Investigation of front seat occupants' acetabulum injury in front impact

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ABSTRACT

Among the proposed amendments to the US-NCAP announced on Dec. 2015, a new acetabulum injury evaluation along with the next-generation THOR dummy has been included [1]. In relation to this topic, numerous research tests and studies are already being conducted by NHTSA. However, 29% of those tests showed that acetabulum injury has occurred due to tensile load rather than a compressive load from the femur. Therefore, in this research, we investigated whether similar injury mechanism actually occurred in real world accidents using NASS-CDS (CY2000-10) data. It is observed that 95% of acetabulum injuries in real world accidents were injuries accompanied by fractures, and 82% of these injuries were related to interaction with the instrument panel. This suggests that most of the acetabulum injuries occur by a compressive load and they are far less likely to occur with tensile load.
In addition, by analyzing the mechanism of injury occurrence of the research tests, there are the two influential factors for the difference between the crash test results and real world accidents. They are i) the difference between the THOR dummy and the human body around the hip joint and ii) the problem of acetabulum injury criterion. In the future, further research is necessary in order to propose a more appropriate injury risk evaluation.

INTRODUCTION

Related to the injuries at and around the hip joint of vehicle occupants during a frontal crash, a number of research reports were already published. Dakin, et.al found that the number of hip injury is highly dependent on angle of impact [2]. Based on PMHS (Post Mortem Human Surrogate) experiments, Rupp, et.al reported the tolerance levels of fractures occurring at the hip joint and the connecting femur bone [3]. Martin, et.al analyzed real world accidents related to Narrow offset and Oblique Frontal Crash accidents and compared the pelvic injuries of THOR-NT dummy with human body [4]. Kuwabara, et.al compared acetabulum loads of the THOR dummy, HybridⅢ dummy and THUMS. And, they analyzed the mechanism of acetabulum injury by numerical analysis using detailed vehicle model [5]. However, there are few published research works addressing the consistency between research tests and real world accidents, especially focusing on the mechanism of acetabulum injury. Therefore, in this study, we focused our analysis on (i) acetabulum injury of NHTSA research tests using THOR dummy, (ii) acetabulum injury in real world accidents and (iii) the difference of injury mechanism between the research tests and the real world accidents.
Based on the above mentioned background research works, NHTSA proposed the introduction of 1) the Oblique test in addition to the conventional Full Frontal Rigid Barrier test and 2) a new dummy THOR with improved biofidelity to be used in the frontal crash tests in the revised US-NCAP draft announced in Dec. 2015. Compared to the current HybidⅢ dummies, using the THOR dummy, more injuries can be evaluated and the acetabulum injury is one of them. In response to numerous research studies being conducted by NHTSA, we in this research (i) changed the viewpoint from conventional research, (ii) analyzed the frequency and mechanism of occurrence of acetabulum injury in real world and vehicle crash tests and finally (iii) carried out a comparison of them.

1. Analysis of NHTSA research tests

1.1 List of tests

Injuries for the Driver and Passenger occupants in Left Oblique, Right Oblique and Full Frontal Rigid Barrier tests using the THOR dummy are analyzed in detail. Those tests having failure in data recording or not having proper test reports are excluded. Data selection for the present analysis is as shown in Table 1. In the following sections, Left Oblique will be denoted by "LO", Right Oblique by "RO" and Full Frontal Rigid Barrier by "FRB", respectively.

Table1.
Selection of NHTSA research tests (Refer to Appendix A)

		Abbreviation	Occupants(side)	Number of tests
Oblique	Left	LO	Driver (left)	22
			Passenger (right)	16
	Right	RO	Driver (left)	8
			Passenger (right)	
Full Frontal Rigid Barrier		FRB	Driver (left)	5

1.2 Acetabulum load measurement location and evaluation method

Using the THOR dummy, it is possible to measure three axial loads of the acetabulum. As shown in Fig. 1, the load cells are highlighted by indicated within the dotted box. The Acetabulum injury value, as proposed in new US-NCAP, is based on the total resultant value of three axial loads recorded by the load cell [1].

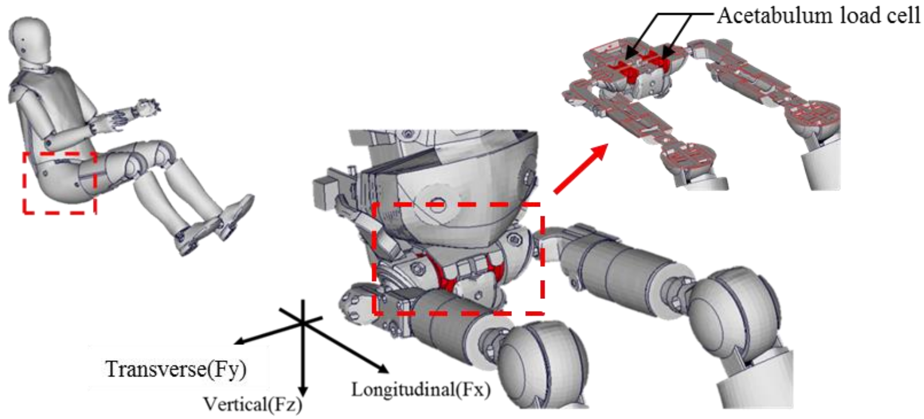


Figure 1. Acetabulum load measurement position

1.3 Proportion of injuries exceeding IARV in each body region

Table 2 shows the lists of body regions, injuries, IARV (Injury Assessment Reference Value) and the corresponding criteria for serious injury.

We examined the percentage of injuries of each body region with respect to the total number of injuries, only for those injuries which exceeded the IARV as shown in Fig.2.

