A look-up diagram for rapid estimation of occupant injury risk applied to frontal motor vehicle crashes

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I. INTRODUCTION

Fatality and injury severity in motor vehicle crashes (MVCs) are affected by a combination of various factors arising from the road, the vehicle and the occupant [1-2]. Rapid and accurate safety estimation prior to the collision events can reduce casualties by optimising restraint and safety devices for individual characteristics [3], or by improving the trauma triage process after an accident [4]. Previous prediction functions on injury severity have been developed using accident databases with a focus on accident scenarios, but occupant parameters, such as the driving or sitting posture, have not been fully considered [5].

To fill this gap, the goal of this study is to illustrate the development of a look-up diagram for rapid estimation of injury risks taking into account both occupant diversity and vehicle configuration using computational biomechanical analysis. A finite element (FE) human body model (HBM) was morphed to diverse statures and postures. The parameter configuration in simulation cases followed orthogonal experimental design. Injuries on different body parts were evaluated separately and the safety estimation functions were obtained through regression method.

II. METHODS

A FE vehicle-occupant model was developed consisting of an occupant and a sled model to simulate the kinematics and kinetics of a low-velocity frontal impact under LS-DYNA environment (Fig. 1). FE method is selected because it is more biomechanically developed and also provides the possibility to check the injury outputs by analyzing the strain/stress distribution and load transmission path. A 30 km/h crash pulse was scaled from a real world vehicle impact test with delta-v of 39.90 km/h [6]. A sled model was obtained in-house as part of ongoing research efforts, representing the vehicle interior construction. The sled model includes seat, seatbelt, steering wheel, airbag, instrument panel, foot rest, wind shield, roof and floor. Model validation was performed using a vehicle crash test in NHTSA database (No. 9065). The method of ISO/TS 18571 was used for a quantitative comparison between model output and experimental result. The ISO ratings of most signals were between 0.57 and 0.75, which indicated that the sled simulation model was capable of representing a real-world vehicle frontal collision. The Total Human Model for Safety (THUMS) was used as the baseline HBM, the biofidelity of which was validated in various loading situations [7].

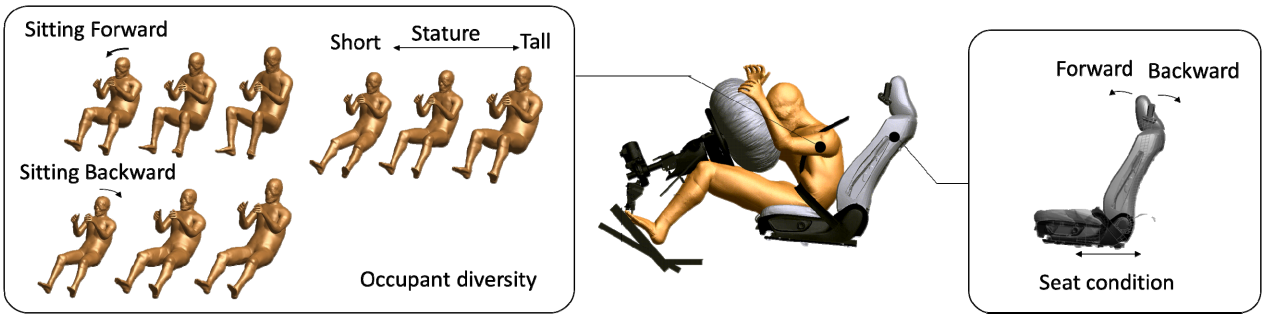

Fig. 1. FE modelling setup of the vehicle-occupant simulation matrix taking into account occupant diversity and vehicle configuration.

Kinematic and kinetic parameters were measured in simulation to indicate the occupant injury. Developed

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criteria were used for characterisation of the injury severity on main body parts, i.e. head, neck, thorax and femur [8]. Skull fracture and brain injury were characterised by Head Injury Criterion (HIC) and Brain Injury Criteria (BrIC), while injury on neck, thorax and femur were characterised by Neck Injury Criteria (N_{ij}), the maximum chest deflection (D_{max}) divided by chest depth, and femur section force, respectively.

To compose a simulation matrix for prediction function, four factors were selected as independent variables considering the significance of the factor and FE feasibility [3]: occupant stature, body mass index (BMI), sitting posture and seatbelt load limiter. Due to the high computational cost of FE simulations, orthogonal experimental design was used for main effect analysis and regression. To date, we have completed nine simulation cases which represent the initial findings. Parametric modelling for those cases was based on real-world anthropometric database and a combination of open source software and in-house code. The injury severity analysis and risk estimation were performed by body parts. Injury prediction functions were generated by regression method and formed a look-up diagram for a rapid and practical safety estimation.

III. INITIAL FINDINGS

Linear regression and quadratic regression, which were commonly used for preliminary fitting and exploration of regularity, were performed to demonstrate the generation of safety estimation function (Table I). Some other functions (i.e. hyperbolic function and logarithmic function) were discarded because of negative values or large errors in some cases. The Normalized Root-Mean-Square Deviation (NRMSD) of the two selected regression methods was 18±5% and 10±7%, respectively, which was calculated with the regressed value (or the predicted value) and the value from simulation. Compared with linear regression, quadratic regression showed better agreement with the simulation results and lower error value. The safety estimation functions revealed that head and brain injury criteria were simple quadratic equations of stature and BMI, while the regressions of neck and thorax injury criteria were more complicated, involving the primary and quadratic combinations of various influencing factors.

