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Research on the Driver Neck Movement and Injury in the Late Stage of Frontal Collision

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Abstract: The aim of this study is to investigate the driver's neck movement and injuries in the late stage of frontal collision. Firstly, the simulation model of the driver restraint system was developed and validated. Secondly, the design parameters of airbag and safety belt were optimized globally in the early stage of frontal collision. Finally, the driver's neck movement state and the effects of the design parameters of driver seat on the neck injuries in the late stage of frontal collision were studied. The movement state of the driver's upper and lower neck could be divided into three phases, and the peak extension bending moments of the upper and lower neck all occur in the second phase. By reducing the headrest stiffness and the upper seatback stiffness of driver seat, the rotational stiffness of the seatback recliner of driver seat, the upper and lower neck injuries can be decreased significantly.

Keywords: frontal collision; injury; late stage; movement; neck

1 INTRODUCTION

Researches on the neck damage in the automotive traffic accident mainly focused on the influence of the design parameters of the diver seat on the whiplash injuries of the driver's neck in the rear collision.

Most researchers agree that the whiplash injuries are related to the relative motion between the head and torso, and that the reduction of this relative motion would lead to a decrease in the incidence of these injuries. Further, it has been shown that the relative motion between the head and neck was greatly affected by seat design, and in particular by the position of the headrest relative to the head. Headrest height and backset (horizontal distance between the head and headrest) were the two seat design parameters most commonly used to evaluate the response of a driver to a rear collision [1].

Automotive seats are rated as good, acceptable, marginal and poor on their abilities to prevent the whiplash injuries in the rear collision based on the headrest height and backset. Mang et al. [2] compared the performance of some good-rated and poor-rated seats. The results showed that the differences between the good-rated and poor-rated seats were very obvious in the upper neck loads and moments for the collision speed changes greater than 6 km/h.

Romilly and Skipper [3] studied the influence of the headrest stiffness and seatback recliner rotational stiffness on the neck injury criterion (NIC) and neck displacement criterion (NDC). The results indicated that the larger headrest stiffness resulted in the decrease of NIC and NDC, and the smaller recliner rotational stiffness resulted in the increase of NDC.

Xiao and Yang [4] found that increasing the seatback stiffness could slightly increase the maximum head-torso displacement, however, a stiffer lower seatback combined with a softer upper seatback led to a clear reduction of the head-torso displacement to radically improve the neck protection in the rear collision.

Jo and Kim [5] pointed out that a proper stiffness combination of the headrest, upper seatback and lower seatback could reduce the whiplash injuries significantly.

Radu et al [6] investigated the effect of the recliner rotational stiffness of the seatback on the head and neck response. The softer seat's rigidity would reduce the head's acceleration and the whiplash injuries due to the increase of the angular displacement of the seatback, resulting in the more absorption of collision energy.

Jin et al. [7] considered a series of different parameter combinations between the headrest and seatback recliner, and their influence on the whiplash injuries. The results demonstrated that as the headrest was near to the head and it was high, a large recliner rotational stiffness shall be applied; as the headrest stiffness and its rotational stiffness were large, a large recliner rotational stiffness shall be applied; contrarily, a small recliner rotational stiffness shall be applied. Both match manners may decrease the probability of neck injuries.

Zhang et al [8] investigated the overall performance of an energy-absorbing sliding seat for the whiplash neck injury prevention. The sliding seat's seat pan can slide backward under the certain restraint force in order to absorb the crash energy in the rear impact. The effects of headrest position and stiffness, seatback stiffness, recliner characteristics and sliding energy-absorbing restraint force on the neck injury criteria were analysed. The sliding seat with the appropriate restraint forces can significantly lower the neck injury risk in the rear impact with no negative effects on the other crash load cases.

Mansour and Romilly [9] created the simulation model using the LS-DYNA to determine whether the addition of energy-absorbing foam to the seat base acts to reduce the risk of neck injury resulting from a rear collision.The results showed that the foam can absorb the collision energy transmitted to the driver's body, and the stress vs volumetric strain curve, length and cross-sectional area of the foam can affect the degree of neck injury.

In the rear collision, the movement process of the driver could be divided into the following two stages.

The first stage: from the moment when the driver's back begins to contact with the seatback under the action of the collision inertia force to the moment when the driver's torso begins to bounce forward under the action of the anti-elastic force of the headrest and the seatback. After the driver's back contacts with the seatback, the driver's head contacts with the headrest subsequently.

The second stage: from the moment when the driver's torso bounces forward to the end of the rear collision. After the driver's torso bounces forward, the safety belt places a restraint on the driver.

In the frontal collision, the movement process of the driver could be divided into the following three stages.

The first stage: from the moment when the driver begins to move forward under the action of the collision inertia force to the moment when the driver's back begins to contact with the seatback after the driver makes a backward resetting movement under the action of the anti-elastic force of the airbag and the restraint force of the safety belt.