Table 2
List of body region, injury, IARV and criteria for serious injury

Body Region	Injury	Unit	IARV	Criteria for serious injury when above IARV
Head	HIC15		700	11.2% risk of AIS 3+ injury [6]
	BrIC		0.87	50% risk of AIS 3+ brain injury[7]
Neck	Nij		1.0	22% risk of AIS 3+ injury[6]
Chest	Upper Chest deflection	mm	53	-[8]
	Lower Chest deflection	mm	46	-[8]
Abdomen	Abdomen deflection	mm	90	50% risk of AIS 3+ injury.[9]
Lower extremity	Acetabulum	N	3280	25% risk of a hip fracture (AIS 2+, or AIS 3+ if open fracture) [4] [10]
	Femur	N	9040	25% risk of AIS 2+ injury [11]
	Proximal Tibia Axial Compression	N	5600	25% risk of AIS 2+ injury [11]
	Distal Tibia Axial Compression	N	5200	25% risk of AIS 2+ injury [11]

For those cases where the IARV is exceeded, 16% were acetabulum related injury. The number of data exceeding IARV in each category of LO, RO and FRB is shown in Appendix B.

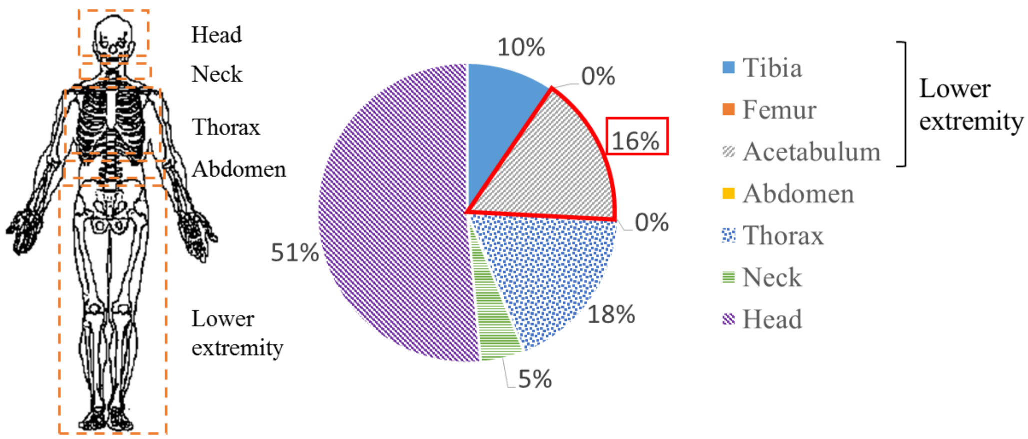
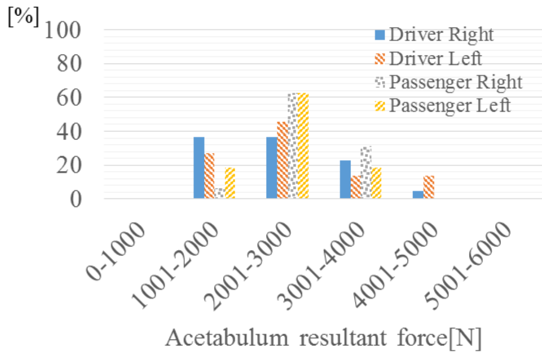


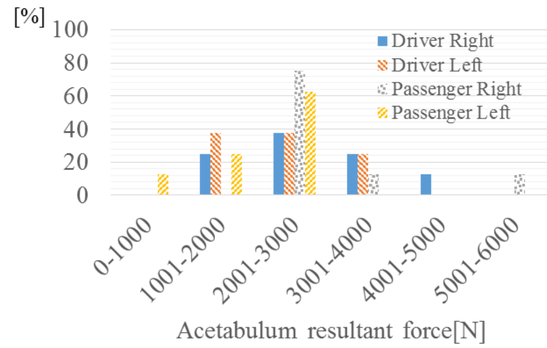
Figure 2. Proportion of injury of each body region exceeding IARV (except for upper extremity)

1.4 Magnitude of resultant load and occurrence frequency of acetabulum injuries in research tests

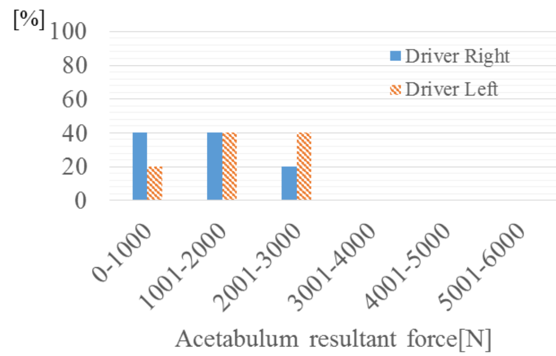
Fig. 3 (a-c) show the frequency distributions of acetabulum resultant loads (including those cases below the IARV level) in left and right lower extremities for LO, RO and FRB groups. The horizontal axis shows the resultant load with groups of 1000N increments and the vertical axis indicates the corresponding frequency or the percentage of those groups. For example, with the LO Driver Right leg, the number of tests where the maximum acetabulum resultant load is within the range of 1001-2000N is 8. The total number of tests is 22 as indicated in Table 1. So the ratio in this range of 1001-2000N, is 8/22(36%).
Although, in general, one may expect that the acetabulum resultant load of the near-side passenger for the cases of larger intrusion of the instrument panel to be always high, but such tendency was not very evident from the distributions of Fig. 3(a-c).
Hence, there is a possibility that only a compressive load transferred from the instrument panel to the hip joint through femur, is not always the main influencing factor for the occurrence of acetabulum injury. Also, the percentage of tests where the maximum acetabulum resultant load exceeded IARV(3280 N) level was 34%.



