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Finite element simulation of lower limb injuries to the driver in minibus frontal collisions

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ABSTRACT

Purpose: This study aims to explore the biomechanical mechanism of lower limb injuries to the driver by establishing a finite element (FE) simulation model of collisions.

Methods: First a minibus FE model was integrated with a seat belt system. Then it was used to rebuild two collisions together with the total human model for safety (THUMS) provided by Toyota Motor Corporation: a rear-end collision between a minibus and a truck and a head-on collision of a minibus to a rigid wall. The impact velocities of both collisions were set at 56 km/h. The vehicle dynamic response, vehicle deceleration, and dashboard intrusion in the two collisions were compared.

Results: In the minibus rear-end truck collision, the peak values of the von Mises equivalent stress at the tibia and the femur were 133 MPa and 126 MPa respectively; while in the minibus head-on rigid wall collision, the data were 139 MPa and 99 MPa. Compared with the minibus head-on rigid wall collision, the vehicle deceleration was smaller and the dashboard intrusion was larger in the minibus rear-end truck collision.

Conclusion: The results illustrate that a longer dashboard incursion distance corresponds to a higher von Mises equivalent stress at the femur. The simulation results are consistent with the driver's autopsy report on lower limbs injuries. These findings verify that FE simulation method is reliable and useful to analyze the mechanisms of lower limb injuries to the driver in minibus frontal collisions.

Introduction

According to the road traffic safety report released by the Ministry of Public Security Traffic Management Bureau, by the end of 2013, the number of motor vehicles nationwide has exceeded 250 million, indicating that China has been a leader in the automobile industry. Although the road safety situation is generally stable, people's awareness of road safety remains inadequate. The report also pointed out that in recent years; the market demand for minibus has been increasing. In 2013, the nationwide number of minibuses reached 14.38 million, 53.7% of which were used in rural areas. Meanwhile, the rate of minibus accidents has been rising annually, often causing serious casualties.[1] Based on the Communications in Computer and Information Science database, Pattimore et al[2] studied the type and region of the lower limb injuries of 2080 occupants who were bounded in the front-seat in 1991. The study revealed that, of the lower limb injuries, 76.5% was located below the knee area, and 92% was located in the thigh region. Recently, Li et al[3] conducted data collection and in-depth investigation of minibus head-on collision accidents in China and found that thigh injuries were involved in a large proportion of minibuses rear-end truck collisions. To clarify the mechanisms of the driver's lower limb injury, we constructed a finite element (FE) simulation model to analyze the injury mechanisms and the vehicle dynamic response process.

Materials and methods

In this study, a seat belt system was further built on a pre-built minibus FE model that has been verified by a real vehicle collision

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test using the HyperMesh software. Thereafter it was integrated with the total human model for safety (THUMS) provided by Toyota Motor Corporation to establish a complete minibus occupant restraint system. A real car crash test to the minibus has been conducted previously,[4] the results of which showed that the vehicle deformation mode, impact force, and B pillar acceleration[5] were highly consistent with the FE simulation results. Besides, the hourglass can be controlled below 5% of the total energy. These findings verify that FE model and numerical simulation are effective. On this basis, we reconstructed the rear-end collision between a minibus and a truck and the head-on collision of a minibus to a rigid wall under the same boundary condition and load. The simulations were calculated by LS-DYNA ls971s R5.1.1 with the hardware being a HP-Z820 workstation and the operating system being Windows7 X64.

A real case

In 2015, a minibus rear-ended a truck in the Chongqing Expressway section, in which the minibus driver died (Fig. 1). According to the autopsy report, the driver's lower limbs had open laceration with irregular wound edge and visible subcutaneous & muscle tissue. Epidermal exfoliation and subcutaneous hemorrhage were observed in the upper section of the left thigh at which fracture was palpable. These symptoms were more severe at the left interior knee joint and multiple fractures were found in the lower limbs. According to the appraisal report provided by an accident forensic center in Chongqing, when the accident occurred, the speed of the minibus was 56 km/h.

FE model of the occupant restraint system

Driver FE model

The selected driver model was the THUMS (version 4.0, seating posture) FE model, which was jointly developed, designed, and verified by the Toyota Motor Corporation and the Toyota Technical Center (Japan).[6] The element quantity of this FE model was more than two million, and the definitions of its materials and properties met the basic need of crash regulations. We adjusted the model's position to ensure that the model was placed on the seat accurately and ideally.

