Effect of the Footwell Design Parameters on Driver Lower Extremity Injuries in Frontal Impacts and Countermeasures

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Abstract –Using safety belts and airbags in passenger car has greatly reduced injuries of thorax and head of drivers and passengers, but injury frequency of lower extremity has been a prominent problem today. By means of dynamic simulation of multi-body and finite element methods, investigate the influence of the footwell design parameter to driver lower extremity injuries in passenger car frontal impact to improve safety design of car to reduce injury risk of lower extremity. The paper proposed a couple of countermeasures to mitigate the severity of lower extremity injuries.
Keywords: frontal impact, lower extremity, injury prevention

1 Introduction

Lower extremity injuries are not necessarily life threatening, but very often cause considerable pain and frequently require long-term treatment and rehabilitation and they can even result in permanent disability, so we must work to mitigate these injuries and reduce the cost to society.

Nahum et al. examined the 1ower extremity injuries of 186 vehicle occupants involved in mostly front impact, they found that lower extremity injury increases as speed of impact increases, they said the mechanism of ankle/foot injury was twisting or bending at impact [1]. Thomas found that both footwell intrusion and brake pedal has great relationship with lower extremity injury, footwell intrusion increase the risk of leg injury separate from and to a greater extent than delta-V, intrusion is shown not to be a proxy variable for delta-V. The pedals increase the risk of leg injury by 54% when there is 20 cm of footwell intrusion [2]. Huelke et al. began the examination of lower extremity injuries in the National Accident Sampling System (NASS) files and found there is a reduction in the frequency of injury for belted occupants [3]. Dletmar Otte et al. proved it in their research [4]. D.Otte et al. found that 3/4 of all foot fracture are caused by footroom deformation, technical solution for that can only be found in a modified construction in geometry of the pedal system [5]. Niklas Hoglunde et al. studied the influence of frontal airbag on lower extremity injury; the percentage differences with and without airbag were calculated for each lower limb response in all combinations. They found that the average difference between all peak responses was 1.5%. However, for the most interesting responses, peak axial tibia forces, foot and ankle rotations and moments, the average was less than 1% [6]. That is to say, using frontal airbag cannot reduce lower extremity injuries.

2 Methods and Materials

Multi-body dynamics is the theory basis of MADYMO adopted by this research. Employ some design parameters, discuss the effect of these parameters to lower extremity injury, conclusions are made according to lower extremity correlative injury evaluation index.

2.1 Model description

Represents the driver side of a typical sedan for frontal collisions. It comprises of some key interior surfaces, a collapsible steering column system, a seat, a three-point belt system, an airbag,

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and a latest version of the facet Hybrid III 50th percentile dummy. The facet dummy is restrained with a shell finite element belt, which consists of triangular elements. Conventional belts are used to attach the FE shoulder and lap belts to the anchor points.

Real footwell picture and baseline model of simulation were shown in figure 1 and figure 2.

Fig.1 Footwell

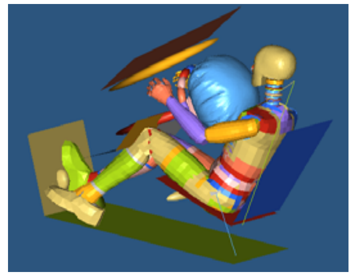


Fig.2 Baseline model

2.2 Variable parameters

Five variable parameters are adopted in this research, shown in table1:

Table.1 parameter variable in simulations

Variable	Value			
Loading condition	20g	30g	40g	50g
Restraint condition	Safety belt, Airbag	Safety belt	Airbag	No restraint
Foot position	Left foot on floor, right foot on brake pedal		Left foot on floor, right foot on accelerator	
Knee bolster stiffness	Low	Middle	High	
Footwell intrusion	Intrusion 1	Intrusion 2	Intrusion 3	

Loading condition in this paper is crash deceleration pulse, peak acceleration is the variable in this research.（The crash deceleration pulse of baseline model is a generic pulse representative for a zero degrees full frontal impact of a mid-sized passenger car, shown in figure 3）. Three kinds of knee bolster stiffness are: low stiffness, flexible material stiffness; middle stiffness, plastic material stiffness; high stiffness, rigid material stiffness. The research simulates 108 different models according to different parameters assemblies.

