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Investigation into the Crash Injury Mechanisms of a 5th Percentile Female Driver with Chinese Anthropometry in Small Overlap Frontal Crashes

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Abstract: To address the deficiency in automotive passive safety design for female occupants, this study investigates the biomechanical responses of a 5th percentile Chinese female driver under extreme Small Overlap frontal crash (SOB) conditions. Utilizing a highly biofidelic finite element (FE) human model and sled simulation technology, the crash environment was reconstructed according to C-IASI (2023) protocols. Results indicate that severe vehicle yaw and lateral displacement induced pronounced lateral kinematics in the driver, diminishing airbag protective efficacy. Due to her forward seating posture, head injuries were dominated by initial linear impacts during airbag deployment (HIC15=458, BrIC=0.86). While macroscopic neck loading remained low, localized stress reached 8.47 MPa due to the yaw effect. The thorax endured asymmetric compression from torso lateral sliding, exposing solid organs (e.g., lungs, spleen) to elevated localized strain risks. Without directly striking the instrument panel, the femurs primarily sustained gradual axial compressive stress (13.67 MPa) transmitted via the pedals. Ultimately, this study elucidates the distinct injury mechanisms of 5th percentile female drivers, providing crucial data to develop intelligent restraint systems optimized for small-statured females.

1. Introduction

In recent years, with the continuous development of automotive safety technologies, the overall casualty rate of traffic accidents has been effectively controlled. However, existing automotive safety designs still exhibit significant deficiencies regarding gender equality. A substantial amount of real-world traffic accident statistical data indicates that in frontal collisions of equal severity, female occupants face a significantly higher risk of injury than males. According to an analysis of the Fatality Analysis Reporting System (FARS) database by the National Highway Traffic Safety Administration (NHTSA), belted female occupants have a 47% higher risk of sustaining severe injuries (AIS3+ level injuries)[1] and a 17% higher fatality rate[2] compared to males. Specifically regarding injury body regions, females are three times more likely to suffer cervical "whiplash" injuries than males[3], and the proportion of severe injuries to the thorax, abdomen, and lower extremities remains persistently high. The fundamental cause of this safety disparity lies in the limitations of existing New Car Assessment Programs (NCAP) and crash test protocols. Currently, the vast majority of crash tests worldwide still rely on the 50th percentile male dummy, which represents a medium-sized male, as the primary evaluation benchmark. Although some tests have introduced the 5th percentile female dummy, this dummy was initially designed merely as a geometric scale-down of the male dummy, failing to adequately account for the authentic physiological and structural characteristics of females[4-5]. Females fundamentally differ from males in aspects such as pelvic width, cervical muscle strength, thoracic stiffness, and mass distribution. This male-oriented safety evaluation system renders existing restraint systems (e.g., seatbelt load-limiting thresholds, airbag deployment timing, and inflation force) unsuitable for females. Small-statured female drivers, being petite and lighter in weight, typically adjust their seats further forward while driving. For them, such mismatched restraint systems provide relatively weaker protection and may instead inflict severe secondary injuries at the exact moment the airbag explosively deploys.

Among various frontal crash tests, the 25% small overlap frontal (SOB) crash is currently one of the most stringent and destructive load cases. This test was first introduced by the U.S. Insurance Institute for Highway Safety (IIHS), and subsequently, the China Insurance Automotive Safety Index (C-IASI) incorporated it into its evaluation system, adapting it to domestic road conditions[6]. Under the SOB condition, due to the extremely small overlap area, the primary energy-absorbing structures at the vehicle's front end (such as the bilateral longitudinal beams) function inadequately, causing the massive crash impact force to be directly absorbed by components such as the left front wheel, suspension, and A-pillar[7]. This leads to severe deformation and intrusion into the occupant cabin, while simultaneously generating tremendous vehicle yaw and lateral sliding during the abrupt deceleration. Under this asymmetrical loading state, the kinematic trajectory of the occupants inside the vehicle shifts from a simple unidirectional displacement to a complex three-dimensional spatial movement. Traditional seatbelts and airbags exhibit relatively poor efficacy under this condition; the seatbelt shoulder webbing easily slips off the narrower shoulders of females, resulting in extremely uneven loading on the thoracic cavity. Concurrently, driven by inertia, the driver's head is highly prone to deviate from the center of the airbag, sliding toward the left front, or even directly impacting the A-pillar or the door.