Fig. 1. Image of the traffic accident scene.

Seat belt FE model

The minibus has no airbags, so the seat belt is the most important occupant restraint system. Seat belt has 4 main types: shoulder belt, lap belt, three-point and four-point seat belts. We built a three-point seat belt model by using the Primer software. The model consisted of 324 elements and 396 nodes, including a retractor, a slipring, a webbing (500 mm wide and 1.2 mm thick),[7] a buckle, and other components. The retractor contains a pre-tightening device and a force-limiting device. The belt can effectively simulate its sliding on the driver's body surface during collision.[8]

Full vehicle FE model

The minibus model was provided by an automobile manufacturing company in Chongqing, China, which includes the car body, windshield, seating systems, steering systems, instrument panels, pedals, etc. It was modeled with 727,826 elements. The materials and properties met the basic need of crash regulations. In addition, the dynamic characteristic was successfully verified through head-on collision experiments. The truck model was downloaded from the US national crash analysis center, which included 36,539 elements. The cargo floor is 110 cm from the ground and the bottom of the back anticollision barrier is 60 cm from the ground, highly consistent with the real accident vehicle.

Setting of contacts

During collisions, a lot of contacts occur between road and vehicle, between vehicles, and between vehicle and driver. The contact type between THUMS model and components in the vehicle can be defined as Automatic-Surface-To-Surface. The ground was simplified as a rigid wall since it was not deformed.[7] The road property of the real crash described above was asphalt, so the friction coefficient between the road and the vehicle was set as 0.70, that between the human and the vehicle was 0.65, and between the minibus and the truck was 0.6.[9]

Boundary condition and load

The truck did not move obviously in the real crash. Thus, the translation and rotation in the directions of X, Y and Z were strictly limited. The acceleration of gravity imposed on the vehicles and THUMS models was 9.8 m/s^2. In the two simulated collisions, the impact velocities were set at 56 km/h. Fig. 2 shows the rear-end collision between the minibus and the truck (Fig. 2A) and the head-on collision of the minibus to the rigid wall (Fig. 2B).

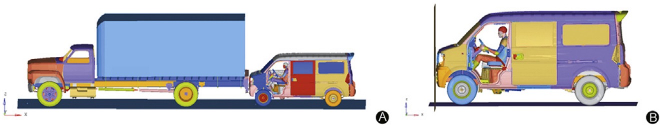

Fig. 2. Two collision models. A: The rear-end collision between the minibus and the truck. B: The head-on collision of the minibus to the rigid wall.

Results

Vehicle dynamic response

Fig. 3 shows the dynamic response process of the rear-end collision between the minibus and the truck. At 9 ms, the front of the minibus began to contact the truck tail and the seat belt began exerting pre-tightening effect on the driver. At 45 ms, the driver's lower extremity started to contact the dashboard. At 63 ms, the

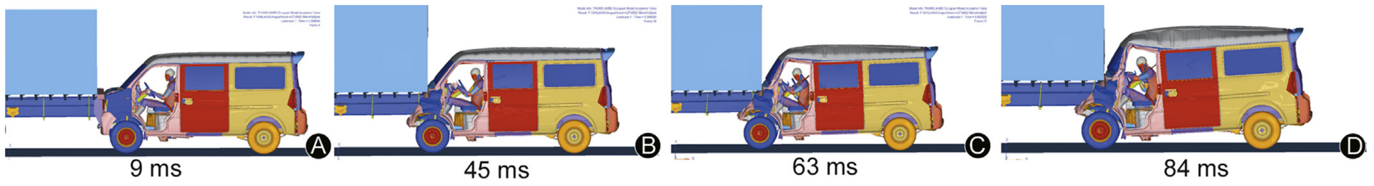

Fig. 3. Rear-end collision between the minibus and the truck.

contact force between the lower extremity and the dashboard reached the maximum. The front of the minibus was severely deformed. At 84 ms, the driver leant forward to the farthest and then began to bounce back. Meanwhile, the body of the minibus was deformed seriously. The simulation results of the deformation were coincident with that in the real crash described above.

