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Injury Mechanisms of an Unrestrained Occupant in Urban Bus Frontal Collisions Based on a Human Finite Element Model

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Abstract: To investigate the injury mechanisms of an unrestrained occupant in urban bus frontal collisions, a simulation study was conducted based on a validated THUMS AM50 human finite element model and an urban bus finite element model. A typical seated occupant posture was established, and a frontal collision acceleration-time curve was applied as the boundary condition. The occupant kinematic response and biomechanical injury indicators of the head, neck, and abdominal organs were analyzed. The results show that, during the frontal collision, the occupant moved forward significantly under inertial loading and the head violently impacted the front-row seat, resulting in a high risk of head injury. The HIC15 and 3 ms resultant acceleration of the head center of mass were 915.1 and 96.3 g, respectively, both exceeding the corresponding low-performance limits. The BrIC value was 0.8, corresponding to an approximately 30% probability of AIS 4 brain injury. In addition, the maximum principal strain of brain tissue reached 38.8%, exceeding the injury threshold of 17.7%, indicating a strain-dominated risk of brain tissue injury. In contrast, the cervical von Mises stress, cervical mechanical loads, Nij, and abdominal organ MPS values were all below the corresponding injury thresholds. Therefore, under the frontal collision condition, the primary injury risk for an unrestrained bus occupant is concentrated in the head and brain, while the risks of severe cervical structural injury and abdominal organ injury are relatively low. The findings can provide a theoretical basis for the optimization of bus interior structures and occupant protection systems.

Keywords: Human body finite element model; Urban bus; Frontal collision; Occupant injury; Biomechanics

1. Introduction

With the continuous acceleration of urbanization and the ongoing improvement of public transportation networks in China, buses, as an important carrier of green travel, have experienced a steady increase in passenger volume and play an important role in the daily travel of urban and rural residents. However, during frontal collisions, occupants are prone to multiple injuries caused by inertial effects, including head impact, cervical whiplash, and lower-extremity compression. Therefore, it is necessary to further investigate the injury mechanisms of bus occupants under frontal collision conditions, so as to provide theoretical support for improving the passive safety performance of buses and preventing occupant injuries.

Zhou et al. [1] investigated the injury risks of bus occupants in collision and non-collision accidents based on a police-reported dataset containing injury information for 17,383 bus occupants. The results showed that elderly female occupants are highly susceptible to fatal or severe injuries in non-collision accidents when they lose balance while boarding, alighting, or standing in a bus. Anton et al. [2] developed a coach sled model coupled with multibody and finite element methods, and investigated the effects of seat layout, restraint system arrangement, seat stiffness, and vehicle acceleration pulse on occupant safety during frontal coach collisions. Palacio et al.[3] selected three typical standing positions in buses and, combined with common bus acceleration pulses, simulated non-collision injuries of elderly standing occupants under sudden acceleration and emergency braking conditions. They further evaluated the causes of such injuries and proposed injury prediction methods and safety recommendations for elderly passengers.

He et al. [4] established a multibody dynamic model of a child and a bus using MADYMO, analyzed the motion characteristics of child occupants during emergency braking, including the initial and secondary impacts with interior handrails, and evaluated child occupant injuries based on dummy injury curves, thereby proposing optimization measures for bus interior design. Gerardo et al. [5] established a finite element model of a low-floor bus, calculated the acceleration pulses under frontal, side, and rear-end collision conditions, and applied the simulated pulses to sled tests. The kinematic characteristics and injury mechanisms of 5th, 50th, and 95th percentile passengers were analyzed. The results indicated that head and neck injuries are common among bus occupants, and these injuries are mostly caused by impacts between occupants or between occupants and interior components such as seats. Qian et al. [6] established a coupled partition-seat-occupant model and evaluated the injury severity of front-row occupants under different restraint conditions. The results showed that occupants without seat belts and those using only lap belts suffered the most severe injuries. Sun et al. [7] investigated the effects of different sleeping postures on occupant injuries in frontal coach collisions. The results showed that a head-tilted posture increased the risk of head injury, a neutral posture reduced head injury, and a torso-rotated posture reduced neck injury.