At present, research on the kinematic responses of drivers under SOB conditions predominantly relies on traditional physical dummy crash tests. Physical dummies, constructed with steel skeletons and rubber skins, struggle to authentically replicate human kinematic postures under complex loading, let alone measure deep-seated true injuries such as the asymmetric compression of internal organs, internal stresses within the brain, and bone fractures [8]. Furthermore, there remains a scarcity of research focusing on the whole-body injury mechanisms of the 5th percentile female driver—who truly represents the small-statured population—under the C-IASI SOB condition.

This study utilizes a highly biofidelic finite element (FE) model of a 5th percentile female driver with Chinese anthropometry and detailed human anatomical structures[9]. Combined with occupant cabin sled simulation technology, the multi-directional acceleration pulses extracted from a real C-IASI SOB crash were applied to the sled, accurately reconstructing the complex three-dimensional loading environment during the vehicle collision. The study thoroughly analyzes the biomechanical responses and injury mechanisms across multiple body regions—including head impact, cervical spine loading, internal organ compression, and lower extremity femoral loading—of the small-statured female driver in extreme offset crashes. This research not only identifies the protective deficiencies of existing restraint systems for small-statured females but also provides crucial theoretical support and data references for the future development of more equitable and intelligent automotive safety systems.

2. Research Methods

2.1 Occupant Cabin Model Setup

To investigate the frontal crash injury mechanisms of a 5th percentile female driver with Chinese anthropometry under the SOB condition, an SOB crash simulation system featuring a highly biofidelic biomimetic injury model of a Chinese driver was constructed. The occupant cabin subsystem used for the simulation was derived from a high-fidelity finite element (FE) model of a 2024 mid-size sedan publicly released by the National Highway Traffic Safety Administration (NHTSA). It fully retains the key structures that may interact with the driver during a collision, comprising a driver's seat with foam cushions and a frame structure, a three-point seatbelt system integrated with a pretensioner and a retractor, a steering wheel and steering column, a driver-side airbag, door trim panels, an accelerator pedal and floor structure, as well as the lower instrument panel trim that the knees and lower legs might contact, as shown in Figure 1.

The airbag was configured with a uniform pressure setting, meshed with quadrilateral shell elements, connected using the *CONSTRAINED_SPOTWELD command, and subjected to a folding process. The specific parameter settings for the airbag are detailed in Table 1. This model comprehensively replicates the potential crash environment the driver might experience during a collision. The human body model employed is an FE model of a 5th percentile female driver with Chinese anthropometry, which has been rigorously validated through Post-Mortem Human Subject (PMHS) tests in previous studies. This model features highly detailed anatomical structures, including brain tissue, cervical spine sequences, thoracic ribs, internal solid organs (heart, lungs, liver, spleen, kidneys), and lower extremity skeletal structures.

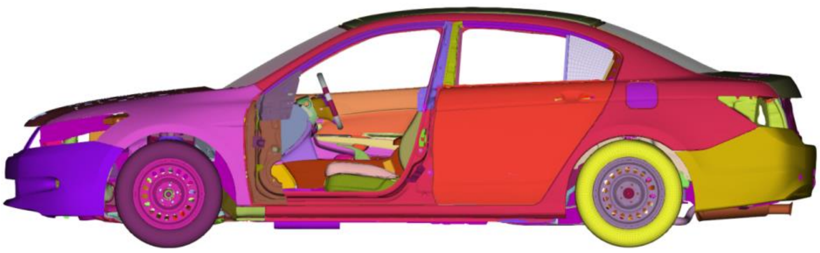

Figure 1: High-fidelity finite element model of a 2024 mid-size sedan

Table 1: Airbag parameter settings

Material Property	Value
Density	$825 kg/m^3$
Young's modulus	200MPa
Poisson's ratio	0.3
Damping coefficient	0.05