Fig. 4 shows the dynamic response process of the head-on collision of the minibus to the rigid wall. At 9 ms, the front of the minibus began to touch the rigid wall, and the seat belt began exerting a pre-tightening effect on the driver. At 33 ms, the driver's lower extremity started contacting the dashboard. At 51 ms, the contact force between the lower extremity and the dashboard peaked along with obvious deformation of the front of the minibus. At 72 ms, the driver leant forward to the farthest and then began to bounce back; at the same time, the car tail reached the highest point.

Driver's lower extremity injuries

Fig. 5 shows the status of the femur, tibia, fibula, patella in two collisions when the von Mises equivalent stress at each region reached the maximum value. In the rear-end collision, the von Mises equivalent stress at the femur, tibia, fibula, and patella reached the peak at 63 ms (126 Mpa), 63 ms (133 Mpa), 48 ms (85 Mpa), and 69 ms (73 Mpa) respectively (5A, 5C, 5E, 5G). While the corresponding data in the head-on collision were 39 ms (99 Mpa), 30 ms (139 Mpa), 33 ms (126 Mpa), and 51 ms (101 Mpa) respectively (5B, 5D, 5F, 5H).

Discussion

In car accidents, the lower limbs are prone to injury. In a head-on collision, the speed of the vehicle is reduced sharply, so the

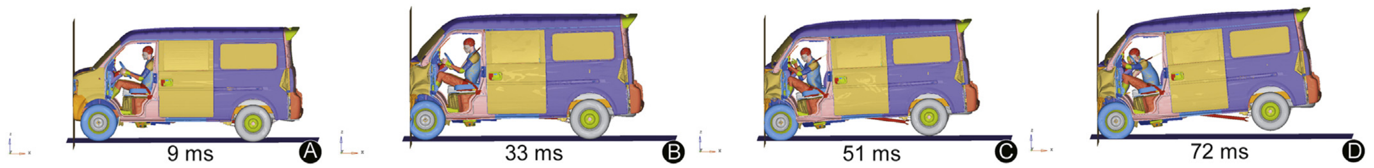

Fig. 4. Head-on collision of the minibus to the rigid wall.