The second stage: from the moment when the driver's back contacts with the seatback to the moment when the driver's torso begins to bounce forward under the action of the anti-elastic force of the headrest and the seatback. After the driver's back contacts with the seatback, the driver's head contacts with the headrest subsequently.

The third stage: from the moment when the driver's torso bounces forward to the end of the frontal collision. After the driver's torso bounces forward, the safety belt places a secondary restraint on the driver.

In this paper, the first stage of the driver movement in the frontal collision is defined as the early stage of the frontal collision, and both the second and the third stage are defined as the late stage of the frontal collision.

The driver movement process in the late stage of the frontal collision is similar to the driver movement process in the rear collision. Therefore, it is necessary to study the driver's neck movement and the effects of the design parameters of the driver seat on the neck injuries in the late stage of the frontal collision.

The study in the paper was divided into the following three steps.

Firstly, the simulation model of the driver restraint system was developed through MADYMO software and validated by the 50 km/h frontal collision test.

Secondly, the design parameters of airbag and safety belt were optimized globally in the early stage of the frontal collision, in order that the whole injury criterion *WIC* of the driver was minimized.

Finally, after the whole injury criterion *WIC* of the driver in the early stage of the frontal collision was minimized, the movement state of the driver's upper neck and lower neck in the late stage of the frontal collision was studied, and the effects of the design parameters of the driver seat on the driver's neck injuries in the late stage of the frontal collision were analysed.

2 MATERIALS AND METHODS

2.1 Model Development and Validation

Computer models have been widely used in the automobile research and industry. Firstly, the 3D geometry model of a driver seat was established by UG software (Siemens PLM Software, Plano, TX), and then the 3D model was converted into a finite element (FE) model in Hypermesh software (Altair, Troy, MI), the FE model was shown in Fig. 1, the driver seat included the headrest, upper seatback, lower seatback and cushion. Finally, the simulation model of the driver restraint system was developed based on a vehicle model in MADYMO software (TNO, Rijswijk, The Netherlands).

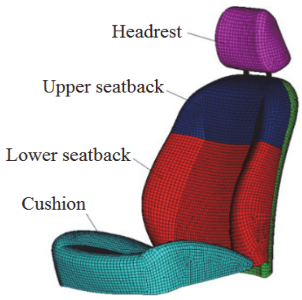
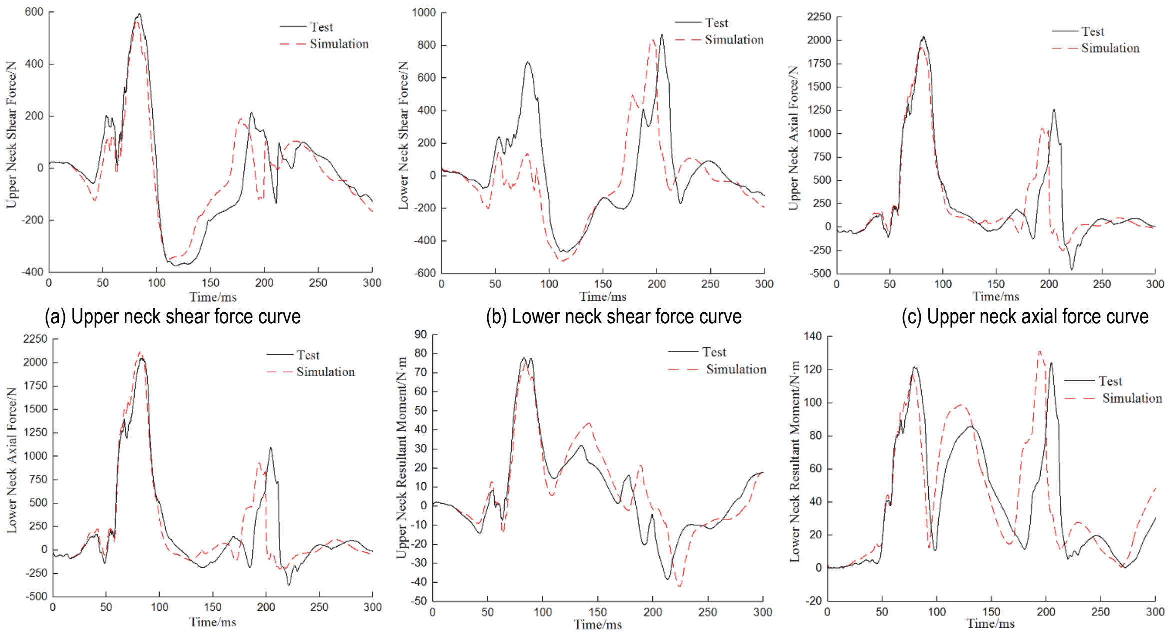