2.2 Acceleration Pulses and Driver Posture Positioning

Since the SOB condition is not a simple longitudinal deceleration but a complex three-dimensional kinematic event involving severe vehicle rotation, this study did not adopt the traditional unidirectional sled loading method. Instead, complex waveform data at the center of gravity (CG) of the occupant cabin were accurately extracted from a 64 km/h real-vehicle C-IASI 25% offset crash test. These included the X-axis longitudinal deceleration pulse, the Y-axis lateral acceleration pulse, and the Z-axis yaw angular acceleration pulse, as illustrated in Figure 2. In the simulation setup, the extracted multi-directional acceleration pulses were applied directly to the local coordinate system of the occupant cabin sled, coupled with a global gravity field of 9.8 m/s^2. This method effectively simulates the complex deceleration and posture variations induced by offset loading when the vehicle collides with a rigid barrier at a 25% overlap rate.

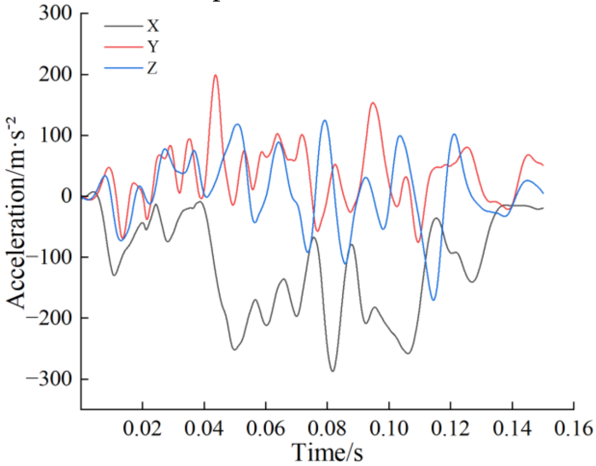

Figure 2: Acceleration pulse under SOB condition

Regarding the driver's posture positioning, ergonomics and crash test protocols were strictly referenced. By adjusting the seat track position, it was ensured that a reasonable safety clearance was maintained between the 5th percentile female driver's knees and the lower instrument panel trim, the feet precisely fitted the accelerator pedal, the arms maintained a natural gripping angle, and the line of sight was kept horizontal. Based on these configurations and in accordance with the C-IASI (2023 version) frontal crash test requirements, seat pre-compression and seatbelt modeling were completed using Primer software. The seatbelt load limiter was set to 2.5 kN, the pretensioner load limit to 3.0 kN, the pretensioner firing time at 15 ms, and the driver-side airbag deployment time at 25 ms. Interactions between the driver and the seat, seatbelt, and interior trims were all defined using surface-to-surface contacts, with friction coefficients assigned as 0.1 (seat), 0.2 (seatbelt), and 0.25 (interior trims), respectively.

2.3 Injury Evaluation Criteria

To scientifically evaluate the injury mechanisms of the 5th percentile female driver during the collision, this study analyzed both the macroscopic overall loading criteria of traditional dummies and the deformation characteristics of authentic human organs.

In the head injury assessment, the Head Injury Criterion (HIC15) and Brain Injury Criterion (BrIC) were adopted to measure the severity of linear impacts and lateral twisting sustained by the head. Furthermore, the Von Mises stress, shear stress, intracranial pressure, and maximum principal strain of the brain tissue were introduced to deeply predict the microscopic risks of internal cerebral contusions or neurological structural damage. Regarding neck injuries, the primary metrics extracted were the shear force (F_x), axial compressive force (F_z), flexion/extension bending moment (M_y), and the Neck Injury Criterion (N_{ij}) sustained by the cervical spine. Additionally, for thoracoabdominal and internal organ injuries, this study not only utilized chest compression and the Viscous Criterion (VC) to evaluate the overall skeletal depression and instantaneous dynamic compression of the thorax, but also employed the first principal strain as an indicator. This allowed for a detailed investigation into the actual probabilities of rupture and failure in solid organs (e.g., lungs, heart, liver, spleen, and kidneys) and hollow organs (e.g., stomach and intestines) under asymmetric compression.

