

Review

Reclined Seating Postures on Passive Safety Performance in Automotive Seats: A Review

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Abstract

The increasing adoption of reclined seating postures in modern vehicle interiors challenges the assumptions underpinning current passive safety systems and occupant protection assessment frameworks. While restraint technologies and certification protocols have historically been developed for upright configurations, emerging trends in autonomous driving and comfort-oriented designs promote relaxed postures that fundamentally alter occupant kinematics, loading path, and consequently the injury mechanisms. This review critically synthesizes experimental and numerical studies addressing occupant biomechanics, restraint system performance, and injury risk in reclined seating. Evidence from crash tests using Anthropomorphic Test Devices and Post-Mortem Human Surrogates, alongside high-fidelity numerical Human Body Models, is analyzed to identify consistent trends and methodological limitations. The results highlight increased forward excursion, elevated submarining propensity, and posture-dependent abdominal and lumbar loading as critical consequences of increased seatback recline. Furthermore, this review discusses the effectiveness of adaptive restraint strategies, including active repositioning and modified airbag–belt integration. By identifying existing research gaps and regulatory limitations, this work aims to provide a roadmap for the development of future safety systems that ensure robust protection for all occupants in the era of automated mobility.

Keywords: passive safety; reclined seating posture; occupant biomechanics; Anthropomorphic test devices (ATDs); human body models (HBMs); submarining; autonomous vehicles; adaptive restraint systems



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1. Introduction

The rapid evolution of vehicle technology, driven by electrification, automation, and novel mobility concepts, is reshaping vehicle interiors and occupant usage [1,2]. In highly automated vehicles, occupants can increasingly disengage from the driving task, adopting relaxed, reclined, or non-standard postures [3–7]. While improving comfort, these configurations challenge passive safety systems traditionally optimized for conventional upright seating [8–11].

Passive safety research has historically focused on occupant protection through the synergy of structural crashworthiness and restraint systems [12]. Decades of optimization

in vehicle structures, seatbelts, airbags, and test procedures have substantially reduced fatality rates. Consequently, these technologies are now mature, albeit optimized for a limited set of well-defined crash scenarios and occupant configurations, despite the known prevalence of non-nominal postures among front-seat passengers [13].

Regulatory and consumer assessment programs have been central to this progress by promoting standardized test procedures. While ensuring repeatability and comparability, these standards constrain safety evaluations to a narrow subset of postures and behaviors [14,15]. However, emerging trends in automation, comfort-oriented design, and an increasingly diverse, aging population now challenge these long-standing assumptions [16]. Increased seatback recline significantly alters occupant kinematics and restraint interaction, potentially increasing injury risk [8,9]. Consequently, assessing safety performance solely under upright assumptions may result in a significant underestimation of real-world injury risk [17,18].

Figure 1 illustrates the conceptual framework of this review, outlining the current workflow for passive safety assessment. The framework highlights a regulatory gap (represented by the dashed red arrow) that arises when traditional upright seating assumptions are applied to reclined postures. By emphasizing how changes in seating posture challenge existing evaluation methods, this diagram demonstrates the need for methodologies that include reclined seating postures. These methodologies, focusing on testing and outcomes, are discussed throughout this work.