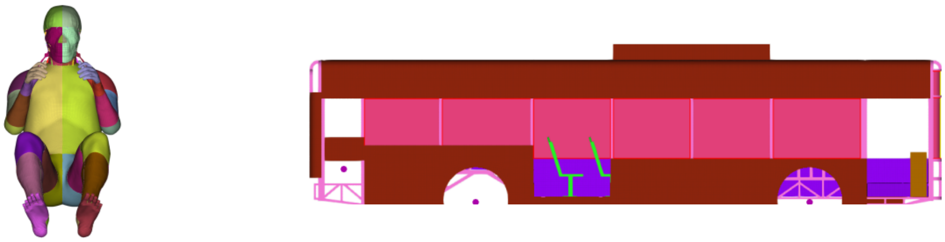
However, most existing studies have focused on accident statistics, dummy-based injury assessment, or specific restraint configurations, while detailed biomechanical responses of unrestrained seated bus occupants based on human finite element models remain insufficiently discussed, especially in terms of brain tissue strain, cervical loading, and abdominal organ deformation.

Based on the above, this study employs a validated bus finite element model and the THUMS AM50 human body model to investigate the kinematic and biomechanical responses of an unrestrained seated occupant under frontal collision conditions. The aim of this study is to reveal the injury mechanisms of bus occupants in frontal collisions and to provide a theoretical basis for bus occupant protection and interior safety design.

2. Methods

2.1 Model Description

In this study, the THUMS AM50 human finite element model and a finite element model of a bus [8] were employed for simulation analysis, as shown in Figure 1(a) and Figure 1(b). The bus finite element model consisted of 821,000 elements, and the curb weight of the whole vehicle was 9,010 kg. The THUMS AM50 model can describe in greater detail the anatomical structures of the human body, including the skeleton, brain tissue, internal organs, and muscles, as well as their mechanical properties. Therefore, it enables detailed analysis of multiple types of injuries, such as fractures, traumatic brain injuries, and visceral injuries, and has important application value in the study of vehicle occupant protection and restraint system optimization.

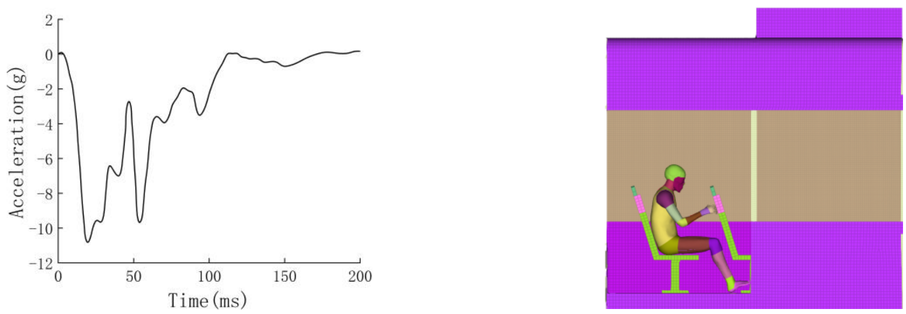


(a) (b)

Figure 1: THUMS AM50 model and finite element model of the bus: (a) THUMS AM50 model; (b) finite element model of the bus.

2.2 Frontal Collision Simulation Setup

In ANSA, the finite element model of the urban bus and the human finite element model were imported sequentially, and the THUMS AM50 model was positioned in a typical seated posture of a bus occupant using the MOVE function. The model position and posture were then adjusted so that the midsagittal plane of the human model coincided with the center plane of the seat. Under the condition of no initial penetration, proper contact was ensured between the buttocks and thighs and the upper surface of the seat cushion, as well as between the plantar surfaces of both feet and the bus floor, thereby reproducing a realistic seated posture. The model coordinate system was defined as follows: the positive X-axis pointed forward, the positive Y-axis pointed to the right side of the model, and the positive Z-axis pointed upward, perpendicular to the bus floor. Subsequently, the frontal collision acceleration-time curve of the bus obtained experimentally by Gerardo Olivares[5] was applied as the boundary condition, and the friction coefficient between the occupant model and the seat as well as the bus floor was set to 0.3. Figure 2 shows the acceleration-time curve and the frontal collision simulation setup, with Figure 2(a) presenting the acceleration-time curve and Figure 2(b) showing the simulation setup.



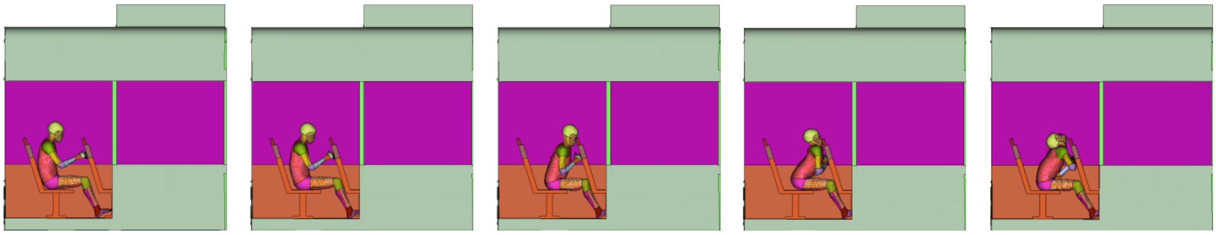
(a) (b)

Figure 2: Acceleration-time curve and frontal collision simulation setup: (a) acceleration-time curve; (b) frontal collision simulation setup.