(a) LO



(b) RO

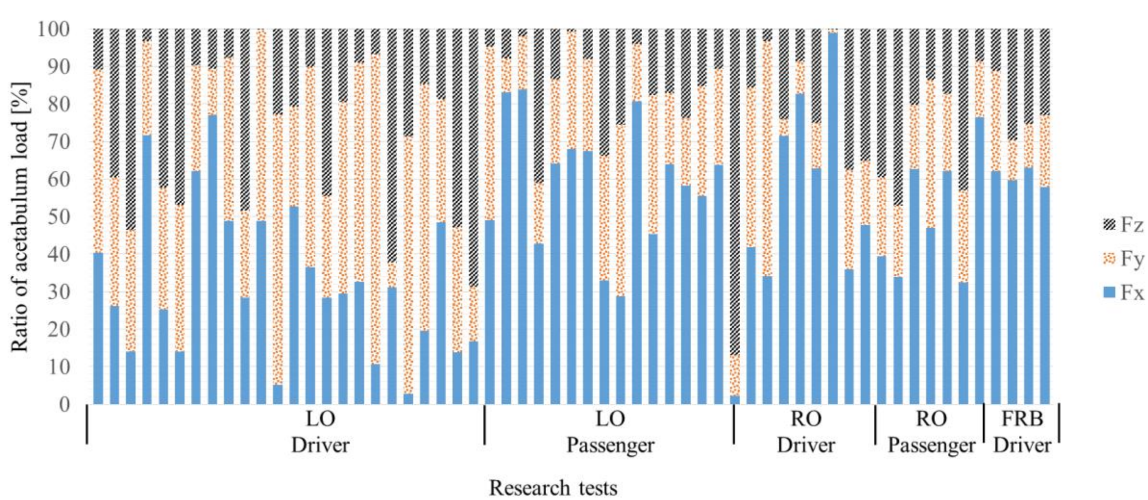


(c) FRB

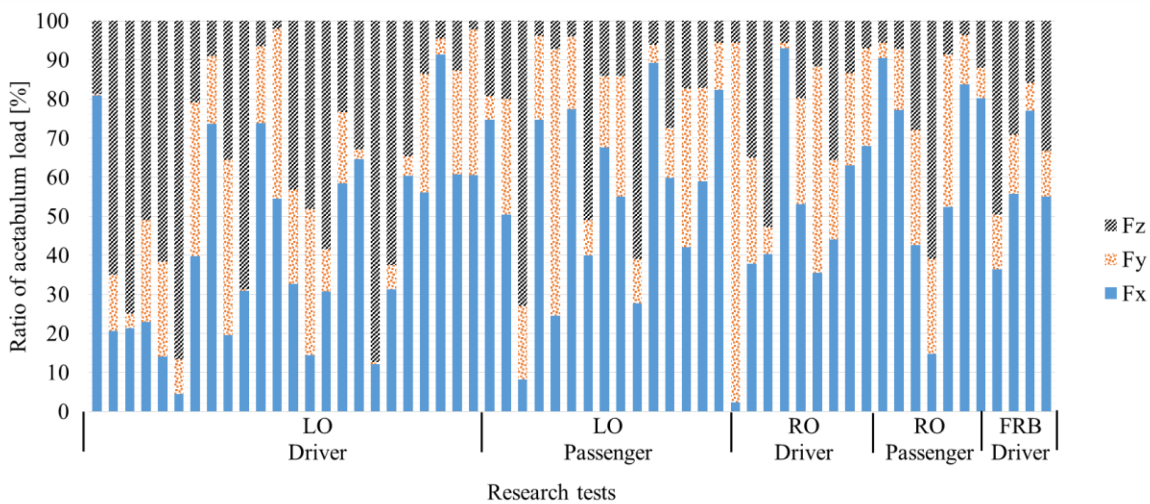
Figure 3. Frequency distribution of acetabulum resultant load

1.5 Proportion of x, y, z components in Acetabulum resultant load

Next, Fig.4 shows the proportions of each individual component (Fx, Fy, Fz) at the instant of time when the resultant load of acetabulum reaches maximum. The horizontal axis corresponds to each test and vertical axis shows the proportion of each individual component (Fx, Fy, Fz). It is observed that the percentage of cases with Fx as the highest load is quite high, about 60% of total cases and 71% within in the cases which exceed IARV level. Hence, in following part of our study, we focused on acetabulum Fx component.



(a) Right leg



(b) Left leg

Figure 4. Ratio of acetabulum load

1.6 Frequency of tensile / compressive load occurrence in acetabulum Fx

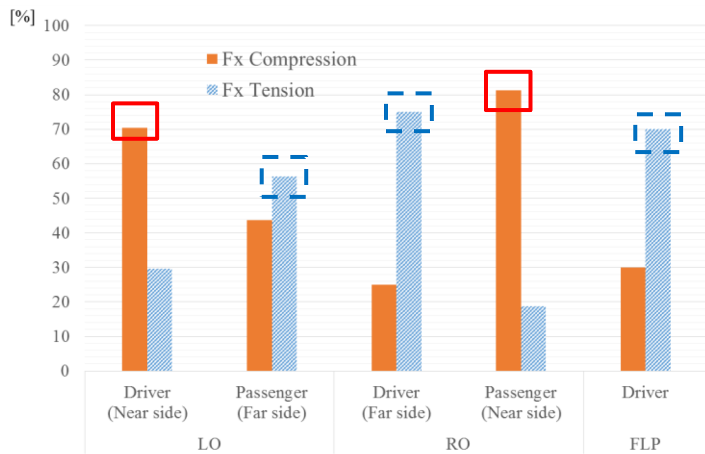
The result of classifying the Fx component at the maximum of the resultant load into compression / tension is shown in Fig. 5 (a) for each collision type and occupant. We found the following trends:

i) *Near side occupant of LO/RO:* compression cases are as high as 70% or more (solid line frame in Fig. 5a).