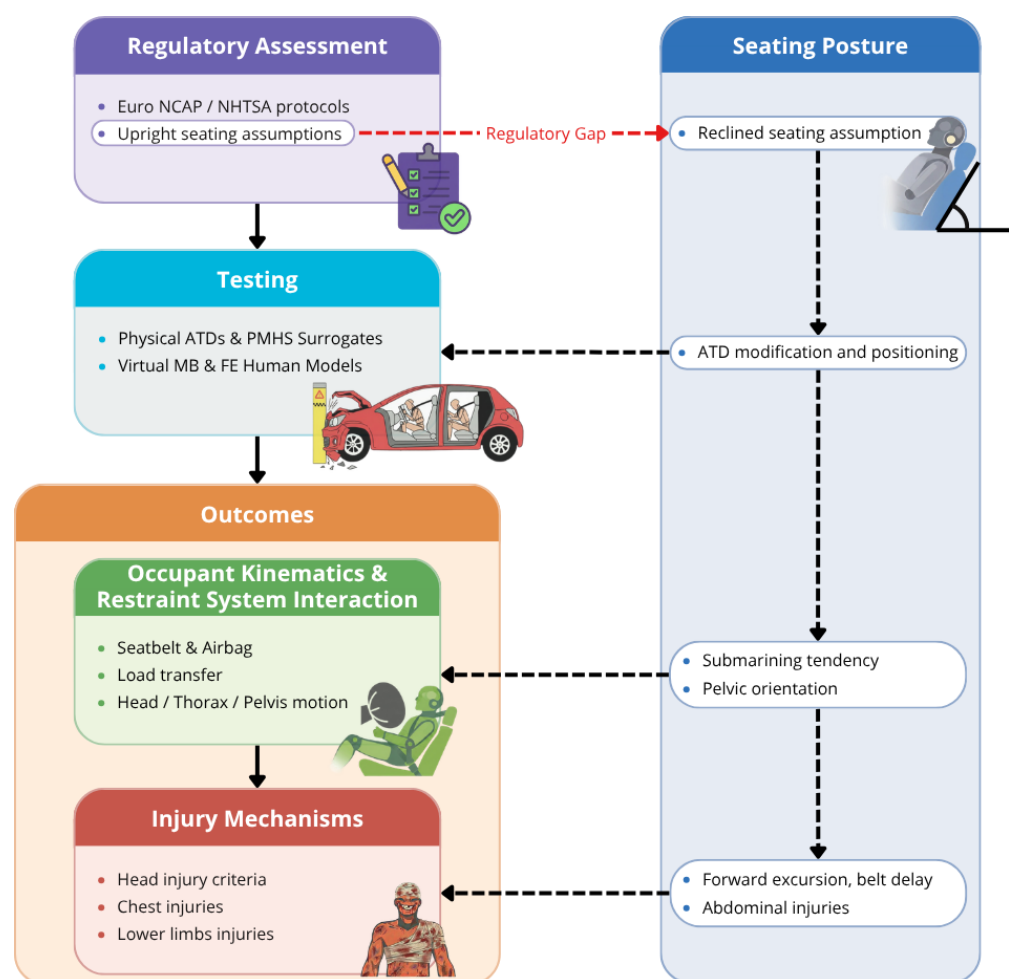


Figure 1. Conceptual framework illustrating the current passive safety assessment workflow and the identified regulatory gap (red arrow) when upright seating assumptions are extended to reclined postures. The right-hand side shows how the recline seating posture influences the assessment workflow, particularly: testing; occupant kinematics and restraint system interaction; injury mechanisms.

This review synthesizes the current state of knowledge on the safety implications of reclined seating, establishing a direct link between fundamental biomechanical principles and a practical regulatory gap. By integrating experimental findings with an analysis of occupant kinematics and load transfer pathways, this work identifies the critical limitations of current restraint systems. Ultimately, it provides an integrated framework that serves as a roadmap for developing seating posture safety strategies, ensuring that occupant protection evolves alongside the transition toward automated and comfort-driven vehicle interiors.

2. Testing Protocols and Regulatory Frameworks

Standardized testing protocols provide the baseline for evaluating occupant safety, led by the National Highway Traffic Safety Administration (NHTSA) [19] in the U.S. and the United Nations Economic Commission for Europe (UNECE) through the Working Party on Passive Safety (GRSP) [20]. These regulations primarily assume occupants will be in an upright position, with testing procedures and injury criteria designed accordingly. However, this creates a gap, as reclined seating configurations are not accounted for in existing protocols, which focus on fixed seating and standard ATD positioning.

Challenges include inconsistent surrogate positioning, limitations in ATD biofidelity for non-upright postures, and a lack of standardized testing conditions for reclined positions. As a result, current regulations may not adequately reflect the safety of new seating designs. Research initiatives like OSCCAR [21] and VIRTUAL [22] have pioneered methods, including sled testing and virtual human body modeling (HBM), to assess occupant kinematics in reclined and non-standard postures. These frameworks aim to unify posture definitions and injury metrics, ensuring consistent safety assessments across diverse occupant types and vehicle designs [23].

Consumer programs, notably Euro NCAP, have further accelerated safety standards beyond legislative minimums. Their fitment policies have been instrumental in the market-wide adoption of technologies such as curtain airbags, ISOFIX, and advanced driver assistance systems [14,15]. Recently, Euro NCAP's Vision 2030 roadmap [24] signaled a shift toward greater inclusivity, addressing diversity in age, sex, stature, and body mass. This transition is driven by evidence that restraint systems optimized for the 50th percentile male may offer suboptimal protection for females, children, elderly people, or obese occupants [25–31].