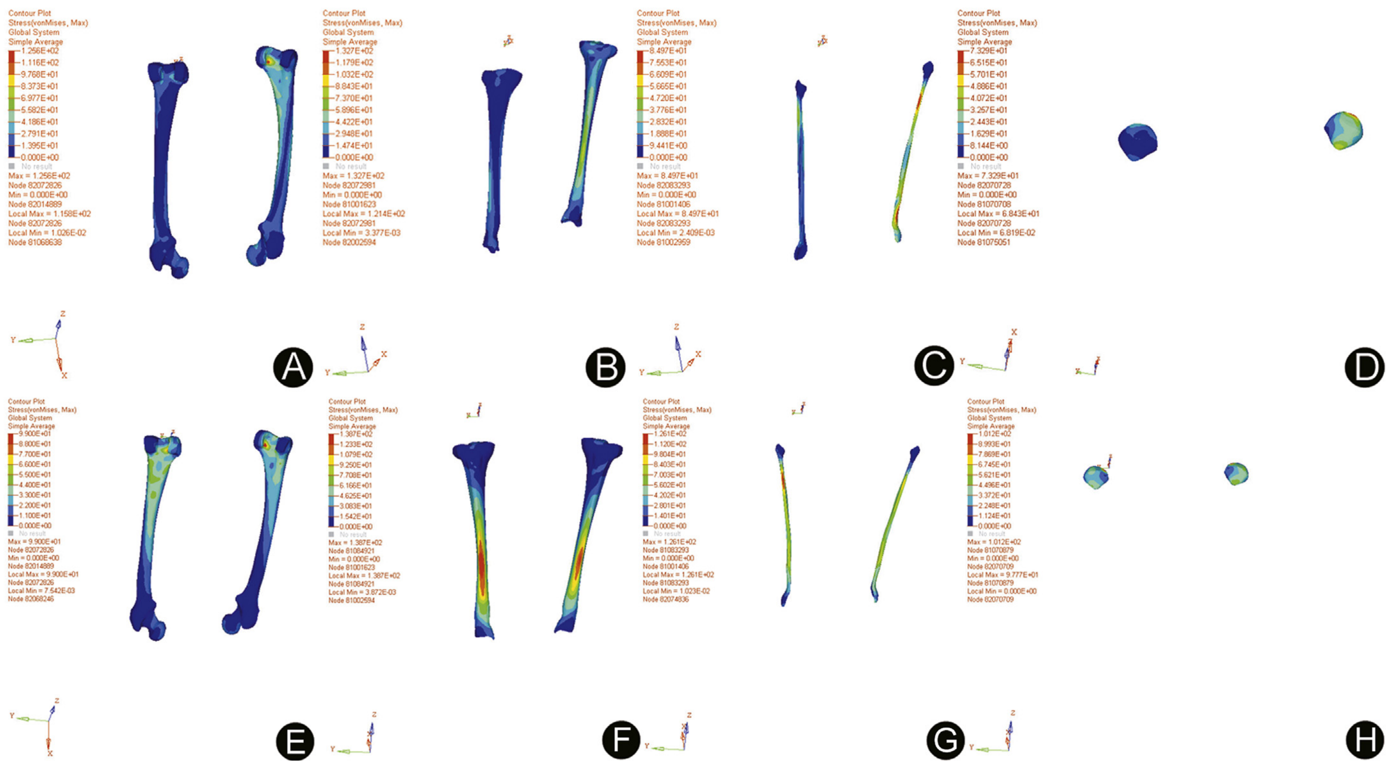

Fig. 5. von Mises peak stress cloud of the two collisions.

Table 1
von Mises peak stress on different parts under two collisions.

Collision	Peak von Mises equivalent stress							
	Femur		Tibia		Fibula		Patella	
	Time (ms)	Value (Mpa)	Time (ms)	Value (Mpa)	Time (ms)	Value (Mpa)	Time (ms)	Value (Mpa)
Rear-end	63	126	63	133	48	85	69	73
Head-on	39	99	30	139	33	126	51	101

occupants will easily lean forward due to inertia effect. When the lower limbs begin to contact with the dashboard, they suffer a great impact. The femur injury was mainly caused by axial compressive stress and bending stress at the bone end, whereas the tibia and fibula injuries were mainly due to the shear stress directly through the collision between the lower limbs and the dashboard and the axial force passed from the foot. The patella is located in the thigh and leg joints and mainly injured by its impact on the dashboard. Thus, this paper analyzed the differences between the two collisions in terms of femur, tibia, fibula, and patella injuries.

In 1976, Burstein[10] et al found that the yield strength of the femur ranges within 104–120 Mpa. In 2002, MizunodK[11] et al discovered that the failure stress of the tibia and the fibula is in the range of 100–125 Mpa. However, in the minibus rear-end truck condition, the driver's von Mises equivalent stress of both the femur and the tibia exceeded the yield stress range. Consequently, the femur and the tibia had a high risk of fracture, which coincided with the autopsy reports showing multiple fractures in the lower limbs. The results reveal that FE simulation method can effectively predict the risk of lower limb injuries in vehicle collisions. Table 1 shows a more intuitive comparison of the two conditions in various parts of the von Mises equivalent stress.

As shown in Table 1, the peak values of the von Mises equivalent stress at the tibia, fibula and patella in the rear-end collision were lower than those in the head-on collision; while the peak stress at the femur was higher by 27 Mpa. The maximum tibial von Mises equivalent stress at two collisions were similar (133 MPa and 139 MPa), both exceeding the failure stress range of 100–125 MPa. To further compare the two collisions, we analyzed the vehicle deceleration and the intrusion of the dashboard. Fig. 6 shows the vehicle deceleration curves of two collisions. We can see that the curve for the rear-end collision was more flat, with a slower and smaller peak value of acceleration.

Analysis of the dynamic process of the vehicle reveals that in the rear-end collision, the engine compartment is the main energy-absorbing part. Given that the structural strength of the engine compartment parts is lower than that of the front bumper and the frontal longitudinal beam, the deformation of the engine compartment may become larger and the duration may become longer. Consequently, the maximum value of the vehicle deceleration is reduced, which is the reason why the maximum von Mises equivalent stresses of the tibia, fibula and patella are smaller in the rear-end collision.

In the head-on collision, the volume of the intrusion of the dashboard reduces the driver's leg space, thereby increasing the lower limb injuries. In this article, two points were chosen to measure the leg space changes of minibus driver: a point on the dashboard that faces the driver's left leg and another point on the middle of the front edge of the driver's seat. After collision simulation, the change curve of the distance between these two points in the X direction could be obtained, as shown in Fig. 7.