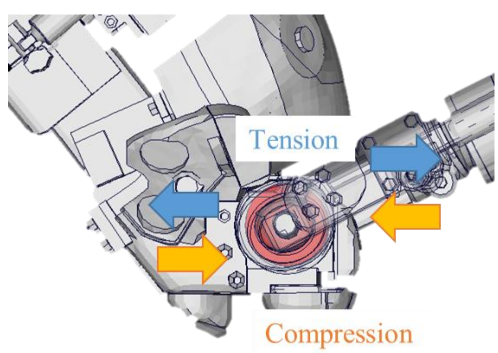
ii) *Far side occupant of LO/RO and FRB:* tension cases are as high as 55% or more (broken line frame in Fig. 5a)

Generally speaking, the magnitude of instrument panel's intrusion is less for far side impact than near side impact. For the case(i), there will be a strong interaction between the knee and instrument panel with the forward movement of the pelvis and it results in a large compressive input load to the acetabulum from the knee through the thigh as illustrated by Fig. 6.

On other hand, for the case(ii), as the magnitude of instrument panel's intrusion is small, the interaction between the knee and instrument panel would be weaker. So, due to inertia of the femur and the lower part of the leg, the forward movement of the thigh is not fully restrained by a less intruded instrument panel. This leads to inertia induced tensile load in acetabulum.



(a) Ratio of tension / compression for each type of crash and occupant



(b) Compressive/tensile load direction

Figure 5. Ratio of acetabulum Fx tension / compression

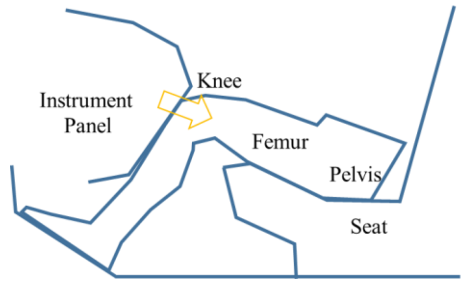


Figure 6. Load path from knee to acetabulum

1.7 Mechanism of the occurrence of acetabulum Fx

The mechanism of occurrence of acetabulum Fx was classified into 4 groups (Groups A - D). Representative examples are shown in Figs. 7-10. Horizontal axis is the relative pelvis movement (stroke) calculated from the logitudinal acceralation of the pelvis and the deceleration pulse of the vehicle.

Compression Pattern

Group A: Femur Fz compressive load (axial direction of femoral region) is increased by a compressive load input from the knee. Along with that, the compressive load of the acetabulum Fx also increases. The acetabulum compressive load reaches its maximum at the instant of maximum compressive load of femur Fz.

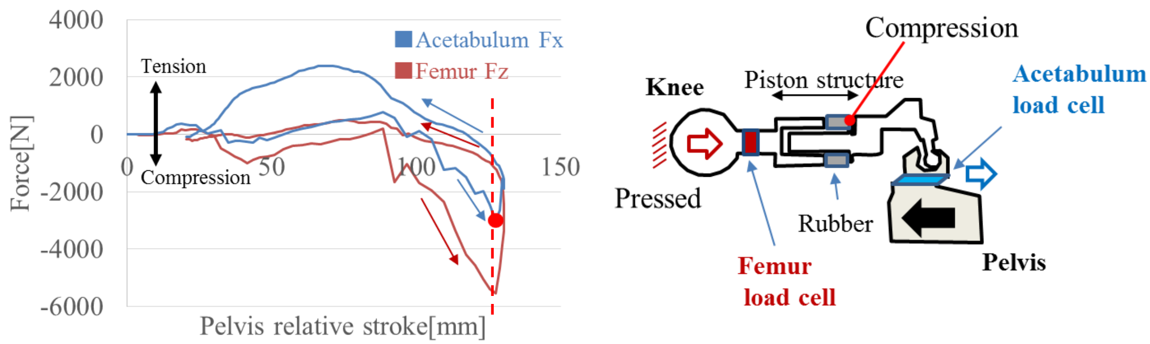


Figure 7. Mechanism of compressive load (Group A)

Tension Pattern

Group B: Initially, a compressive load of acetabulum Fx is developed similar to Group A. With the rebound of the pelvis, Fx changes from compression to tension. The acetabulum resultant load reaches maximum at the timing of the peak tensile load.

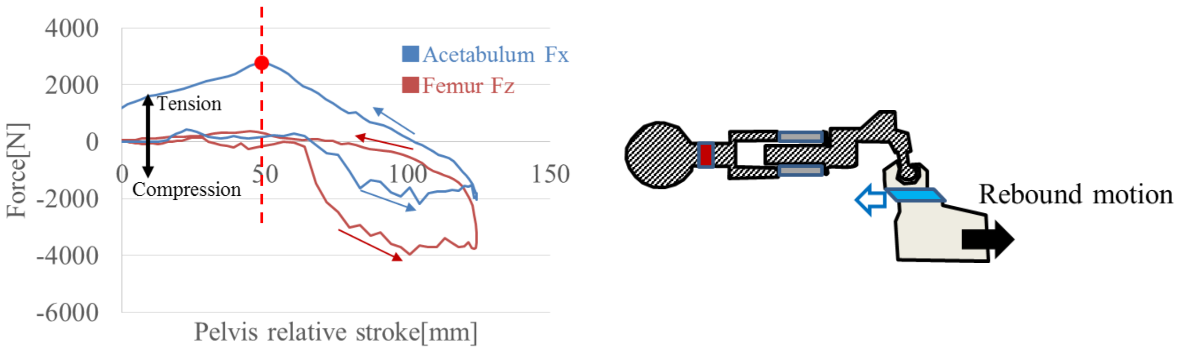


Figure 8. Mechanism of tensile load (Group B)

Group C: Tensile load occurs from the beginning, and it reaches a peak before the rebounding phase of pelvis. This will happen when the pelvis is restrained by the belt and the thigh moves forward due to inertia.