The 2030 roadmap also acknowledges the need to evaluate a broader range of seating configurations. While current protocols remain anchored in upright postures, there is a clear trend toward using virtual simulations to assess restraint robustness in reclined positions. Currently, however, these assessments remain largely confined to monitoring activities and virtual frameworks rather than being integrated into core rating tests [24].

Field data analyses provide crucial real-world context to these laboratory-based protocols. Investigations using NASS-CDS and CIREN databases have identified a small but significant subset of “out-of-position” occupants. For instance, in one study, it was noted that while only 0.5% of occupants were classified as out-of-position, they tended to be younger, less frequently restrained, and at a higher risk of injury [32]. Similar findings in other studies reinforce concerns regarding restraint effectiveness for occupants outside nominal test parameters [18,33–35]. Despite limited statistical power due to sample sizes, these data underscore the vulnerability of occupants in non-standard postures and the urgent need for adaptive restraint strategies.

The intersection of regulatory standards, consumer expectations, and real-world crash evidence highlights that posture is a critical determinant of injury risk. Understanding how reclined configurations alter kinematics and load transfer requires a deep examination of biomechanical principles under dynamic loading.

3. Biomechanical Foundations

Impact biomechanics provides the scientific framework for identifying injury mechanisms, quantifying human response to dynamic loading, and establishing tolerance limits [36,37]. Seminal studies by DeHaven [38] and Stapp [39] first defined the principles that remain fundamental to modern injury criteria, establishing the relationships between acceleration magnitude, duration, and injury.

Reclined seating significantly alters the occupant's global alignment compared to conventional upright positions, modifying spinal curvature, pelvic orientation, and lower-extremity placement. These posture-dependent changes dictate the body's initial configuration at impact onset, directly influencing the inertial coupling between segments during rapid deceleration [40–45].

Seatback inclination fundamentally dictates kinematics and restraint interaction [46–48]. Multiple studies indicate that increased recline leads to delayed belt engagement, greater forward excursion, and a heightened risk of submarining, primarily due to altered lap belt–pelvis interaction [49–53]. Furthermore, altered thoracic orientation may shift shoulder belt routing and rib loading patterns [40], questioning the validity of injury criteria developed for upright seating [18].

These effects are often exacerbated in occupants whose anthropometry deviates from the 50th percentile male, such as children [35,54,55], females [56], elderly people [16], and individuals with high body mass index [57]. Pediatric occupants exhibit increased forward excursion and altered head–torso coupling, whereas obese and elderly occupants demonstrate modified belt interaction and elevated thoracoabdominal loading patterns [16,57,58]. Collectively, these findings indicate that reclined configurations amplify anthropometry-dependent variability, challenging restraint systems originally calibrated for mid-size adult males [59–62].

From an ergonomic perspective, reclined postures enhance comfort, reduce spinal muscle activation, and delay fatigue in automated driving scenarios [63–67]. However, this comfort-driven trend introduces a fundamental safety trade-off: seating geometries optimized for musculoskeletal relaxation may disrupt optimal belt positioning and airbag coupling, thereby compromising passive restraint performance.

Radiological and quasi-static biomechanical studies confirm that recline systematically alters lumbar lordosis, pelvic tilt, and intervertebral load distribution [68–73]. Although quasi-static findings cannot be directly extrapolated to high-rate crash conditions, they demonstrate reproducible geometric shifts in spinal alignment and pelvic orientation that modify the initial boundary conditions governing dynamic load transfer [28,74]. Reclined seating fundamentally alters the load transfer pathway of the restraint system. In upright configurations, the lap belt is primarily supported by the anterior superior iliac spines, enabling effective load transmission through the pelvic structure. However, as seatback recline increases, pelvic rotation and reduced seat pan support lead to a more horizontal belt orientation, diminishing bony engagement. As a consequence, the load path shifts upward toward the abdomen, increasing the likelihood of soft tissue loading and internal injury. This shift results from posterior pelvic rotation and reduced bony engagement, which diminishes the ability of the pelvis to act as a primary load-bearing structure. Consequently, the restraint forces are redistributed toward compliant abdominal tissues, altering load transmission through the lumbar spine and increasing the risk of combined axial compression and flexion mechanisms.