Figure 1 Driver seat FE model



(a) Upper neck shear force curve (b) Lower neck shear force curve (c) Upper neck axial force curve

(d) Lower neck axial force curve (e) Upper neck resultant moment curve (f) Lower neck resultant moment curve

Figure 2 The comparison of test and simulation curves

The developed simulation model consisted of the above driver seat, the floor, the panel, the windshield, the steering wheel, the airbag, the three-point safety belt, the Hybrid III 50th percentile male dummy which was used to simulate the driver, and so on. In addition, the acceleration field, the contact surfaces and the other features were applied in the simulation model. In the model, the vent leakage coefficient and the fabric permeability of the airbag are 2,0 and 0,01 respectively, the webbing elongation of the safety belt is 13%, and the inflator mass-flow rate curve of the airbag is shown in Fig. 3.

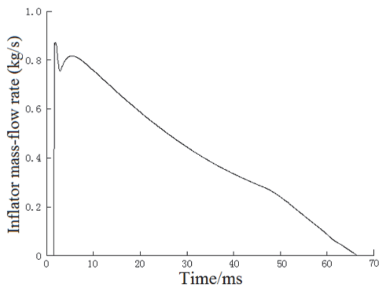


Figure 3 Inflator mass-flow rate curve

The computer simulation cannot substitute the actual car collision test completely, therefore the simulation model must be verified for its reliability on the basis of the 50km/h frontal collision test performed previously.

Fig. 2 shows the comparison between the dummy injury curves in the test and the dummy model injury curves in the simulation. It is shown that the simulation curves are basically consistent with the test curves, therefore the simulation model can reflect the actual collision test on the whole.

2.2 Optimization Method and Boundary Conditions

As the design parameters of airbag and safety belt were the key components of the driver restraint system, the vent leakage coefficient of the airbag, the inflator mass-flow rate of the airbag, the fabric permeability of the airbag, the webbing elongation of the safety belt were selected to optimize globally using the whole injury criterion *WIC* [10-11] which is defined in Eq. (1) as the optimization goal by the response surface optimization design software Design Expert, so that it minimized the driver injuries in the early stage of the frontal collision.

$$WIC = 0.6\left(\frac{HIC36}{1000}\right) + \frac{0.35\left(\frac{C3ms}{600} + \frac{D}{76.2}\right)}{2} + \frac{0.05\left(F_{\text{left}} + F_{\text{right}}\right)}{20000} \quad (1)$$

where *HIC36* is head injury criterion, which is defined in Eq. (2); *C3ms* is the 3ms resultant acceleration of chest, m/s^2; *D* is the peak chest deflection, mm; F_{left}, F_{right} are the peak force of left and right femur respectively, N.

$$HIC36 = \max\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)\,\mathrm{d}t\right]^{2.5} (t_2 - t_1) \quad (2)$$

Value ranges of the design parameters of airbag and safety belt were described as follow:

① The vent leakage coefficient: 1,0 – 3,0;
② The inflator mass-flow rate: decline and rise by 20% along the *y* - axis direction relative to the original curve which was shown in Fig. 3;
③ The fabric permeability coefficient: 0,01 – 0,05；
④ The webbing elongation: 9% - 15%.

Based on the high performance limits for the driver's neck injuries of the frontal collision in 2018 C-NCAP (China New Car Assessment Program), the peak anterior shear force of upper neck F_1, the peak axial tension force of upper neck F_2, the peak extension bending moment of upper neck M_{upper} were selected as the boundary parameters, and M_{upper}, F_1, F_2 should be less than 42 Nm, 1900 kN, 2700 kN respectively.

2.3 Neck Injury Analysis

After minimizing the *WIC* of the driver in the early stage of the frontal collision, ① the moment-time curves of the driver's upper and lower neck in the frontal collision were analysed to investigate the movement state of the upper and lower neck in the late stage of the frontal collision; ② the effects of the headrest stiffness, the upper seatback stiffness and the lower seatback stiffness of the driver seat, the rotational stiffness of the seatback recliner of the driver seat on M_{upper} (the peak extension bending moment of upper neck), M_{lower} (the peak extension bending moment of lower neck) and the neck injury indicators N_{km}, N_{ij} which are defined in Eq. (3) and Eq. (4) respectively in the late stage of the frontal collision were studied. Value ranges of all the above four design parameters of the driver seat: decrease by 10%, 20% 30% relative to the original value (OV), the original value (OV), increase by 10%, 20% 30% relative to the original value (OV).

$$N_{km} = \frac{F_x}{F_{xc}} + \frac{M_y}{M_{yc}} \quad (3)$$

where F_x and M_y are the shear force and sagittal bending moment of the upper neck, respectively. F_{xc} and M_{yc} are the corresponding critical shear force and bending moment reference values, respectively.