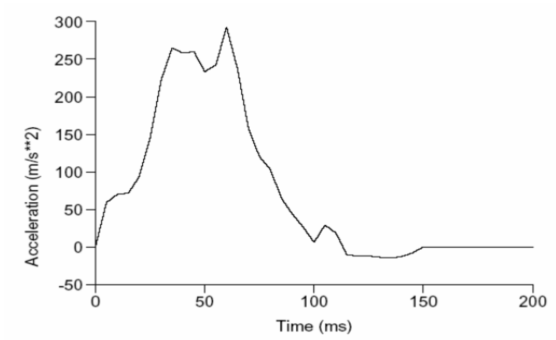


Fig.3 Deceleration pulse in crash in baseline model

2.3 Lower extremity injury valuation index

Human lower extremity is composed of six morphologically distinct regions: the hip, thigh, knee, leg, ankle and foot, this paper concentrates on the thigh、knee、leg and the foot. The lower extremity injury criterion contains: Femur Force Criterion (FFC) 、Tibia Index (TI) and Tibia Compressive Force Criterion (TCFC), Tibia Index educed from formula Ti＝ (F/Fc)+(M/Mc). FFC evaluate femur injury, Ti and TCFC are tibia injury criterion.

Injury of foot and ankle are very complex, which need deeply research and is not the emphases in this paper, so only foot contact force and contact torque output was adopted as injury valuation index of foot and ankle. The output injury valuation indexes of simulation are shown in table 2：

Table 2 injury valuation index

Situation	Left lower extremity injury valuation index	Right lower extremity injury valuation index
left foot on floor, right foot on brake pedal	FFC TCFC TI Knee contact force Contact force of left foot and toeboard	FFC TCFC TI Knee contact force Contact force (torque) of right foot and brake pedal Contact force (torque) of right foot and toeboard
left foot on floor, right foot on accelerator	FFC TCFC TI Knee contact force Contact force of left foot and toeboard	FFC TCFC TI Knee contact force Contact force of right foot and accelerator Contact force of right foot and toeboard

3 Results and Discussion

The outputs of three injury indexes in baseline model are shown in figure 4(foot force describe contact force of foot and brake). The parameter assembly of baseline model in this research is: Peak acceleration field is 30g, right foot on brake pedal, full restraint, and middle stiffness knee bolster, low intrusion.

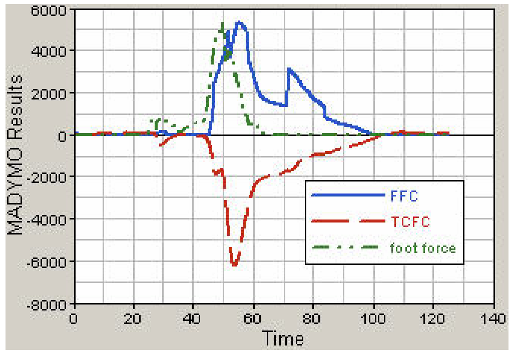


Fig. 4 Output of lower extremity injuries in baseline model

3.1 Effect of accelerate field to 1ower extremity injuries

Results of simulation indicate that all the output indexes rise along with the increase of acceleration field, which means that: As acceleration field in the crash rises, severity of lower extremity injury will certainly increase. Case of left and right lower extremity is approximately the same. All the simulations of every kind of parameter combination educe similar conclusion like this.