3. Injury Mechanisms of the 5th Percentile Female Driver

3.1 Driver Kinematic Responses

Figure 3 illustrates the kinematic trajectories of the head, T1, T12, and pelvis of the 5th percentile female driver during the collision under the C-IASI SOB condition. The red curves in the figure extend from right to left, representing the actual forward motion of the driver driven by inertia following the impact.

As observed in Figures 3(a) and 3(b), the kinematic trajectories of the head and T1 are highly consistent, both exhibiting distinct forward and downward displacement characteristics. During the crash, the head height decreased from an initial 1150 mm to 948 mm, resulting in a downward displacement of nearly 200 mm; simultaneously, the height of T1 dropped from 1050 mm to 887 mm. Conversely, the kinematic trajectories of T12 in Figure 3(c) and the pelvis in Figure 3(d) appear significantly more gradual. The pelvis experienced an initial vertical drop of 80 mm during the early stage of the collision, subsequently sliding forward in a primarily horizontal state. The vertical drop of T12 was also limited to approximately 70 mm.

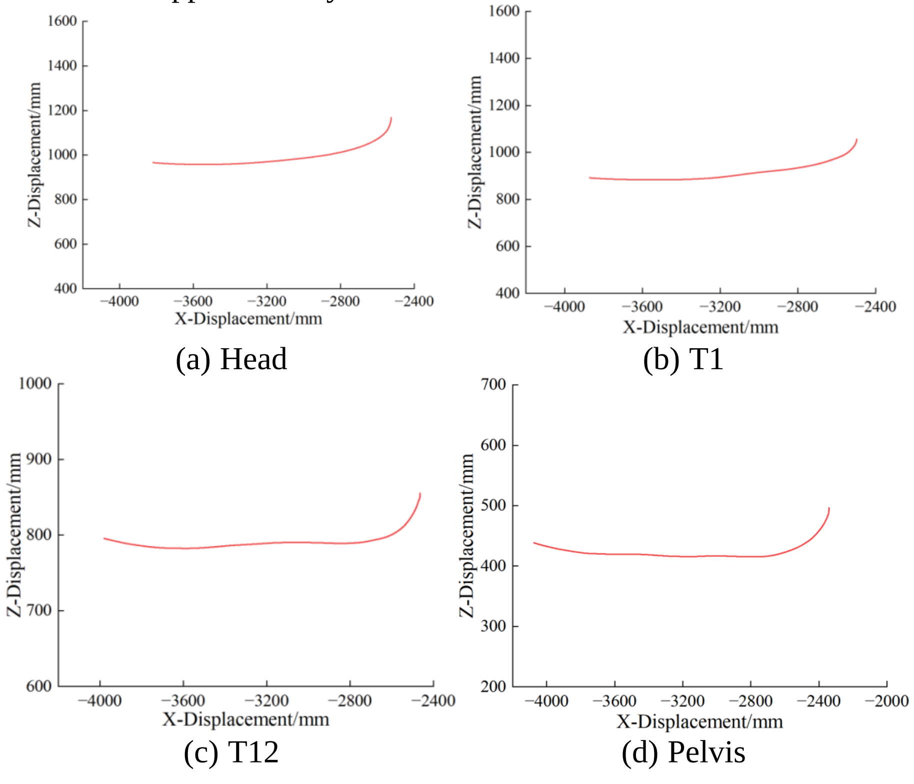

Figure 3: Kinematic trajectories of the head, T1, T12, and pelvis of the 5th percentile female driver model

3.2 Driver Head Injury Analysis

Regarding the macroscopic criteria reflecting the overall loading on the head, the driver's HIC15 value is 458.0, and the 3ms resultant head acceleration (a_{3ms}) is 54.6 (Table 2). Both of these metrics, which represent the severity of linear impacts, are below the high-performance safety limits of 500 and 72, respectively. The Brain Injury Criterion (BrIC), which reflects the injury risk from lateral head twisting, is 0.86; it does not reach the critical danger threshold of 1.0, although it exceeds 0.8.