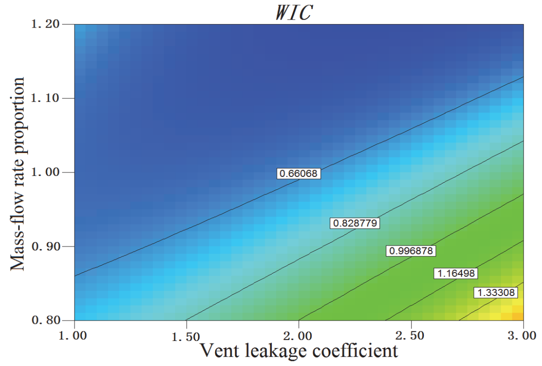
$$N_{ij} = \frac{F_z}{F_{int}} + \frac{M_y}{M_{int}} \quad (4)$$

where F_z and M_y are the axial force and sagittal bending moment of the upper neck, respectively. F_{int} and M_{int} is the corresponding critical axial force and bending moment reference values, respectively.

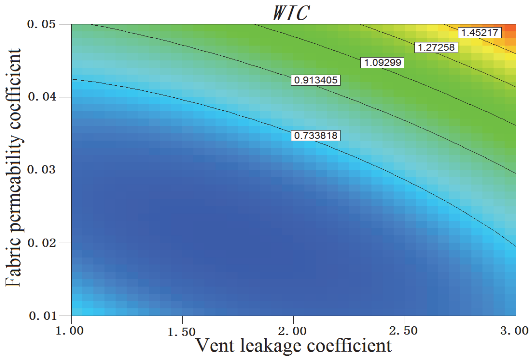
3 RESULTS

3.1 Optimization of the Driver Restraint System

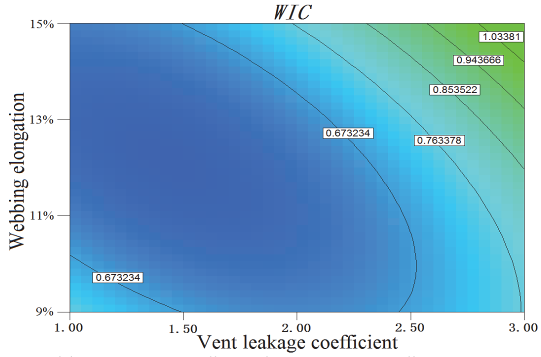
The results of response surface analysis are shown in Fig. 4. Fig. 4 indicates as the vent leakage coefficient, the fabric permeability coefficient and the webbing elongation increases gradually, *WIC* drops gradually; as the inflator mass-flow rate increases gradually, *WIC* rises gradually; and the most significant parameter affecting *WIC* is the fabric permeability coefficient, followed by the inflator mass-flow rate, and then the vent leakage coefficient, while the influence of the webbing elongation is minimal. The optimal parameter combination minimizing *WIC* is as follows: the fabric permeability coefficient is 0.01, the inflator mass-flow rate curve rises by 18% along the *y* - axis direction relative to the original curve, the vent leakage coefficient is 2,75; the webbing elongation is 13%. The protective effects of the optimized restraint system on the driver are shown in Tab. 1.



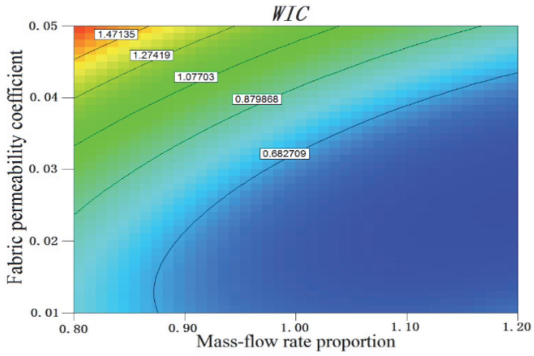
(a) The combined effects of vent leakage coefficient and mass-flow rate on *WIC*



(b) The combined effects of vent leakage coefficient and fabric permeability coefficient on *WIC*



(c) The combined effects of vent leakage coefficient and webbing elongation on *WIC*



(d) The combined effects of mass-flow rate and fabric permeability coefficient on *WIC*

Figure 4 Response surface analysis

Table 1 The contrast of driver injuries before optimization and after optimization

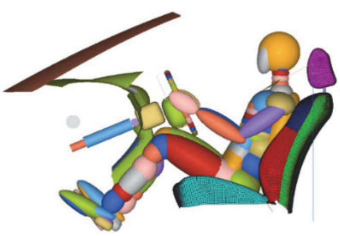
Injury	Before optimization	After optimization	Rate of change
WIC	0,5392	0,4632	−14,09%
HIC36	540,95	437,29	−19,16%
C3ms/ / m/s^2	437,25	401,98	−8,07%
D / mm	31,71	30,68	−3,25%
F_1 / N	594,94	519,95	−12,60%
F_2 / N	2049,43	1735,42	−15,32%
F_{left} / N	2720,43	2638,28	−3,02%
F_{right} / N	2970,66	2711,44	−8,73%

Compared with before optimization, the head injury criterion *HIC36*, the peak anterior shear force of upper neck F_1, the peak axial tension force of upper neck F_2 of the driver drop by 19,16%; 12,60%; 15,32% respectively, and *WIC* declines from 0,5392 to 0,4632, drops by 14,09%; and the other injury criteria also show a downwards trend.