Based on the baseline model, only change acceleration field, three peak right lower extremity injury indexes were shown in figure 5. (Units of all the forces in every figure are KN in this paper. Because of value of Ti is about 1; this value was magnified 10 times in all the figures in this paper)

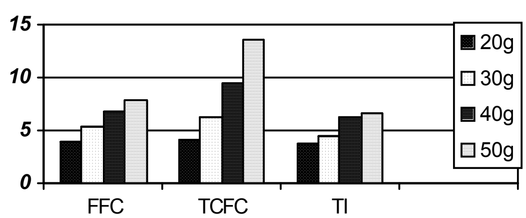


Fig. 5 Change accelerate field, peak 1ower extremity injuries index

3.2 Effect of restraint system on 1ower extremity injuries

Results of simulation indicate that in case of no airbag, for every output force not only peak values are almost the same, but also graphs are almost alike. Which indicate that using airbag almost have no effect on lower extremity injury. When there is no safety belt, every output index includes femur、tibia、knee、foot and ankle greatly increase. Which indicate that for all the parts of lower extremity safety belt has prominent efficiency on injury prevention. Case of left and right lower extremity is approximately the same. All the simulations of every kind of parameter combination educe similar conclusion like this.

Based on baseline model, only change constraint system, three peak right lower extremity injury indexes were shown in figure 6. F1 is knee contact force, F2 is contact force of right foot and brake pedal, F3 is contact force of right foot and toeboard, M1 is contact torque of right foot and brake pedal, M2 is contact torque of right foot and toeboard in all the figures in this paper.

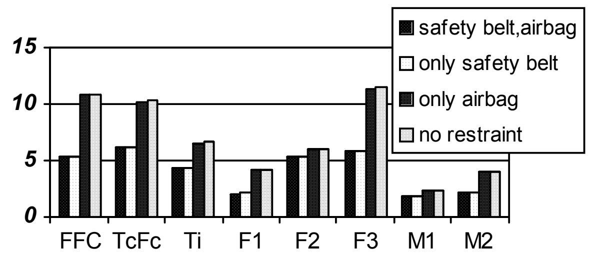


Fig. 6 Change restraint system, peak lower extremity injury index

3.3 Effect of knee bolster stiffness on 1ower extremity injuries

Results of simulation indicate clearly that: As knee bolster stiffness rise, lower extremity injury rises. When right foot was on brake pedal, all the output forces constantly reduced as knee bolster stiffness decline; FFC and knee contact force vary greatly. Based on baseline model, change knee bolster stiffness only, peak right lower extremity injury indexes were shown in figure 7.

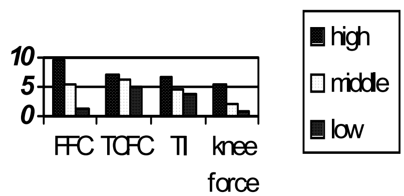


Fig.7 Change knee bolster stiffness, peak right lower extremity injury index

When right foot was on accelerator, except peak tibia force slightly larger, as knee bolster stiffness reduction other peak force constantly reduces in different extent, FFC and knee contact force varied greatly. Based on model of right foot on accelerator, change knee bolster stiffness only, peak right lower extremity injury indexes were shown in figure 8.

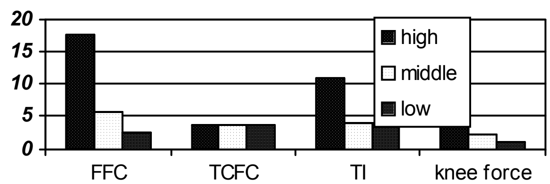


Fig. 8 Change knee bolster stiffness, peak lower extremity injury index

It is obvious that decline of knee bolster stiffness has distinct efficiency mainly on femur and knee protection and some efficiency on tibia protection. Slightly lower plastic stiffness of bolster is probably perfect.

