reclining posture occupants, due to differences in injury mechanisms and systematic variations in load transfer pathways between reclining and standard seated postures. Consequently, the direct application of existing models may lead to misjudgment of occupant injury risks. To address these challenges, adaptive adjustment strategies for reclining posture human body models are proposed along two dimensions: posture reconstruction and parameter calibration. The study highlights essential considerations for extending human body models beyond standard seated posture, supporting the design of safer, multi-posture cabin environments.

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