The trade-off between comfort-oriented seating design and posture-sensitive passive safety performance underscores the need to integrate biomechanical evidence into early vehicle interior development [75–79]. Safety in reclined seating cannot be evaluated through isolated injury metrics or surrogate-specific responses; rather, it must account for

posture-dependent changes in restraint interaction and load transfer during impact [80]. This paradigm shift necessitates rigorous experimental characterization and high-fidelity numerical validation, as discussed in the following section.

4. Experimental and Numerical Studies

Experimental and numerical investigations form the evidence base for understanding how reclined postures affect kinematics, restraint interaction, and injury risk. While variations in surrogates and crash configurations complicate direct comparisons, consistent biomechanical trends emerge across studies.

4.1. Experimental Investigations

Anthropomorphic test devices (ATDs) remain the cornerstone of passive safety assessment due to their repeatability [36,37,81]. However, their applicability to reclined postures is limited; current ATDs were calibrated for upright configurations and may not reliably capture posture-dependent injury mechanisms, such as abdominal loading from lap–belt interaction [82].

Sled testing with ATDs consistently shows that head kinematics and cervical injury risk are highly sensitive to seatback angle. While intermediate recline may minimize some injury criteria, fully reclined postures often present elevated whiplash and cervical risks due to altered internal load paths and pelvis-to-headrest load transmission [83–88]. Conversely, post-mortem human surrogate (PMHS) studies provide vital insight into these mechanisms [89–92]. For instance, altered pelvic kinematics and increased submarining risk were confirmed in [40,41,93,94], noting that axial compression often precedes flexion in reclined impacts. Despite their biofidelity, PMHS data scalability remains limited by sample sizes and ethical constraints.

To bridge this gap, specialized surrogates like the THOR-RS and the THOR-AV have been developed. These modified ATDs incorporate enhanced spinal flexibility, abdominal compliance, and pelvic geometry to better match human kinematics in reclined and “zero-gravity” configurations [95,96]. Sled tests with THOR-AV confirm that increased recline leads to significantly greater torso excursion and abnormal shoulder-belt-to-neck contact, providing critical data for validating numerical models [72,97–99].

Collectively, these experimental studies demonstrate that although ATDs ensure repeatable and posture-controlled testing, current surrogate designs and associated injury metrics do not fully resolve the complex restraint–occupant interactions introduced by reclined seating. PMHS data improve biomechanical understanding but remain constrained in scalability and reproducibility.

These methodological constraints underscore the need for complementary high-fidelity numerical approaches capable of systematically varying posture, anthropometry, and restraint parameters while resolving internal load transfer mechanisms beyond the resolution of physical surrogates.

4.2. Numerical Investigations

Numerical modeling constitutes an indispensable tool for investigating reclined seating configurations, particularly where physical testing is constrained by cost, repeatability, and surrogate biofidelity limitations. While multibody (MB) formulations provide computational efficiency for evaluating global occupant kinematics and restraint interaction [100–103], finite element (FE) Human Body Models, predominantly THUMS and GHBM, are preferred for resolving posture-dependent tissue-level injury mechanisms.

Early numerical studies clarified fundamental submarining mechanisms in rearward-leaning occupants, linking pelvic rotation, hip moments, and lap–belt intrusion during

frontal impacts [104]. Subsequent FE–HBM investigations systematically explored the influence of seatback angle, seat cushion inclination, lumbar lordosis, and pelvic orientation on restraint engagement and injury risk [51,52,54,70]. Across these parametric studies, increased seatback recline consistently amplifies abdominal loading and lumbar spine forces, whereas greater seat pan inclination improves pelvic support and reduces submarining propensity [80]. Recent THUMS v6–v7 simulations further mapped injury metrics across lumbar levels (L1–L5), demonstrating that recline angles of 45° and 65° substantially alter load transfer compared to upright configurations [98].

Flexible and non-conventional seating layouts, including swiveling and zero-gravity concepts, have also been assessed numerically to validate adaptive restraint strategies such as enlarged airbags, knee bolsters, and coordinated active–passive systems [105–108]. To enhance objectivity in identifying submarining onset, automated metrics such as the Nearest Node Dynamic (NND) and Nearest Node Pretensioning (NNP) have been developed and validated across different anthropometries using both HBMs and ATDs [109].