TABLE I
SAFETY ESTIMATION FUNCTIONS BASED ON SIMULATION INJURY RESULTS

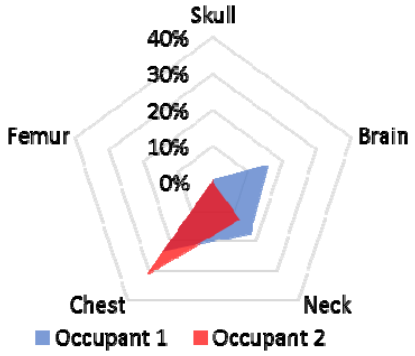
	Linear regression	Quadratic regression
HIC	$393-191.1h$	$-2334+3133h-1007h^2$
BrIC	$1.006-0.01682m$	$1.43-0.26h-0.009m-0.0048hm$
N_{ij}	$0.499-0.0133m-0.138p+0.0411f$	$-0.133+0.012m-0.138p+0.222f-0.00722mf$
D_{max}/Chest depth (%)	$21.07-7.36h$	$32-47.9h+1.54m+0.622p+18.64h^2+1.624p^2-0.84hm$
Femur force (kN)	$-4.26+3.05h+0.0656m-0.423f$	$-15.3+11.48h+2.754f+0.114f^2-2.409hf$

where h is occupant stature (m); m is BMI; p is sitting posture (0: default; -1: sitting 100 mm farther from steering; 1: sitting 100 mm nearer to steering); and f is seatbelt load limiter (kN).

The injury risks on different body parts were estimated based on the injury criteria. The result indicated low injury risk of skull and femur fracture (i.e. <2%), as the impact velocity was relatively low at 30 km/h. A case study was performed between two cases (denoted as 'Occupant 1' and 'Occupant 2') (Fig. 2(a)). Occupant 2, with BMI of 30, sustained lower AIS2+ injury risk on brain compared to Occupant 1 with BMI of 20 (<1.00% vs. 15.79%) and higher AIS2+ injury risk on thorax (31.44% vs. 23.47%). As Occupant 1 was seated 100 mm further from the steering wheel, the AIS2+ injury risk on neck increased from 12.69% to 17.43%, due to lack of timely airbag restraint on the head. Figure 2(b) shows an example of injury risk estimation with occupant characteristics and vehicle configuration, using the developed look-up diagram.

	Occupant 1	Occupant 2
Occupant stature (mm)	1700	1650
BMI	20	30
Seating posture	Default	Forward
Seatbelt load limiter (kN)	4	3

(a)



(b)

Fig. 2. AIS2+ injury risk estimation of two occupants (as an example): (a) occupant characteristics and vehicle configuration, (b) the look-up diagram on injury risk estimation.

IV. DISCUSSION

The influencing parameters in traffic scenarios affect the injury results to different degrees. Given the near real-time requirements and restricted hardware resources for safety systems on-vehicle, a straightforward, quantitative injury prediction is highly necessary for developing an adaptive restraint system and/or post-event emergency assistance. As a preliminary investigation, this study used FE models and regressed a look-up diagram for safety estimation of human body risk. This developed diagram can provide near real-time injury prediction with certain input parameter values in frontal MVCs. It also helps understanding the influence of various factors to injury results, especially those related to occupant characteristics.

Several laws can be revealed from the primary regressed safety estimation functions. For designing restraint, the interaction terms of the seatbelt load limiter and occupant characteristics (i.e. stature and BMI) appeared in the prediction function of N_{ij} and Femur force. It indicates that the restraint strength adjustment needs to follow the individual property and to match the collision condition. It also highlights the significance of restraint system design. For understanding injury mechanisms, the injury on head can be predicted by one or two parameters, while the neck injury is influenced by three parameters. The mechanical loading on the neck is generated by relative motion between head and torso. Restraint force on both the head and the torso will influence the neck injury severity, resulting in a more complicated injury prediction on the neck than on the head.

Compared with previous research based on real-world accident database, this study provided an occupant injury estimation diagram involving both occupant characteristics and vehicle configuration, some of which are hard to get from an accident report. However, several limitations must be noted. The first one is the accuracy of the diagram. In the present injury prediction, there are three key steps in generating the injury prediction diagram, i.e., FE modelling, injury risk calculation, and regression for injury prediction. This forward analysis method can help provide comprehensive understanding of how the injury results were affected by various factors. As the parameter configuration is designed in a simulation matrix, the accuracy in regression was enhanced to about 90%, while excluding the possible error accumulations in the other two steps. Those error can be induced or dominated by the many uncertainties (e.g., seating position, active response), which also reflect the limited performance of models in representing real-world conditions.

The second limitation was the limited applied range. The look-up diagram was generated with orthogonal experimental design of nine cases, which gives a primary result. The application range will be enlarged by further research efforts on a larger simulation matrix with a more advanced approach. Larger-scale simulations can also verify the reliability of the results. Some potential influencing factors, such as impact velocity and muscle effects, can be considered in our subsequent studies. The addition of a new factor will enlarge the simulation matrix two or three times, given the time-consuming nature of FE simulation. The third limitation is that only two regression functions (linear and quadratic) were used here. To which extent other function forms can further improve the estimation accuracy remains unknown, and shall be further investigated.

In conclusion, the safety estimation function provided a practical approach for looking up the primary relation between the influencing parameters at different levels and occupant injury results in frontal MVCs. The present framework preliminarily demonstrated the feasibility of using numerical simulations to generate such an injury

prediction model. In the future, one possible application of this model is to enhance the advanced vehicle safety systems. For example, after enlarging the range of the diagram, it can provide a rough injury prediction, such as distinguishing severe and mild injury on upper and lower body. This rough prediction can serve as an advisory reference to the protection strategy in vehicle. After that, the accuracy of the injury prediction model can be improved progressively, by studying the difference between predicted injury and real world injury results.

V. ACKNOWLEDGEMENTS

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