3.4 Effect of foot position on 1ower extremity injuries

Results of simulation indicate that when right foot was on brake pedal lower extremity injury would be more seriouser, brake pedal mainly result in injury of tibia、foot and ankle rise. Compared to right foot on brake pedal, when right foot was on accelerator, except that FFC and knee force slightly rise, other output forces reduce at different extent. This tibia force is tibia axial force that is mainly caused by brake pedal or accelerator who passed force to tibia through foot. A notable character is that: Right foot on accelerator would distinctly reduce the tibia force and certainly reduce risk of tibia fracture, which means brake pedal is an important causation for tibia injury of driver. Based on baseline model, Change foot position only, peak right lower extremity injury indexes were shown in figure 9. F2 is contact force of right foot and brake pedal (or accelerator) in this figure.

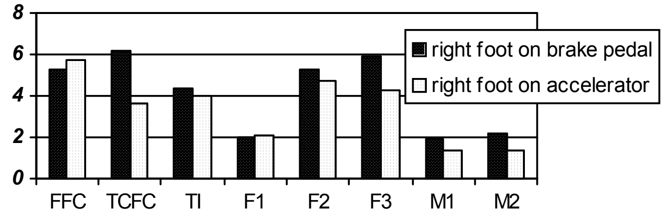


Fig 9. Change foot position, peak lower extremity injury index

3.5 Effect of footwell intrusion on 1ower extremity injuries

Three intrusions were simulated in this research, shown in table 3.

Situation	Depth	
	Toeboard	Panel
Intrusion 1	107.5mm	25mm
Intrusion 2	212.5mm	55mm
Intrusion 3	325mm	85mm

Tab. 3 situation and depth of three intrusions

Results of simulation indicate that as intrusion rise injury surely rise for left and right lower extremity. For both left and right lower extremity, as intrusion rise peak value of FFC and TI rises greatly, while peak of TCFC decline. The difference between left and right lower extremity is: Injury of right foot and right ankle rise as intrusion rise, but left foot and left ankle not, which may due to the brake pedal factor.

For right lower extremity, except that TCFC constantly decline, other peak loads rise. Tibia index and contact force and torque of right foot and toeboard constantly increase, and vary greatly, peak FFC rises evidently, too. Knee contact force and contact force and torque of right foot and brake pedal rise slightly. Based on baseline model, change intrusion only, outputs of right lower extremity were shown in figure 10.

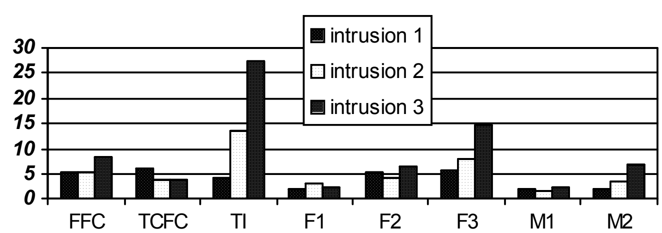


Fig. 10 Change footwell intrusion, peak right lower extremity injury index

For left lower extremity, except that TCFC constantly decline, other peak loads rise. FFC and tibia index constantly increase, and vary greatly. Contact force of knee and contact force of left foot and toeboard increase slightly. Based on baseline model, change intrusion only, outputs of left lower extremity were shown in figure 11, F3 is contact force of left foot and toeboard in this figure.

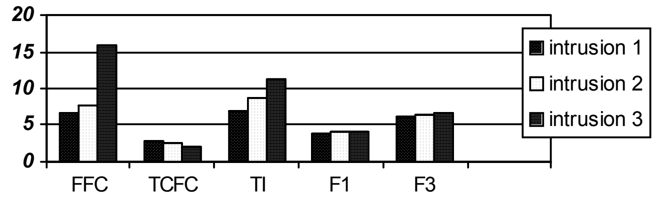


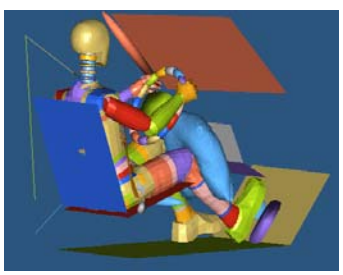
Fig. 11 Change footwell intrusion, peak left lower extremity injury index

The results indicate that increasing footwell intrusion increase the risk of lower extremity injury when the crash acceleration field remains constant, which means clearly that: footwell intrusion increase the risk of leg injury separate from crash condition, intrusion is shown not to be a proxy variable for crash condition.