Comparative investigations reveal that injury predictions remain highly sensitive to model formulation and occupant anthropometry. Significant variability in lumbar injury metrics has been reported across different HBM families despite similar global kinematics [110–112]. Moreover, comparisons between HBMs and physical ATDs, including THOR-AV and Hybrid III, indicate that although global motion trends are often comparable, injury metrics and load timing may diverge. For example, lower-extremity simulations in rearmost seating positions show that the Hybrid III Tibia Index may exceed regulatory thresholds due to mechanical ankle constraints, whereas THUMS predicts lower stress concentrations [43]. Similarly, pelvic and lumbar responses in zero-gravity configurations exhibit differences in peak-load magnitude and timing between ATDs and HBMs [96–98,113].

4.3. Synthesis and Limitations Across Study Types

Across experimental and numerical investigations, reclined seating postures are consistently shown to alter occupant kinematics and restraint interaction in ways that challenge the assumptions underlying conventional passive safety assessment. Independent of surrogate type, modeling approach, or crash configuration, robust trends emerge, including delayed restraint engagement, increased forward excursion, and posture-dependent changes in pelvic rotation and spinal loading.

A key challenge across experimental and numerical investigations lies in reconciling the differences between surrogate types. While ATDs provide robust and repeatable measurements of global kinematics, they lack the biofidelity required to resolve soft tissue deformation and internal injury mechanisms. In contrast, PMHS studies offer direct insight into load transfer and injury mechanisms but are inherently limited in repeatability and statistical representativeness.

Numerical simulations, particularly finite element HBMs, play a critical role in complementing experimental studies by enabling systematic variation of posture parameters and detailed analysis of internal load transfer mechanisms that cannot be resolved using ATDs alone. They enable detailed investigation of tissue-level response and internal load propagation beyond the capabilities of physical surrogates.

Moreover, comparative studies using THOR- and GHBM-based occupant models indicate that, despite consistent global kinematic trends across surrogate types, significant discrepancies persist in predicted injury metrics, particularly in the lumbar spine and abdominal region, due to differences in model formulation, boundary conditions, and posture definition [81,95,114–116]. These discrepancies highlight the need for integrated

experimental–numerical validation frameworks to improve confidence in tissue-level injury prediction for reclined occupants.

Related insights from railway passive safety research further reinforce the importance of posture- and configuration-dependent assessment [117,118]. In rail interiors, where occupants are typically unrestrained and interact freely with interior structures, injury mechanisms and acceptance criteria differ fundamentally from automotive scenarios [119–121]. Optimization-based studies [122,123] have shown that seat geometry, stiffness, and cushioning strongly influence injury outcomes, requiring context-specific injury thresholds that account for kinematic freedom and altered load paths. Although automotive occupants are restrained, these findings highlight a shared principle: occupant safety cannot be evaluated independently of posture, interior layout, and system-level interactions.

The evidence indicates that the safety challenges associated with reclined seating are not purely biomechanical, but arise from the coupled interaction between occupant posture and restraint system design. This necessitates a shift toward a “posture-inclusive” safety paradigm, integrating the passive geometry lessons from railway research with the adaptive, posture-aware surrogates and restraint technologies discussed in the following section.

5. Restraint Systems and Posture Interaction

Restraint systems are designed to mitigate injury by controlling occupant kinematics and distributing impact energy across robust anatomical structures. In reclined configurations, however, the geometric alignment between the occupant and the restraint environment is fundamentally altered, challenging the efficacy of traditional three-point systems [124,125]. To address these shifts, conceptual designs integrating seat, head restraint, and active restraint functions have shown promise in mitigating posture-sensitive injuries such as whiplash [126,127]. While adaptive strategies, including posture-dependent load modulation and auxiliary contact elements, have demonstrated potential in reducing chest and abdominal compression [128–130], their effectiveness remains highly sensitive to the initial seating state. Collectively, these developments underscore the necessity of advancing restraint architectures to meet the evolving demands of future vehicle interiors.

Real-world evidence reinforces these biomechanical considerations. Statistical analyses of out-of-position occupants indicate a marked increase in vulnerability within non-standard seating configurations [32,131]. A pivotal case-based investigation by [8] documented a frontal crash involving a highly reclined occupant who suffered severe cervical spinal cord injury. Integrated analysis of accident reconstruction and medical imaging revealed that the reclined posture caused degraded lap belt–pelvis engagement, leading to pelvic submarining and abnormal shoulder belt loading of the neck. Complementary multibody simulations in MADYMO [132] successfully reproduced these kinematics, confirming that as the seatback angle increases, the operational window for effective restraint engagement narrows significantly [133].