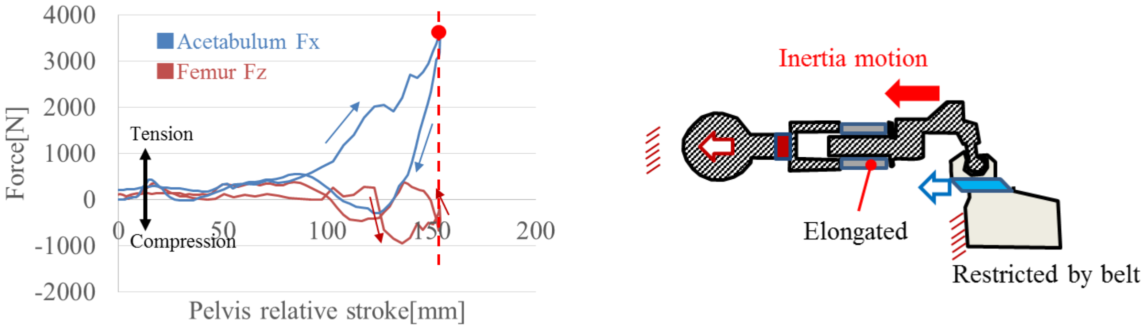


Figure 9. Mechanism of tensile load (Group C)

Group D: Despite the increase in compressive load of femur Fz, the tensile load of acetabulum Fx increases. This phenomenon is thought to be occurred by the following mechanism.

i) The forward movement of the pelvis is restrained by the belt.

ii) Knee is restrained by instrument panel.

iii) The part “a” shown by hatched line in Fig.10, moves forward with inertia. As a result, a tensile load occurs in the acetabulum Fx.

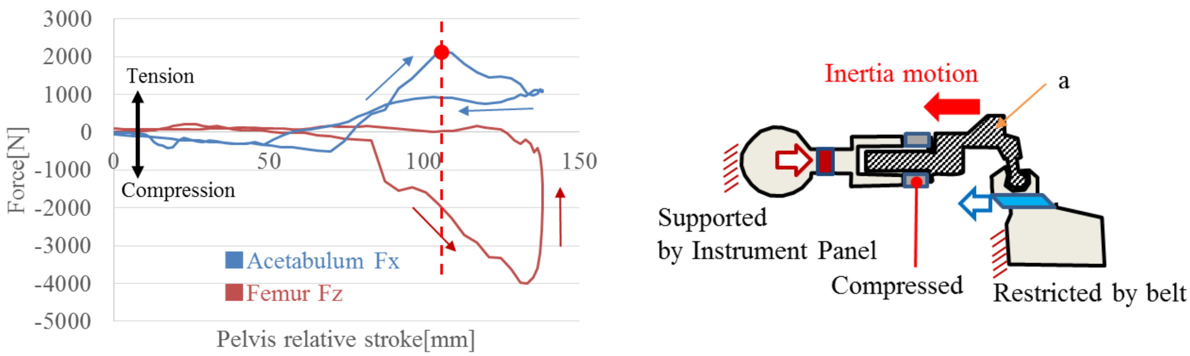


Figure 10. Mechanism of tension load (Group D)

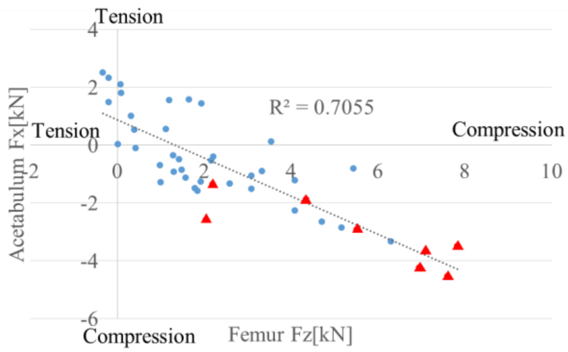
1.8 Relationship between acetabulum Fx and femur Fz load for below and above acetabulum IARV

In femur Fz vs acetabulum Fx plot as shown in Fig. 11(a-e), Groups A to D for each crash type and occupant are identified and plotted. The plotted femur Fz and acetabulum Fx are the values when the resultant load of acetabulum reached its maximum value. As a result,

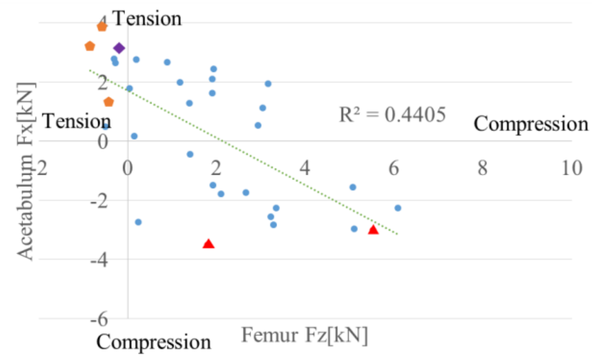
(i) Mode of Group A appeared when the femur load was high and it is most likely that the input of the compressive load from the knee is the main cause of the occurrence of this type injury.

(ii)Mode of Groups B, C appeared when the femur load was low, especially occurred for the far side occupant.

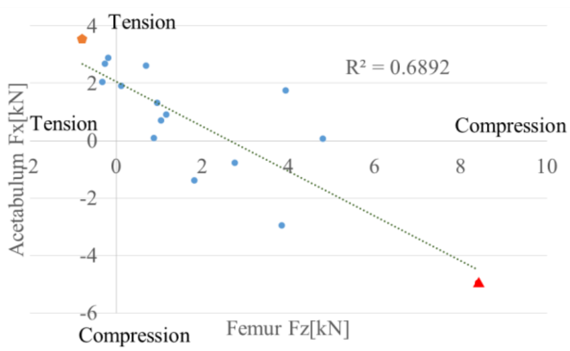
(iii)Mode of Group D did not appear as there is no case exceeding IARV.