Delving into the microscopic criteria within the brain tissue, the intracranial pressure (7.92 kPa), shear stress (3.79 kPa), and maximum principal strain (4.34%) are all far below the lower thresholds for inducing brain injury. This indicates a very low probability of internal neural tearing or severe structural damage within the brain. However, the comprehensive loading (Von Mises stress) on the brain tissue reaches 6.79 kPa, falling exactly into the 6–11 kPa range, which suggests a potential risk of mild cerebral contusion. Overall, under this offset crash condition, the head of the 5th percentile female receives relatively effective protection without facing the threat of fatal or severe brain injury, indicating that the overall safety remains relatively controllable.

Table 2: Head injury metrics of the 5th percentile female driver

Head Metric	F05	Threshold
HIC_{15}	458.0	High-performance limit: 500; Low-performance limit: 700
a_{3ms}	54.6	High-performance limit: 72; Low-performance limit: 80
BrIC	0.86	BrIC = 1, 45% probability of AIS4 brain injury
Von Mises stress / kPa	6.79	6–11 kPa: cerebral contusion; >15 kPa: mild concussion; >38 kPa: severe brain injury
Shear stress / kPa	3.79	6 kPa: 25% probability of mild brain injury; 7.8 kPa: 50% probability of mild brain injury; 10 kPa: 80% probability of mild brain injury; 25 kPa: 100% probability of moderate brain injury
Intracranial pressure / kPa	7.92	>173 kPa: moderate brain injury; >235 kPa: severe brain injury
Maximum principal strain / %	4.34	10%: reversible injury; 20%: functional deficit of the nervous system; 25%: structural failure of the nervous system in brain tissue

3.3 Driver Neck Injury Analysis

Regarding the macroscopic criteria reflecting overall loading, the peak shear force (F_x), which represents the anteroposterior displacement of the cervical spine, is 702.5 N, approximately half of the high-performance limit (1200 N). The axial force (Fz), representing the tension and compression of the cervical spine, is 572.5 N, well below the high-performance safety threshold of 1700 N. The bending moment (My), representing excessive cervical flexion and extension, is a mere 3.6 N ṁ—an extremely low value accounting for only one-tenth of the high-performance limit (36 N ṁ).Based on these three loading metrics, the calculated composite Neck Injury Criterion (Nij) is 0.2, leaving a substantial safety margin from the regulatory critical threshold (1.0). This indicates that, at a macroscopic level, the cervical spine does not face a severe injury risk. However, the maximum localized comprehensive stress (Von Mises stress) on the cervical spine of the F05 driver reached 8.47 MPa. This value substantially exceeds the tissue injury safety threshold of 4.8 MPa, representing an exceedance proportion of over 76%, as shown in Table 3.

Table 3. Neck injury metrics of the 5th percentile female driver

Neck Metric	F05	Threshold
Von Mises stress / MPa	8.47	4.8
F_x/N	702.5	High-performance limit: 1200 N; Low-performance limit: 1950 N; Ultimate limit: 2700 N
F_z/N	572.5	High-performance limit: 1700 N; Low-performance limit: 2620 N; Ultimate limit: 2900 N
M_y/N ṁ	3.6	High-performance limit: 36 N ṁ; Low-performance limit: 49 N ṁ; Ultimate limit: 57 N ṁ
N_{ij}	0.2	1