As illustrated in Figure 2, the complexity of this interaction is further amplified by occupant diversity. Because anatomical landmarks and tissue properties vary significantly with stature, age, and gender, a “one-size-fits-all” restraint geometry is increasingly inadequate in reclined states. For instance, variations in pelvic morphology and subcutaneous adipose tissue directly influence the stability of the lap belt, making certain populations, particularly females and elderly people, more susceptible to submarining even under identical crash pulses [34,134,135].

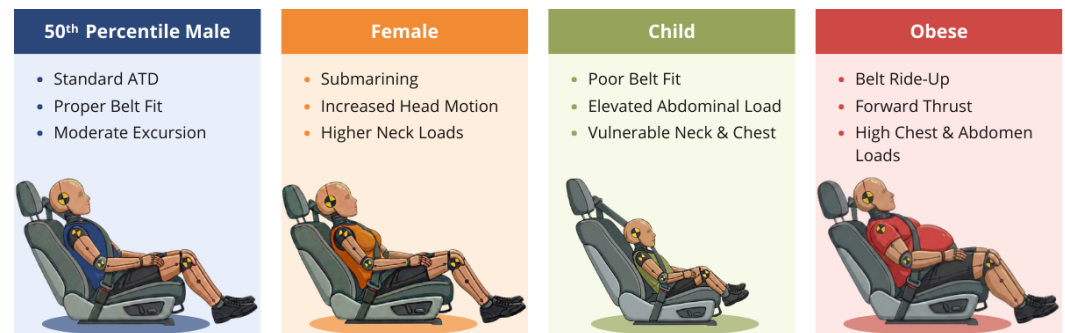


Figure 2. Conceptual overview of how posture-dependent effects are exacerbated by occupant diversity. Differences in anthropometry and biomechanical response necessitate adaptive restraint strategies to maintain protective efficacy across the entire population spectrum.

While low-speed volunteer experiments have provided valuable reference data for defining posture-dependent kinematics and muscle activation under non-injurious conditions [74,136], their applicability to high-severity crashes is inherently limited. This data gap necessitates the use of high-fidelity numerical tools to explore the interaction between these diverse populations and the adaptive strategies of the restraint system.

5.1. Seatbelt and Airbag Interaction

The efficacy of three-point seatbelts depends heavily on pelvic orientation and precise lap belt routing [137]. Compared to upright seating, rearward-leaning occupants exhibit delayed belt coupling and increased forward excursion [129]. A dominant failure mode is the loss of lap belt–pelvis engagement: posterior pelvic rotation reduces contact with the anterior superior iliac spines (ASISs), promoting submarining where the belt slides over the iliac crests and into the soft abdominal tissues [138–140].

To counter this, the Pelvis Restraint Cushion (PRC) has emerged as a critical intervention. By introducing a geometric “ramp” within the seat pan, the PRC maintains the lap belt’s position relative to the pelvis across diverse anthropometries, including 5th percentile females and 50th percentile males [53]. Complementary hardware parameters, such as belt anchorage location and knee bolster stiffness, further govern pelvic control [106,141]. Knee bolsters, in particular, provide essential passive support by preventing the “sliding” motion that leads to belt intrusion [128,142].

Vulnerable populations, particularly children, face unique challenges in these configurations. Numerical investigations using pediatric human body models (PIPER 6YO and 10YO) show that children in booster seats are highly susceptible to lap–belt sliding due to their specific pelvic geometry and pre-submarining postures [143]. While rear-facing seats and specific child restraint systems (CRSs) can enhance head and cervical protection for surrogates like the Q3 dummy, the sensitivity of injury metrics to initial posture remains a critical concern for pediatric safety [144–148].

5.2. Adaptive Strategies and Optimization

To bridge existing safety gaps, occupant protection is shifting from passive hardware to active, posture-adaptive interventions. Pre-crash repositioning strategies, such as Active Seatback Positioning (ASPA), aim to return the occupant to a more favorable upright position (e.g., 45°) prior to impact. Studies using the THOR-AV have demonstrated that ASPA can reduce cervical extension by 66.7% and spinal loads by 38.3%, effectively “resetting” the occupant’s boundary conditions before the crash begins [149–151]. However, the practical implementation of ASPA strategy is limited by short time windows during pre-crash events, making full repositioning from reclined to upright configurations challenging. A more

feasible approach might involve partial repositioning and adaptive restraint deployment. The success of these strategies relies on the coordination of pre-crash sensing systems and restraint activation timing, highlighting the need for integrated, time-critical control architectures.