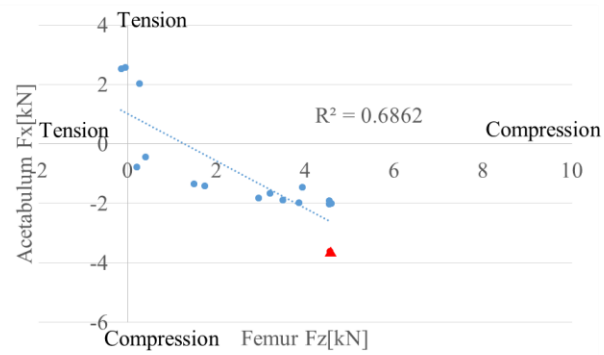
(a) LO Driver (Near side)



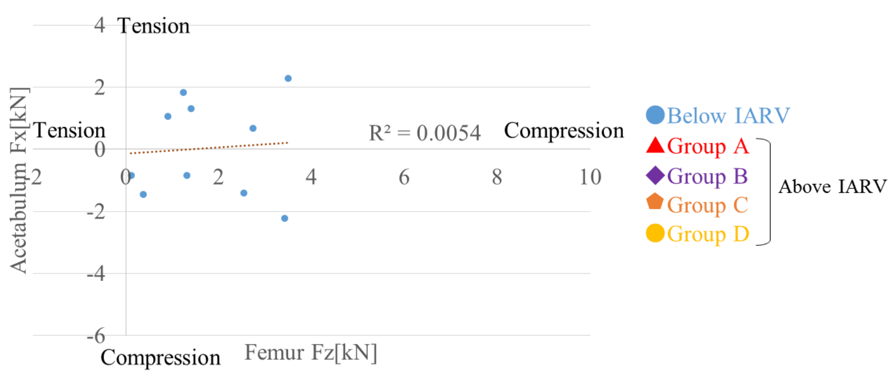
(b)LO Passenger (Far side)



(c) RO Driver (Far side)



(d) RO Passenger (Near side)



(e) FRB Driver

Figure 11. Relationship between Femur Fz and Acetabulum Fx
(● are below IARV and others grouped in A-D are above IARV)

1.9 Frequency of occurrence in Groups A to D

To compare with real world accidents, the occurrence frequencies of Groups A to D, as shown in Fig. 11, are summarized in Fig. 12 for NHTSA research tests. We observed 29% in tension and 71% in compression for Fx.

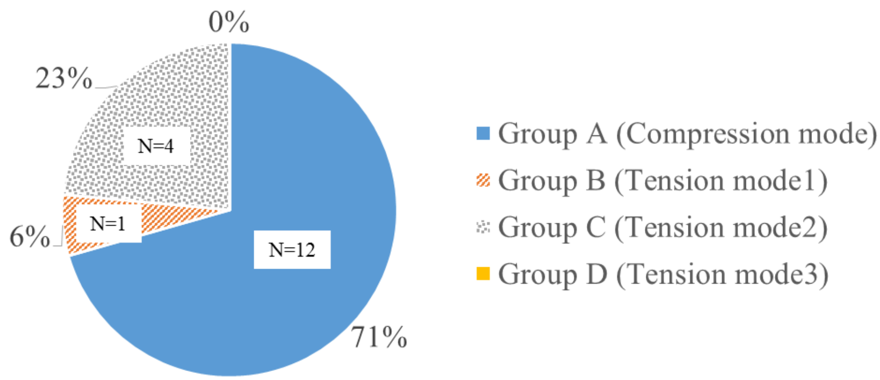


Figure 12. Proportion of each group A~D

2. Analysis of real world accidents
2.1 Selection criteria

A total of 1016 injury numbers were extracted from NASS-CDS database using the following selection criteria to match with the research test conditions as closely as possible (Table 3).

Table3.
Summary of NASS-CDS data condition

Data years	2000~2010
Deformation location	Front
Direction of force	11, 12, 1
Delta-V	40-70kph
Occupant's seat position	Driver, Passenger
Occupant's height	165-185cm
Belt use	Used only
Rollover collisions	Not involved
Object Contacted	Not tree and pole
Multiple collisions	Not involved
AIS	2+ injured

2.2 Proportion of injured parts

Fig. 13 shows the ratio of the number of injuries in each body region starting from head to lower extremity within the full set of extracted injuries. Lower extremity accounts for 48%. In addition, Fig. 14 shows breakdown of lower extremity injuries. Pelvis and femur injuries account for 28%.

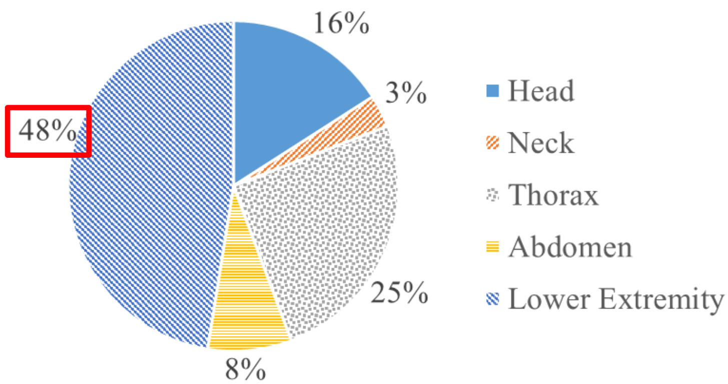


Figure 13. Proportion of injury by body region (except for upper extremity)

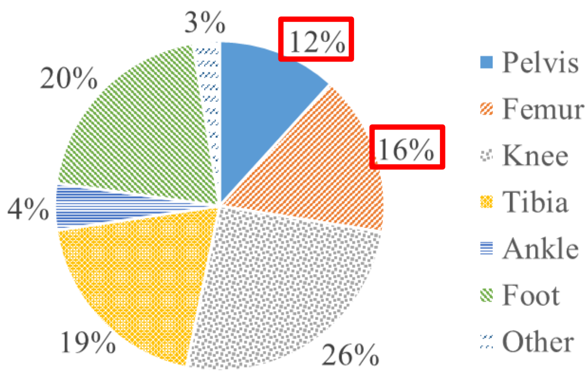


Figure 14. Proportion of lower extremity injury

2.3 Frequency and mechanism of injury related to acetabulum

Positions of pelvis and femur injuries in Fig. 14 are shown in Fig. 15. 47% occurred around the acetabulum consisting of acetabulum 29%, ischium, rami, public bone 10%, and femur neck 8%.