3. Results and analysis

3.1 Occupant Kinematic Response

The kinematic response of the unrestrained occupant under the frontal collision condition is shown in Figure 3. During the 0-100 ms stage, the occupant exhibited obvious forward inertial motion under the vehicle deceleration, and the torso slid forward relative to the seat. The hands and lower limbs first came into contact with the front-row seat. During the 100-150 ms stage, the head impacted the backrest of the front-row seat, and the coupled effect of contact impact loading and torso inertial motion caused obvious head–neck flexion. During the 150-200 ms stage, the occupant gradually rebounded toward the seat under the contact reaction force, while the head and neck still maintained a rotational tendency.



0 ms 50 ms 100 ms 150 ms 200 ms

Figure 3: Kinematic response of the occupant during the frontal collision.

3.2 Occupant Head and Brain Biomechanical Response

The head injury indicators of the unrestrained occupant under the frontal collision condition are summarized in Table 1. The HIC15 value was 915.1, and the 3 ms resultant acceleration of the head center of mass, a3ms, was 96.3 g. Both values exceeded the corresponding low-performance limits, indicating that the head was subjected to severe impact loading during the collision. The BrIC value was 0.8, which did not exceed the threshold of 1. However, this value corresponds to an approximately 30% probability of AIS 4 brain injury, suggesting that the occupant still had a certain risk of brain tissue injury.

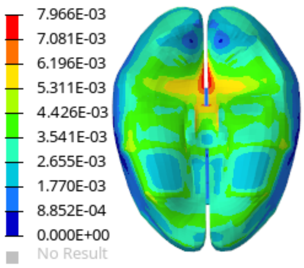
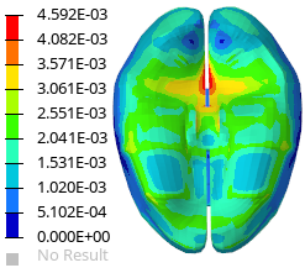
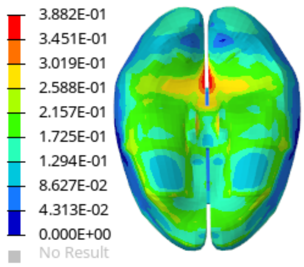
Table 1: Occupant head HIC15, a3ms, and BrIC values and corresponding thresholds.

	HIC_{15}	a_{3ms} (g)	BrIC
Occupant value	915.1	96.3	0.8
Threshold value	High-performance limit: 500 Low-performance limit: 700	High-performance limit: 72 Low-performance limit: 80	1

To further evaluate local brain tissue injury, the von Mises stress, shear stress, and maximum principal strain of brain tissue (MPS) were extracted, as shown in Table 2. The peak von Mises stress, shear stress, and MPS were 8.0 kPa, 4.6 kPa, and 38.8%, respectively. The von Mises stress and shear stress were below the corresponding injury thresholds, whereas the MPS was much higher than the threshold of 17.7%. This indicates that, after the head impacted the front-row seat, the brain tissue did not show obvious stress exceedance, but considerable tensile deformation occurred. Therefore, the main head injury risk in this case can be regarded as strain-dominated brain tissue injury.

Table 2: Stress and strain contours and injury thresholds of the occupant's head.

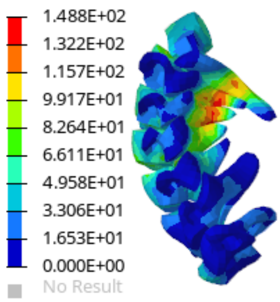
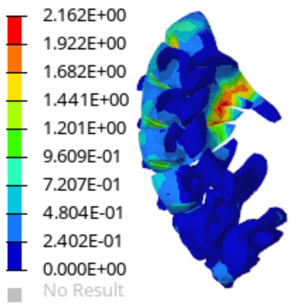
	Von Mises stress (kPa)	Shear stress (kPa)	MPS (%)

Occupant value	 8.0	 4.6	 38.8
Threshold value	15.0[10]	7.8[11]	17.7[12]