Complementing physical repositioning, multi-objective optimization frameworks (e.g., employing the NSGA-II algorithm [152]) are being used to dynamically tune restraint parameters. These include switchable belt load limiters and active airbag venting tailored to specific occupant sizes and seatback angles [153–156]. In reclined seating, adjusting the timing of airbag deployment has been shown to decrease occupant injury, as later activation can increase injury risk across different restraint designs [157]. For complex scenarios like swiveling seats, researchers have proposed enlarged “envelope” airbags and coordinated knee bolster deployment to manage non-linear trajectories [105,106].

Recent studies have extended these approaches to the integration of autonomous emergency steering (AES) with occupant restraint systems (ORSs). Multi-objective optimization of AES–ORS cooperative controls has demonstrated substantial reductions in head, chest, and neck injuries during frontal collisions, with overall injury risk decreased by over 33% compared to baseline designs [108]. These results illustrate the potential of jointly optimizing vehicle control and occupant protection to complement physical repositioning and restraint adaptation.

Industrial-oriented frameworks further exploit large-scale numerical parameter variation and meta-modeling to fine-tune airbag geometries and pre-crash interventions, reducing head and neck injury metrics even in pre-submarining postures [155,158–161]. Altogether, these adaptive strategies represent a shift toward posture-aware safety paradigms, where vehicle systems dynamically harmonize with the occupant’s real-time configuration.

5.3. Synthesis of Restraint Effectiveness

Table 1 categorizes representative restraint strategies by their primary biomechanical objectives, including active repositioning, pelvic stabilization, and optimized deployment triggers. The synthesis of these studies confirms that reclined seating represents a fundamental shift in the occupant–restraint interface rather than a mere comfort modification. Regardless of the surrogate type or impact configuration, a consistent kinematic signature emerges: delayed belt coupling, increased forward excursion, and a significant divergence from intended load paths.

The convergence between experimental and numerical findings indicates that these effects stem from inherent geometric constraints rather than methodological artifacts. Consequently, the performance of upright-calibrated systems cannot be extrapolated to reclined states. While adaptive strategies, such as pre-crash repositioning and enhanced pelvic support—demonstrate measurable injury reductions, their effectiveness remains highly sensitive to the interaction between occupant anthropometry and crash pulse characteristics.

From a system-level perspective, protecting reclined occupants must be addressed as a coupled vehicle–occupant control problem. This necessitates a transition toward a posture-aware safety paradigm, requiring integrated experimental protocols and validated numerical frameworks capable of resolving complex load transfer under non-standard boundary conditions.

Table 1. Representative restraint strategies evaluated for reclined occupants and their primary biomechanical effects.

Biomechanical Objective	Study/Year	Surrogate	Primary Biomechanical Effect
Seat-integrated belt and dual airbag system	Matsushita et al. [158] (2019)	THOR 50M, H3 (05F/95M)	Assessed a novel seat-integrated belt and dual airbag system, demonstrating improved injury outcomes vs. a standard restraint system.
Standard 3-point restraint (frontal)	Somasundaram et al. [86] (2023)	THOR 05F	THOR-05F showed excellent biofidelity with 3-point restraint in upright and reclined positions.
Standard 3-point restraint (rear)	Górniak [85] (2025)	H3 50M	Standard 3-point belts exhibited non-linear cervical risk increases at high recline angles.
Standard 3-point restraint (side)	Diez et al. [129] (2023)	WorldSID 50M	Investigation of 5 postures; large rotations of the seatback lead to high chest compressions.
Load path optimization	Östling and Lubbe [138] (2023)	H3 50M	Validated an advanced 3-point belt with double lap load-limiting, reducing injury risk vs. a conventional system.
Pelvic Stabilization (KB)	Zhang et al. [106] (2025)	THUMS (HBM)	Suggests replacing airbags or adding knee bolsters to reduce injury severity.
Adaptive Pelvic Restraint	Zhao et al. [142] (2019)	Virtual ATDs and HBMs	Confirmed the versatility of seat-integrated anti-submarining systems across multiple crash scenarios.
Pelvic Stabilization (Seat Airbags)	Rawska et al. [53] (2021)	GHBMC (HBM)	PRC airbag showed the highest reduction in pelvis forward excursion for the female model.
Airbag deployment optimization	Abajo et al. [157] (2025)	WorldSID 50M	Earlier restraint activation in reclined posture reduced occupant injury for all systems.
Small-stature occupant protection	Graci et al. [56] (2024)	THOR-AV-5F	Booster-like solutions may be beneficial for small female occupants to reduce head/trunk displacements.
Pre-crash repositioning	Zhou et al. [149] (2025)	THOR-AV 50M	Reduced cervical extension and improved pre-impact alignment via ASPA.
Pre-crash kinematic assessment	Maheshwari et al. [143] (2020)	PIPER 6YO/10YO (HBM)	Evaluated AEB-induced deceleration on pediatric kinematics, highlighting significant pre-impact displacements.
Child Restraint Systems	Hu et al. [144] (2023)	CRABI 12MO, H3 3YO/6YO/10YO	Evaluated child safety in non-conventional seating, highlighting that current CRS may not provide optimal protection in highly reclined positions.