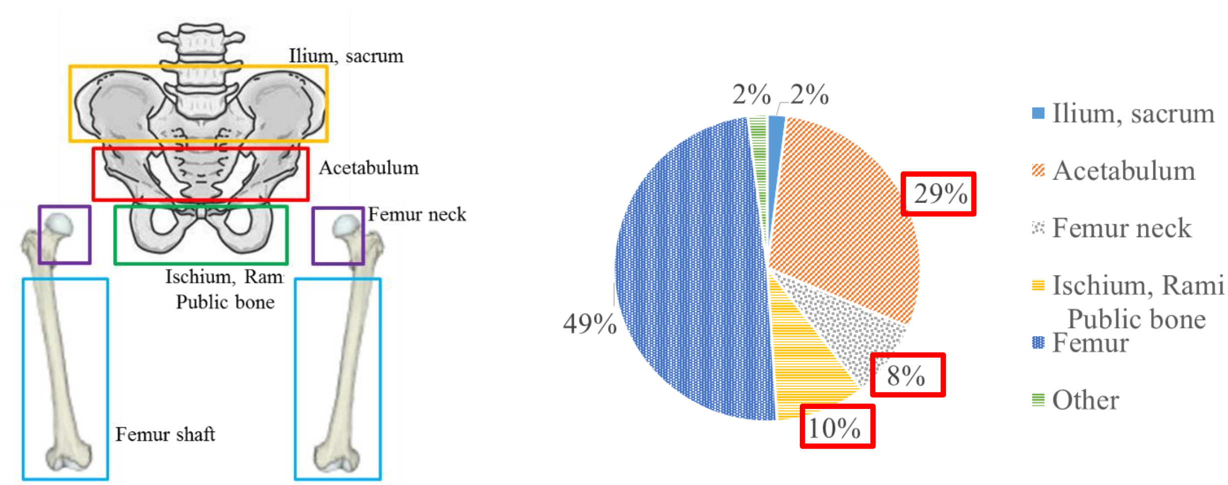


Figure 15. Detail of pelvis and femur injury

Injuries around acetabulum were classified into 3 patterns: (i) fracture only, (ii) fracture & dislocation and (iii) dislocation only (Fig. 16). They are 72%, 23% and 5%, respectively.

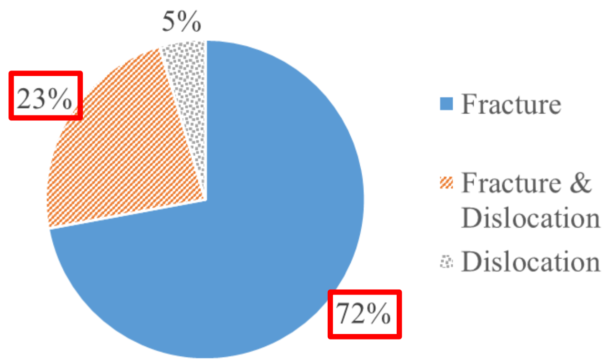


Figure 16. Proportion of injury of around acetabulum

Fig. 17 shows the sources of acetabulum injury accompanied by fracture. 82% occurred due to contact with instrument panel, which is very frequent compared to other sources, such as steering, Belt, TRIM ,etc.

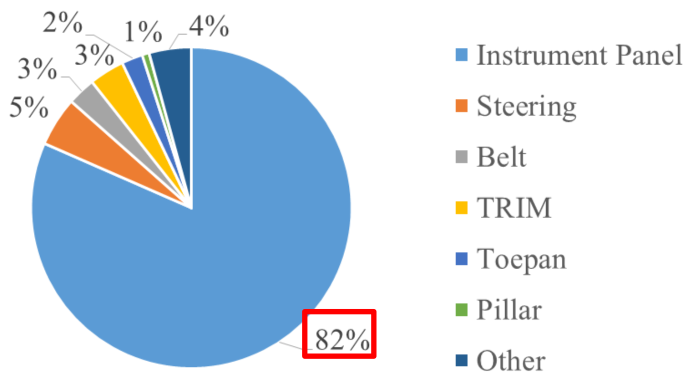


Figure 17. Sources of injury of around acetabulum (fracture, fracture & dislocation)

2.4 Summary

Of the lower extremity injuries in the real world accidents, firstly, extracting the injuries around the acetabulum, and next, analyzing the patterns and the source of injuries. As a result, 95% of the acetabulum injuries were accompanied by fractures and 82% of which were due to contact with the insturument panel. Therefore, it is natural to consider that most of the acetabulum injuries are caused by compressive loads from the peripherial components, such as instrument panel.

DISCUSSION

Results of the NHTSA research tests indicates that the ratio of acetabulum Fx component is higher than those of the other two components Fy and Fz. Also, in the case of lower femur Fz, acetabulum Fx tends to occur in tension. Counting among all the cases exceeding IARV, Fx in tension is 29% and Fx in compression is 71% when acetabulum resultant load reached its highest peak.

On the other hand, 95% of AIS+2 acetabulum injuries in real world accidents involve fractures or fractures with dislocation. It is natural to think that the injuries accompanying these fractures are caused by a compressive load from a outside input load when the knee comes into contact with the instrument panel covering 82% of those modes.

On the basis of the above facts, the following two points are inferred regarding the relationship between the real world accidents and the research tests(Group A to D) in point of the injury occurrence mechanism.

1) The majority of fractures in real world accidents correspond to Group A.

2) The majority of fracture & dislocation in real world accidents are considered to occur mainly during a typical phenomena as illustrated by Fig.18, and correspond to Group A.