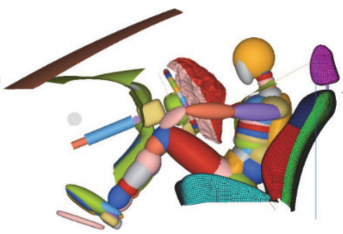
3.2 Studies on the Driver's Neck Movement and Injury

3.2.1 Analysis on the Movement State of Driver's Neck

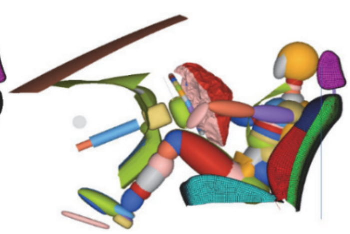
In the model which minimized the whole injury criterion *WIC* of the driver in the early stage of the frontal collision, the simulation animation of the driver movement is shown in Fig. 5, and the moment-time curves of the driver's upper and lower neck around the Y-axis are shown in Fig. 6 and Fig. 7 respectively.



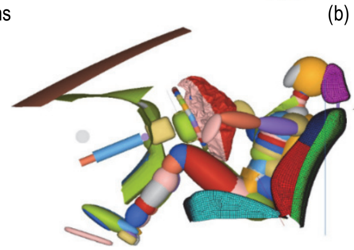
(a) 0 ms



(b) 175 ms



(c) 205 ms



(d) 220 ms

(e) 275 ms

Figure 5 The driver movement animation

According to Fig. 5, Fig. 6 and Fig. 7, the movement state of the driver's upper and lower neck in the late stage of the frontal collision may be divided into the following three phase:

1) From 175 ms to 205 ms: from the moment when the driver's back begins to contact with the seatback to the moment when the driver's head begins to contact with the headrest. Between 185 ms and 205 ms, the upper neck moment is positive, while the lower neck moment is negative, which indicates the upper neck is in the forward flexion state, while the lower neck is in the backward extension state.

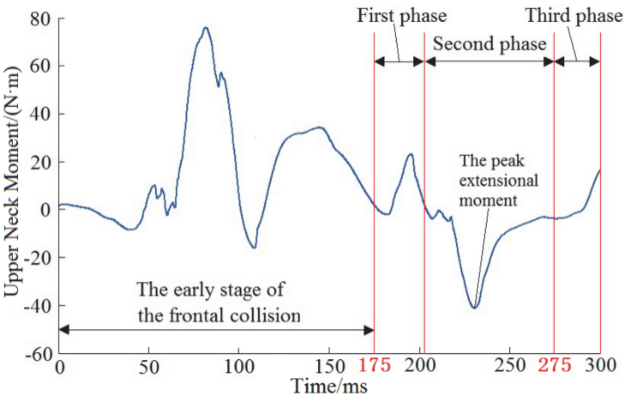


Figure 6 The upper neck moment-time curve

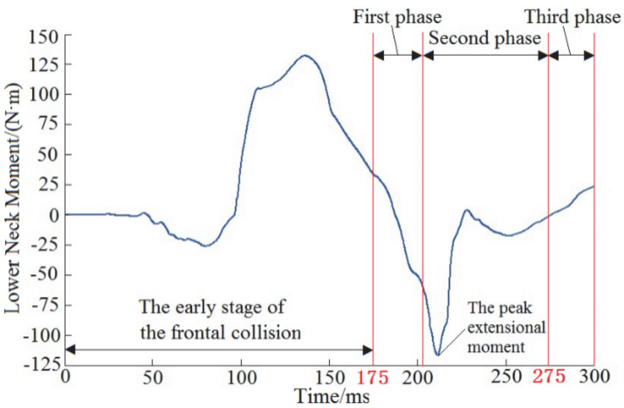


Figure 7 The lower neck moment-time curve

2) From 205 ms to 275 ms: from the moment when the driver's head contacts with the headrest to the moment when the driver's head begins to rotate forward relative to the chest. Under the action of the headrest rebound force, the centroid of the driver's head begins to move forward horizontally relative to the headrest at 220 ms, but at the time, the head is still rotatig backward relative to the chest, then the chest rebounds forward relative to the seatback. In the phase, the upper neck moment and the lower neck moment are negative, so the upper neck movement state transforms from the forward flexion between 185 ms and 205 ms to the backward extension between 205 ms and 275 ms, and the lower neck movement state still keeps the backward extension. In addition, M_{upper}, M_{lower} occur in 230 ms and 210 ms separately.