6. Future Perspectives and Research Recommendations

The shift toward reclined seating represents a fundamental change in the boundary conditions of occupant protection rather than a mere comfort enhancement. As demonstrated throughout this review, the conventional upright-based paradigm is insufficient to guarantee equivalent safety performance in vehicles equipped with automated driving systems. Bridging the gap between current capabilities and emerging interior configurations requires coordinated progress along three research pillars:

- (i) **Standardization and Virtual Testing:** Establishing benchmark “Reference Reclined Postures” is essential to ensure methodological comparability across studies. Accelerated integration of validated virtual testing frameworks will enable scalable and cost-effective evaluation across diverse occupant statures and seating geometries.
- (ii) **Advanced Biofidelity and Inclusivity:** Future safety assessment must move beyond the midsize male benchmark. This entails enhancing surrogate biofidelity, particularly for systems such as THOR-AV and THOR-RS, and expanding the validated application domain of human body models representing vulnerable populations to resolve posture-dependent, tissue-level injury mechanisms.
- (iii) **Adaptive, Data-Driven, and Anticipatory Systems:** Next-generation restraint systems should evolve into posture-aware and responsive architectures that adapt in real time to the occupant’s state. The integration of sensing, control, and predictive modeling is essential to enable this transition. Advances in artificial intelligence and machine learning can support real-time occupant state estimation and injury risk assessment. However, these approaches also introduce challenges related to model robustness, validation under safety-critical conditions, and integration within real-time control architectures.

Reclined occupant protection should therefore be addressed as a core requirement of future automated vehicle interiors rather than a peripheral design case. Achieving this objective demands coordinated action among academia, industry, and regulatory authorities. Initiatives such as Euro NCAP Vision 2030 provide a strategic foundation for posture-inclusive assessment; however, dedicated evaluation protocols, posture-specific injury criteria, and harmonized validation procedures remain to be formally established. Establishing this posture-inclusive safety framework will define the next generation of restraint system engineering in automated vehicles.

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Abbreviations

The following abbreviations are used in this manuscript:

AES	Autonomous Emergency Steering
ASIS	Anterior Superior Iliac Spine
ASPA	Active Seatback Positioning
ATD	Anthropomorphic Test Device
CIREN	Crash Injury Research and Engineering Network
CRS	Child Restraint System
FE	Finite Element
GHBM	Global Human Body Models Consortium
GRSP	Working Party on Passive Safety (<i>Groupe de Rapporteurs sur la Sécurité Passive</i>)
HBM	Human Body Model
ISOFIX	International standard for attachment points for child safety seats
KB	Knee Bolster
MB	Multibody
NASS-CDS	National Automotive Sampling System - Crashworthiness Data System
NCAP	New Car Assessment Programme
NHTSA	National Highway Traffic Safety Administration
ORS	Occupant Restraint Systems
OSCCAR	Future Occupant Safety for Crashworthy Car Structures
PRC	Pelvis Restraint Cushion
THUMS	Total Human Model for Safety
UNECE	United Nations Economic Commission for Europe
VIRTUAL	Open Access Virtual Testing Protocols for Enhancing Road User Safety

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