3.3 Cervical Biomechanical Response of the Occupant

The cervical von Mises stress contours of the C1-C7 cortical bone, cancellous bone, and intervertebral discs are shown in Table 3. Although the neck underwent a certain bending deformation with head flexion during the frontal collision, the overall stress level remained relatively low, and no obvious stress concentration was observed. The peak von Mises stress of the C1-C7 cortical bone was 148.8 MPa, which was lower than the injury threshold of 236 MPa. The peak von Mises stress of the cancellous bone was 2.2 MPa, far below the injury threshold of 59 MPa. These results indicate that the cervical bony structures were not subjected to concentrated loading exceeding the material injury limits, suggesting a relatively low risk of fracture or structural injury.

Table 3: Stress contours and injury thresholds of the occupant's neck.

	Von Mises stress of cortical bone (MPa)	Von Mises stress of cancellous bone (MPa)
Occupant value	 148.8	 2.2
Threshold value	236[13]	59[13]

The cervical mechanical loads and the neck injury criterion N_{ij} are summarized in Table 4. The cervical shear force F_x, axial force F_z, bending moment M_y, and N_{ij} were 345.2 N, 157.5 N, 18.0 N·m, and 0.52, respectively, all of which were lower than the corresponding injury thresholds. Compared with the threshold values, F_x and F_z remained at relatively low levels, indicating that the neck was not subjected to excessive shear or axial compressive loading. Although M_y showed a certain bending response, it was still below the limit of 36 N·m. Overall, the cervical load level was relatively low, and N_{ij} did not reach a dangerous level, suggesting a low risk of severe neck injury.

Table 4: Cervical Fx, Fz, My, Nij, and injury thresholds of the occupant.

	F_x (N)	F_z (N)	M_y (N·m)	N_{ij}
Occupant value	345.2	157.5	18.0	0.52
Threshold value	1700	1200	36	1

3.4 Abdominal Biomechanical Response of the Occupant

The MPS values and injury thresholds of the major abdominal organs are shown in Table 5. The MPS values of the large intestine, small intestine, and stomach were 23.4%, 15.8%, and 19.4%, respectively, which were all much lower than the injury threshold of 130%. The MPS values of the spleen, right kidney, left kidney, and liver were 16.2%, 11.5%, 10.6%, and 13.1%, respectively, also remaining below the threshold of 30%. These results indicate that the abdominal organs experienced limited compression and deformation during the frontal collision. The overall strain level did not reach the injury criterion, suggesting a low risk of severe abdominal organ injury.

Table 5: MPS contours and injury thresholds of the occupant's abdominal organs.

	Large intestine	Small intestine	Stomach	Spleen	Right kidney	Left kidney	Liver
Occupant value	23.4	15.8	19.4	16.2	11.5	10.6	13.1
Threshold value	130[14]	130[14]	130[14]	30[15]	30[15]	30[15]	30[15]

4. Conclusions

Based on a validated urban bus finite element model and the THUMS AM50 human body model, a frontal collision simulation case was established to analyze the injury mechanisms of an unrestrained seated occupant. The main conclusions are as follows.

First, the frontal collision induced obvious forward inertial motion of the occupant. The torso slid forward relative to the seat, and the head subsequently impacted the backrest of the front-row seat. This impact process was the main cause of occupant injury. The HIC15 and a3ms values exceeded the corresponding low-performance limits, and the BrIC value indicated a certain probability of AIS 4 brain injury. In addition, the brain tissue MPS exceeded the injury threshold, indicating that the head injury risk was mainly associated with large tensile deformation of brain tissue.

Second, the cervical injury response remained relatively low. The von Mises stresses of the C1–C7 cortical and cancellous bones were lower than the corresponding injury thresholds. The cervical shear force Fx, axial force Fz, bending moment My, and Nij were also below their threshold values, suggesting that the risk of severe cervical fracture or structural injury was relatively low. Third, the abdominal organ injury risk was also limited. The MPS values of the large intestine, small intestine, stomach, spleen, kidneys, and liver did not exceed the corresponding injury thresholds.

Overall, the injury risk of the unrestrained occupant in the urban bus frontal collision was mainly concentrated in the head and brain, while the cervical and abdominal injury risks were relatively limited. Therefore, reducing forward occupant displacement and mitigating head impact with the front-row seat should be key objectives in bus interior safety design and occupant protection. Future studies should further consider different occupant percentiles, sitting postures, seat layouts, and passive protection devices such as headrests and two-point seat belts to improve the applicability of the conclusions.

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