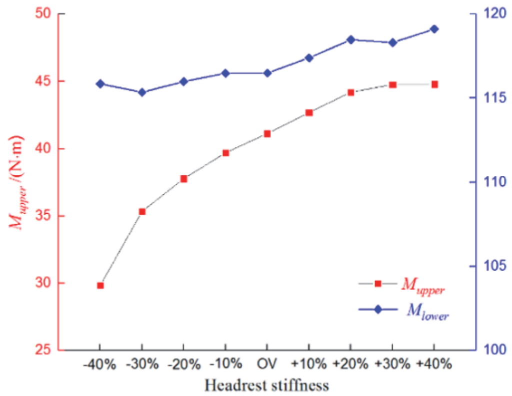
3) From 275 ms to 300 ms: at 275 ms, the driver's head begins to rotate forward relative to the chest. In the phase, the lower neck moment is positive, and the lower neck is in the forward flexion state. Between 275 ms and 290 ms, the upper neck moment is negative, and the upper neck is in the backward extension state. Between 290 ms and 300 ms, the upper neck moment is positive, and the upper neck is in the forward flexion state.

3.2.2 Analysis on the Design Parameters of Driver Seat

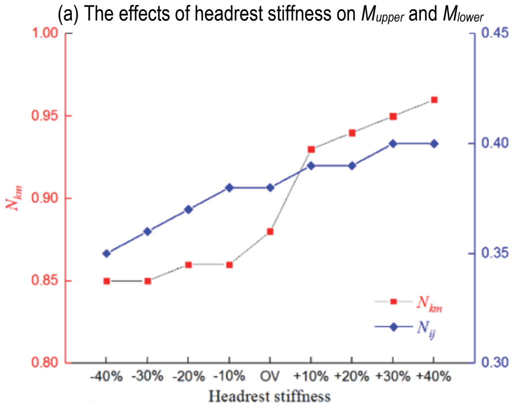
In the model which minimized *WIC* of the driver in the early stage of the frontal collision, the effects of the headrest stiffness, the upper seatback stiffness and the lower seatback stiffness of the driver seat, the rotational stiffness of the seatback recliner of the driver seat on M_{upper}, M_{lower}, N_{km} and N_{ij} in the late stage of the frontal collision were analysed.

(1) Headrest Stiffness.

The headrest stiffness determines the energy absorption capacity of the headrest. The effects of headrest stiffness on M_{upper}, M_{lower}, N_{km} andN_{ij} are presented in Fig. 8, which indicates M_{upper}, N_{km} and N_{ij} have a downward trend, but M_{lower} changes a little with the reduction of the headrest stiffness. As the headrest stiffness reduces by 60% relative to the original stiffness, M_{upper}, N_{km} *and* N_{ij} drop by 27,52%; 3,41% and 7,89% separately.



(a) The effects of headrest stiffness on M_{upper} and M_{lower}



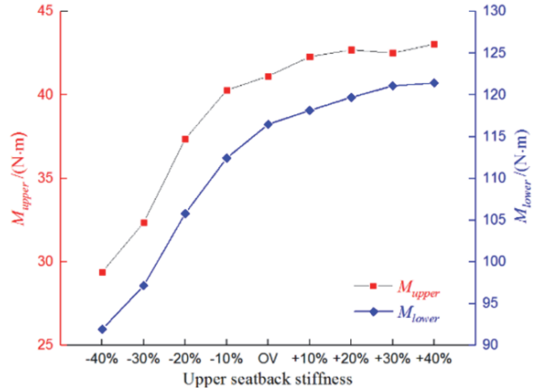
(b) The effects of headrest stiffness on N_{km} and N_{ij}

Figure 8 The effects of the headrest stiffness on the driver's neck injuries

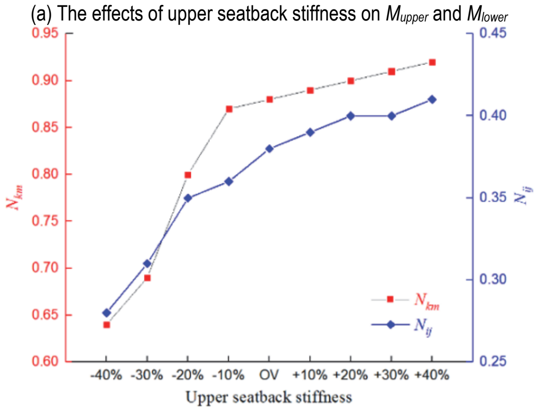
As the headrest stiffness decreases, the energy absorption capacity of the headrest enhances, which reduces the forward rebound velocity of the driver's head centroid to mitigate the degree of the backward extension movement of the upper neck, causing M_{upper}, N_{km} and N_{ij} to cut down.The reason why M_{lower} changes a little is that the extension moment of lower neck is already very close to the peak value before the head is fully in contact with the headrest in the head backward movement process, so the effect of the headrest stiffness on M_{lower} may be negligible.