4 Countermeasures

4.1 Knee airbag protection

To reduce the damage of dashboard to driver lower extremity, protection efficiency of knee airbag was researched. Knee airbag was installed under knee bolster, and simulation model was shown in figure 12.



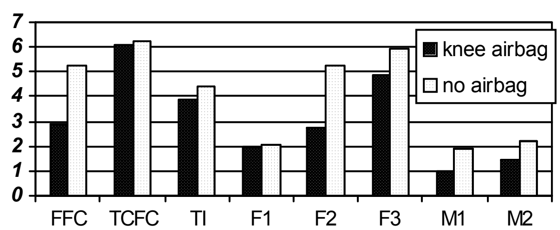


Fig. 12 Model installed knee airbag **Fig. 13 Using or no knee airbag, peak right lower extremity injury index**

Using or no knee airbag, peak right lower extremity injury indexes were shown in figure 13; F1 is contact force of knee and knee bolster (or knee airbag) in this figure.

Results of simulation indicate clearly that: When knee airbag was used, all the output forces constantly decline. Peak values of FFC and contact force of right and brake pedal vary greatly. Knee airbag can protect thigh and foot effectively.

4.2 Foot airbag protection

To reduce the damage of footwell and floor to driver lower extremity, protection efficiency of foot airbag was researched. Foot airbag was installed under footwell, and simulation model was shown in figure 14.

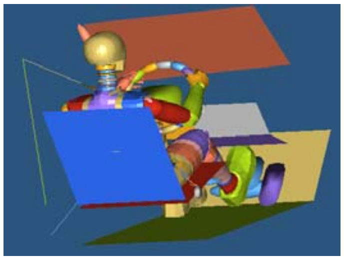


Fig. 14 Model installed foot airbag

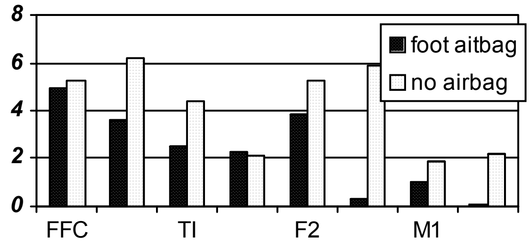


Fig. 15 Using or no foot airbag, peak right lower extremity injury indexes

Using or no knee airbag, peak right lower extremity injury indexes were shown in figure 15. F3 is contact force of right foot and toeboard (or foot airbag); M2 is contact torque of right foot and toeboard (or foot airbag) in this figure.

Results of simulation indicate clearly that: When foot airbag was used, except that knee force had slightly risen, other output forces decline evidently. Contact force and torque of right foot decline greatly. Foot airbag can protect foot and ankle effectively and has some protection efficiency on leg and knee, but has less efficiency on thigh and knee.

5 Conclusions

Variety of impact acceleration field has great influence on lower extremity injuries. As acceleration field in crash rise, lower extremity injury rise. Using safety belt has prominent efficiency to reduce lower extremity injuries, but frontal airbag has little effect on it. Using knee bolster with lower stiffness can reduce the loads to femur, knee and tibia. The right foot placed on the brake pedal will increase the risk of foot injury evidently. Variety of footwell intrusion induced by impact deform of forepart of car will influence lower extremity injuries severity to a certain degree. As intrusion rises, lower extremity injury rises.

Because more than half of the drivers apply the brakes before hitting the collision partner, improvement of geometry character and deform character of brake pedal is very important. Using knee airbag and foot airbag have prominent efficiency to reduce lower extremity injuries, efficiency of knee airbag is mainly on thigh and foot, but efficiency of foot airbag is mainly on foot and ankle.

6 References

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