3.4 Driver Thoracoabdominal Injury Analysis

Based on the chest injury evaluation metrics extracted from the charts, the thoracic loading of the 5th percentile (F05) female driver in the offset crash exhibits inconsistent results between two indicators. Regarding the metric representing the overall depression of the thorax, the chest compression is 14.2 mm, which is successfully controlled within the high-performance safety limit of 18 mm and is far below the low-performance limit of 42 mm, demonstrating a robust structural safety margin. However, concerning the Viscous Criterion (VC), which measures the degree of instantaneous rapid compression of thoracic soft tissues, the value reached 0.55 m/s. This slightly exceeds the high-performance limit of 0.5 m/s but safely remains below the low-performance limit of 1.0 m/s, as shown in Table 4.

Table 4. Chest injury metrics of the 5th percentile female driver

Chest Metric	F05	Threshold
Chest compression / mm	14.2	High-performance limit: 18 mm; Low-performance limit: 42 mm
VC / $m \cdot s^{-1}$	0.55	High-performance limit: 0.5 m/s; Low-performance limit: 1.0 m/s

As observed from the maximum principal strains of the internal organs extracted from the charts, the injury conditions of various internal organs for the 5th percentile female driver in the small overlap crash exhibit significant discrepancies. For hollow organs such as the stomach, large intestine, and small intestine, the deformation strain values are 0.15, 0.50, and 0.70, respectively. These values are all well below the safety threshold of 1.3, demonstrating an extremely high safety margin. The strain value for the heart is 0.27, which is also successfully controlled within the critical safety threshold of 0.3.However, the remaining solid organs and the lungs all exhibit varying degrees of threshold exceedance. Specifically, the liver (0.38) and kidneys (0.47) both exceed the injury threshold of 0.3. The data for the spleen and lungs are the most severe; the strain value of the spleen reaches as high as 0.56 (nearly double the 0.3 threshold), and that of the lungs reaches 0.49 (significantly exceeding the critical limit of 0.28). This indicates that the driver's spleen and lungs face an extremely high risk of tissue rupture and failure, as shown in Table 5.

Table 5. Internal organ injury metrics of the 5th percentile female driver

Organ (Maximum principal strain)	**F05**	Threshold
Heart	0.27	**0.3**
Liver	0.38	**0.3**
Spleen	0.56	**0.3**
Kidneys	0.47	**0.3**
Stomach	0.15	**1.3**
Large intestine	0.50	**1.3**
Small intestine	0.70	**1.3**
Lungs	0.49	**0.28**

3.5 Driver Lower Extremity Injury Analysis

The maximum Von Mises stress sustained by the driver's femurs is 13.67 MPa. This value is below the critical threshold of 20 MPa, maintaining a safety margin of over 30% from the safety limit, as shown in Table 6.

Table 6. Lower extremity injury metrics of the 5th percentile female driver

Lower Extremity Metric	**F05**	**Threshold**
Von Mises stress (Femur) / MPa	**13.67**	**20**

4. Discussion

In small overlap frontal crash scenarios, the whole-body injury mechanisms of a 5th percentile female driver exhibit significantly different mechanical characteristics from those of an average-sized male. These differences fundamentally arise from the driver's small stature, an extremely forward seating position due to the limited adjustment range, and the pronounced yaw and lateral sliding motion of the vehicle body inherent to offset collisions. The deep coupling of these three factors fundamentally alters the protective efficacy of the restraint system.

Head and neck response: In the early phase of the crash, the driver's head makes early contact with the airbag while it is still in the high-pressure inflation phase and has not yet begun to deflate. Although this early contact promptly stops the forward motion of the head and prevents a rigid impact with the steering wheel-thus keeping macroscopic force indicators within safe limits-the instantaneous high-pressure "strike-back" from the airbag directly leads to a sharp increase in microscopic stress within the brain tissue, which becomes a primary cause of cerebral contusion. Due to the vehicle yaw, the torso undergoes significant lateral sliding, causing the head to deviate from the optimal protective zone and slip toward the edge of the airbag. This deviation not only reduces the cushioning effect of the airbag but also forces the head and neck into a severe torsion. Under this complex posture, despite the relatively low overall macroscopic tension in the neck (due to the light head mass), the cervical spine is subjected to a combined loading of *rear-extension* and *acute lateral bending*, resulting in a high risk of injury.