(2) Upper Seatback Stiffness.

The effects of the various upper seatback stiffness on M_{upper}, M_{lower}, N_{km} and N_{ij} are shown in Fig. 9. Fig. 9 shows as the upper seatback stiffness decreases gradually compared to the original stiffness, M_{upper}, M_{lower}, N_{km} and N_{ij} have a significant downward trend. When the upper seatback stiffness reduces by 60% compared to the original stiffness, M_{upper}, M_{lower}, N_{km} *and* N_{ij} drop by 28.54%; 21,07%; 27,27% and 26,32% separately. Reducing the upper seatback stiffness makes it easier for the chest to move backward in the backward movement process of the head and chest, mitigating the backward movement degree of the head relative to the chest to cause M_{lower} to decline. In the same way, the backward rotational angle of the head relative to the chest in the rebound process of the head and chest becomes smaller when the chest is in the posterior position before rebound, making M_{upper}, N_{km} and N_{ij} drop significantly.



(a) The effects of upper seatback stiffness on M_{upper} and M_{lower}



(b) The effects of upper seatback stiffness on N_{km} and N_{ij}

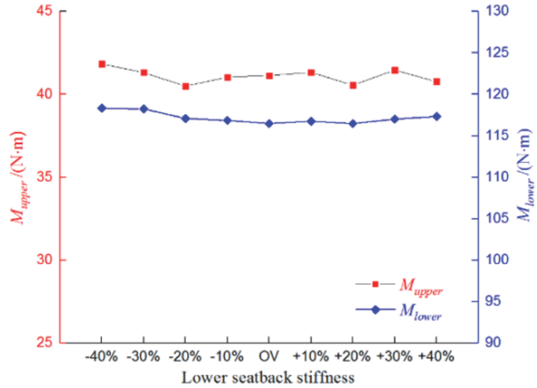
Figure 9 The effects of the upper seatback stiffness on the driver's neck injuries

(3) Lower Seatback Stiffness.

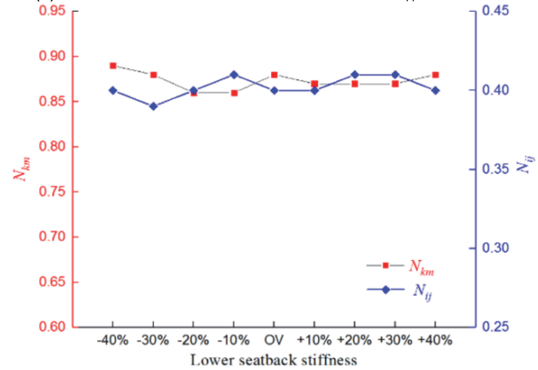
The change of the lower seatback stiffness has no obvious effect on M_{upper}, M_{lower}, N_{km} and N_{ij} of the driver as shown in Fig. 10.

(4) Seatback Recliner Rotational Stiffness.

As is shown in Fig. 11, M_{upper}, M_{lower}, N_{km} *and* N_{ij} decline significantly with the decrease of the recliner rotational stiffness of the seatback, and M_{upper}, M_{lower}, N_{km} *and* N_{ij} drop by 27,52%; 21,59%; 28,95% and 23,40% respectively when the recliner rotational stiffness reduces by 60% relative to the original stiffness. Reducing the recliner rotational stiffness enhances the backward rotation degree of the driver's torso after the back contacts with the seatback, which is conductive to cut down the backward movement of the head relative to the chest in the backward movement process of the head and chest to markedly decrease M_{lower} In the same way, although the torso excessive backward rotation delays the contact time between the head and the headrest, reduces the degree of the backward movement of the head relative to the chest in the torso rebound process, making M_{upper}, N_{km} and N_{ij} decline.