At the beginning of the collisions, the driver's leg space was 303.42 mm. In the rear-end collision, the leg space in X direction minimized to 112.37 mm at 90 ms. Therefore, the maximum distance of deformation was 191.05 mm. In the head-on collision, the minimum distance between the driver's legs in X direction was 226.79 mm, obtained at 51 ms, whereas the maximum distance of deformation was 76.63 mm. This means that in the rear-end collision, the dashboard intrusion was 114.42 mm larger than that in the head-on collision. Such a large amount of invasion reduced the driver's sliding distance on the seat. When the driver's lower limbs contacted the dashboard, the seat belt's restraining forces on the human body was reduced. As the main connection between the calf and the torso, the femur will withstand greater force to prevent the torso from moving forward. Thus, the lager the intrusion of the dashboard is, the greater the risk of femur injury will be.

In the rear-end collision, cargo floor and back anticollision barrier of the tuck were high, causing the main energy-absorbing parts of the minibus to be located at higher positions. These parts typically consisted of the engine hood, the engine compartment, the A-

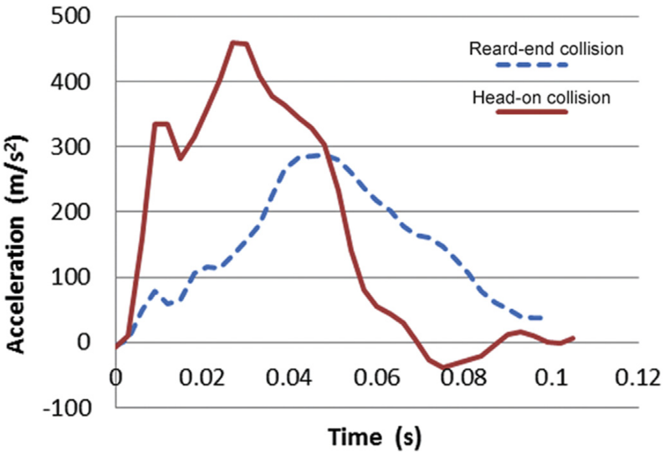

Fig. 6. Vehicle deceleration curves of two collisions.

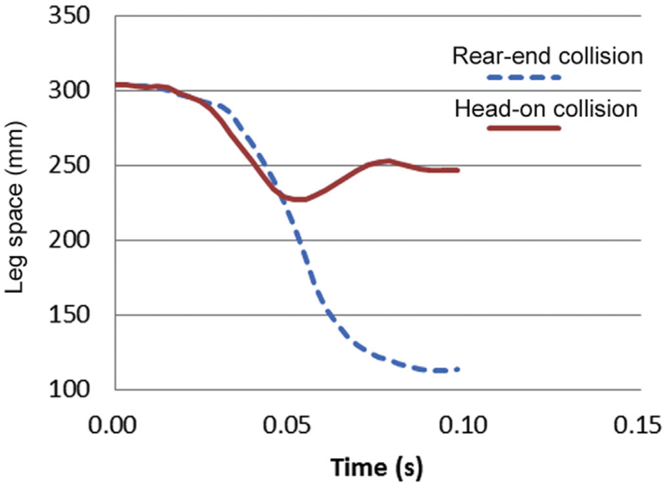

Fig. 7. Leg space in the X direction.

pillar, and so on. Given that the structural strength of these parts is much lower than that of the front bumper and the frontal longitudinal beam, the dashboard intrusion was greatly increased. The excessive intrusion of the dashboard is the main cause of the driver's femur injuries. Therefore, reducing the height and built-in distance of back anticollision barrier of the truck, along with increasing the structural strength of the engine compartment and A-pillar of the minibus are useful in protecting the driver's limb from injuries. Another effective approach is to install a high bumper at the front of the minibus. In the two collisions, both the maximum von Mises equivalent stress of the tibia exceeded the failure stress range, indicating that the driver had a high risk of tibia fracture in the minibus frontal collisions at a speed of no less than 56 km/h.

FE simulation technology is playing an increasingly important role in the reconstruction of traffic accidents. It has become a primary method for scholars to explore the biomechanical mechanism of traffic injuries and to conduct related investigations. Moreover, this approach presents strong advantages in the exploration of vehicle safety. Different from the traditional crash simulation method that is to load vehicle B pillar deceleration for the dummy, the minibus and the driver FE model were loaded at the same initial speed in this study to create a more real scenario.

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