Thoracoabdominal region: The lateral sliding of the vehicle body disrupts the original geometric equilibrium of the seatbelt, causing the shoulder belt to shift. This leads to rapid, uneven, and dynamic tightening on the lower part of one side of the chest. Owing to the intrinsically narrow thoracoabdominal space of a small-statured female, which lacks cushioning room, the fixed, solid organs (e.g., lung and spleen) cannot evade the local high pressure. They sustain excessive asymmetrical mechanical compression, posing a very high risk of rupture. In contrast, the highly mobile and soft hollow organs can accommodate the load by shape change.

Lower extremity protection: Small-statured females exhibit a specific geometric advantage. Although the front-left part of the cockpit often undergoes severe intrusion and collapse, the driver's relatively short lower limbs maintain a sufficient safety clearance between the knee joint and the intruding lower instrument panel; thus, no direct rigid interference occurs. Consequently, the load on the lower-limb bones originates almost entirely from the reaction force transmitted upward through the pedal under the foot. This pure axial compression along the leg bone lacks destructive bending or shearing components, thereby effectively preserving the structural integrity of the lower-limb skeleton.

This study has certain limitations. The human body finite element model used primarily reflects the passive biomechanical response of the driver. In real-world collision events, drivers typically perform emergency braking and other evasive actions before impact. The resulting active muscle response-i.e., muscle tension and contraction-would influence the driver's initial posture and the distribution of neck muscle forces. Future research should consider coupling an active human body model to more accurately reproduce the complex responses throughout the entire crash sequence.

5. Conclusion

This paper conducted an in-depth investigation into the biomechanical responses and injury mechanisms of a 5th percentile female driver with Chinese anthropometry under a 25% small overlap frontal crash condition. The main conclusions are as follows:

First, complex lateral motion impairs the effectiveness of conventional restraint systems. The extremely forward seating position of a small-statured female, combined with the severe yaw of the occupant compartment under the small overlap condition, induces a pronounced three-dimensional compound lateral sliding motion of the driver. This serves as the core physical trigger for region-specific injuries.

Second, the head-neck region exhibits a “globally safe but locally injured” loading pattern. Early head contact with the inflating airbag-although preventing rigid impact-subjects the brain tissue to a momentary high-pressure strike from the airbag, which can readily cause microscopic cerebral contusion. Furthermore, lateral torso sliding causes the head to slip toward the edge of the airbag, forcing the cervical spine into a combined loading of extension and lateral bending. Consequently, local stresses in the lower cervical spine rise sharply, posing a risk of occult soft-tissue neck injury.

Third, internal organ injuries show strong spatial specificity. Body sliding induces seatbelt misalignment and asymmetric tightening. Due to the inherently narrow thoracoabdominal space of a small-statured female, solid organs such as the spleen and lungs-lacking room for cushioning or avoidance-face a very high risk of compressive rupture. In contrast, hollow organs such as the stomach and intestines are relatively safe under such loading.

Fourth, lower extremity loading exhibits a specific geometric protective advantage. Owing to the shorter lower limb length of the 5th percentile female, even when structural intrusion of the occupant compartment occurs, a sufficient safety clearance remains between the knee joint and the forward instrument panel. The lower limb bones are subjected only to pure axial compressive forces transmitted through the pedals, effectively avoiding bending and shear fractures.

Based on the above mechanisms, current passive safety systems designed for the average-sized male cannot adequately protect the 5th percentile female in complex offset frontal crashes. Future efforts should focus on developing adaptive, intelligent restraint systems tailored to the specific lateral sliding trajectories and micro-scale tissue tolerances of small-statured females.

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