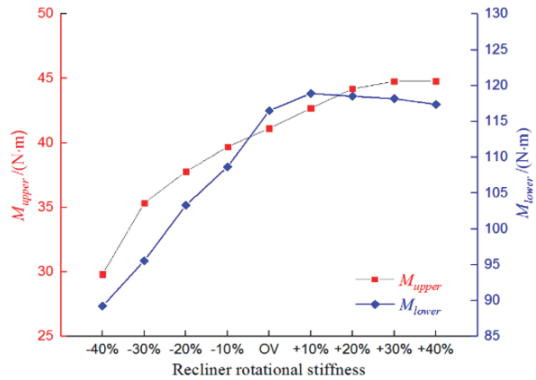


(a) The effects of lower seatback stiffness on M_{upper} and M_{lower}

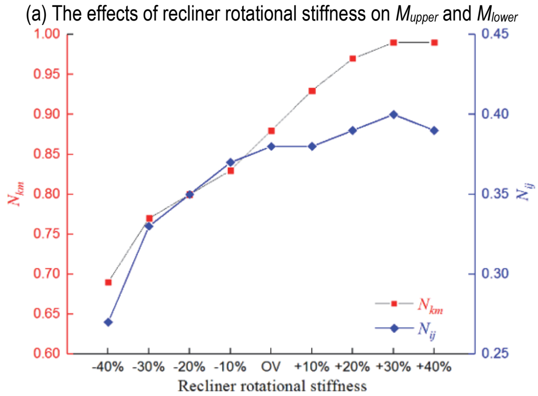


(b) The effects of lower seatback stiffness on N_{km} and N_{ij}

Figure 10 The effects of the lower seatback stiffness on the driver's neck injuries



(a) The effects of recliner rotational stiffness on M_{upper} and M_{lower}



(b) The effects of recliner rotational stiffness on N_{km} and N_{ij}

Figure 11 The effects of the recliner rotational stiffness on the driver's neck injuries

4 DISCUSSION

A number of research results concerning the driver's neck injuries in the low speed rear collision indicates the neck injuries would be decreased by increasing the headrest stiffness and the lower seatback stiffness, and by reducing the upper seatback stiffness and the recliner rotational stiffness of the seatback [12-16]. Differences of the driver's neck injuries between in the late stage of the frontal collision and in the low speed rear collision lie in the effects of the headrest stiffness on the neck injuries, which are opposite, and increasing the lower seatback stiffness can reduce the neck injuries in the low speed rear collision; however, the change of the lower seatback stiffness has no obvious effect on the neck injuries in the late stage of the frontal collision. Therefore, the future research should consider comprehensively the influences of the design parameters of the driver seat on the neck injuries in both the frontal and the rear collision, in order to reduce the neck injuries to an ideal range in two kinds of collisions.

5 CONCLUSIONS

The simulation model of the frontal collision was used to study the driver's neck movement and injuries in the late stage of the frontal collision after minimizing the whole injury criterion *WIC* of the driver in the early stage of the frontal collision.

The movement state of the driver's upper and lower neck could be divided into the three phases, and both M_{upper} and M_{lower} occur in the second phase. Parametric studies indicate that the headrest stiffness and the upper seatback stiffness of the driver seat, and the rotational stiffness of the seatback recliner of the driver seat have a significant effect on the driver's neck injuries. By reducing the headrest stiffness, the upper seatback stiffness and the recliner rotational stiffness, the neck injuries can be decreased significantly. The above results provide the guidance for the driver's neck protection in the late stage of the frontal collision.

In order to reduce the driver's neck injuries to an ideal range at the same time in both the late stage of the frontal collision and the rear collision, it is necessary to study comprehensively the influences of the design parameters of the driver seat on the neck injuries in both two kinds of collisions.

6 LIMITATIONS

(1) The movement state of the driver's head, neck, chest and abdomen in the early stage of the frontal collision has the direct influence on the movement state and injuries of the driver's upper neck and lower neck in the late stage of the frontal collision. When the driver moves forward under the inertial force in the early stage of the frontal collision, the head, neck, chest and abdomen of the driver restrained by the 3-point safety belt would be subjected to the bending moment around the x - axis, the y - axis and the z - axis as the 3-point safety belt is asymmetric. The driver movement process in the late stage of the frontal collision is similar to the driver movement process in the rear collision. Many studies used BioRIDII50th percentile male dummy model to investigate the driver'sneck injuries in the rear collision. In this study, the reasons of using Hybrid III 50th percentile male dummy model to investigate the movement state and injuries of the driver's upper neck and lower neck in the late stage of the frontal collision are followed as below: ① The head, neck, chest and abdomen of BioRIDII50th percentile male dummy model are connected by the revolute joints which can only rotate around the y - axis, the upper body of BioRIDII50th percentile male dummy model cannot generate the bending moment around the x - axis and the z - axis; ② The head, neck, chest and abdomen of Hybrid III 50th percentile male dummy model are connected by the spherical joints and free joints which can rotate around the x - axis, the y - axis and the z - axis, the upper body of Hybrid III 50th percentile male dummy model can generate the bending moment around the x - axis, the y - axis and the z - axis; ③ Hybrid III 50th percentile male dummy model is more suitable to simulate the movement state of the driver's head, neck, chest and abdomen in the early stage of the frontal collision than BioRIDII50th percentile male dummy model, and Hybrid III 50th percentile male dummy model can also simulate the driver movement in the rear collision.

(2) Only a test (the 50 km/h frontal collision test) was conducted to verify the reliability of the simulation model.

(3) Although Hybrid III 50th percentile male dummy model cannot generate N_{km} directly, N_{km} can be obtained by indirect calculation of the shear force and bending moment of the upper neck generated by Hybrid III 50th percentile male dummy model according to Eq. (3).

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