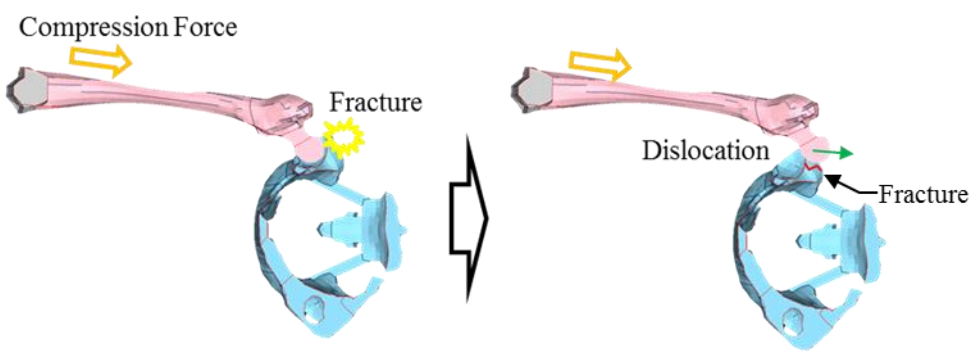


Figure 18. Assumed mechanism of fracture & dislocation (cross section of pelvis and femur)

The respective incidence rates are shown with help of a comparison bar chart in Fig. 19. Group A which accounts for 71% of the research tests is considered to correspond to fracture and fracture & dislocation mode in real world accidents. However, the remaining 29% is an injury mainly caused by tension, which may not have occurred in real world accidents. The most probable reasons for this are 1) basic structural differences between THOR dummy and the human body around the hip joint and 2) lack of a rational and proper evaluation procedure to measure acetabulum injury.

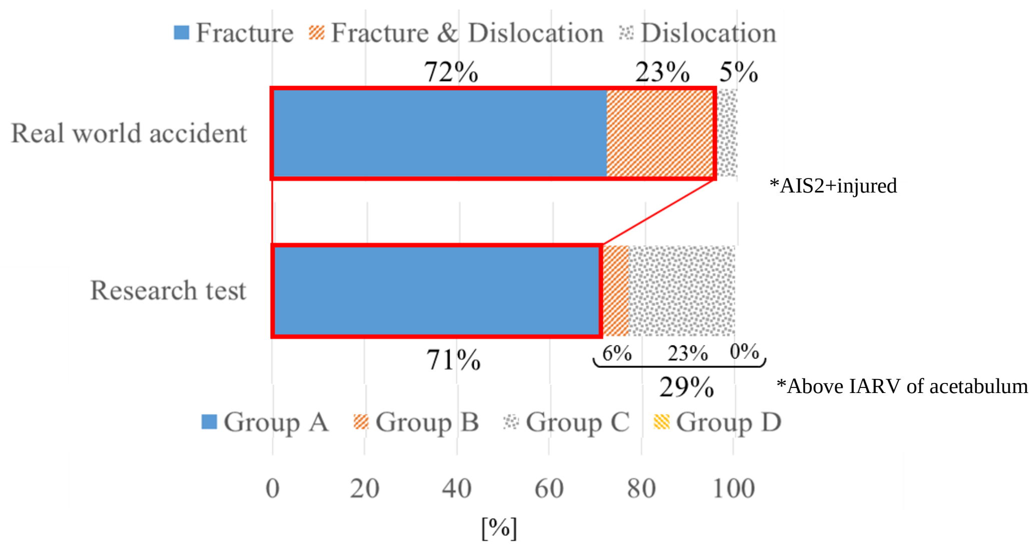
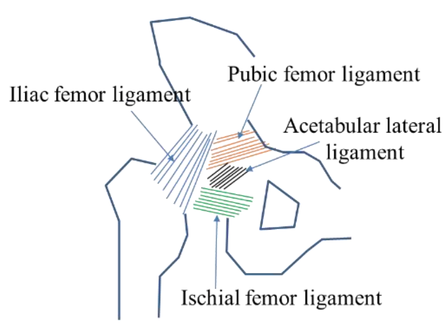


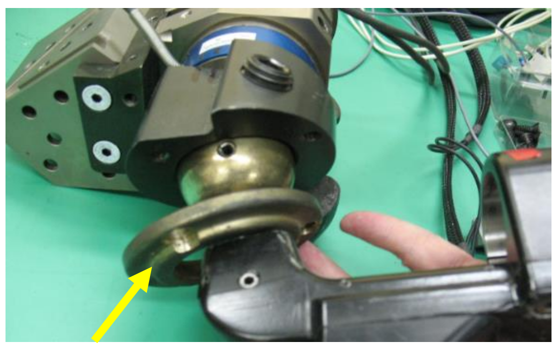
Figure 19. Comparison of research tests and real world accidents acetabulum injury

1) Structural difference between THOR dummy and a human anatomical structure around the hip joint

As shown in Fig. 20, in the human body, the acetabulum and the femoral head are connected by complex 3-D ligaments. On the other hand, in THOR dummy they are connected with a simple metal ball joint. When a tensile load is applied from the femur, the ligaments extend in the human body, but in THOR dummy, a high tensile load corresponding to the rigidity of the metal part is transmitted directly to the acetabulum. For this reason, it is expected that there is some difference in the amount of transmitted tensile load between them.



(a)Human



(b)THOR dummy

Figure 20. Around of acetabulum of right side

2) Evaluation method of acetabulum injury

Although the current existing injury criterion is based on injuries due to compression [3], the effect of compression and tension modes are equally treated in the proposed revision of the new US-NCAP [1]. There is a possibility that this may affect the occurrence frequency of those cases which are judged as serious injury. Figure 21 shows the ratios of injuries in each part to the total number of injuries in the research tests and real world accidents. In comparison with the research tests and the real world accidents, the injury of acetabulum are 16% and 6.3%, respectively. The percentage of research tests is higher than that in real world accidents. Excluding the tensile load of acetabulum Fx from the evaluation, that is, without counting those cases belong to groups B to D which occurred due to the tension in Fig. 19, the ratio of acetabulum injury in the research tests is about 12%. Then, the relative proportions of research tests will be closer to that of the real world accidents. Therefore, by improving the criterion appropriately, there is a possibility to close the gap or difference in acetabulum injury occurrence mode between the research tests and the real world accidents, by matching them closer to each other.

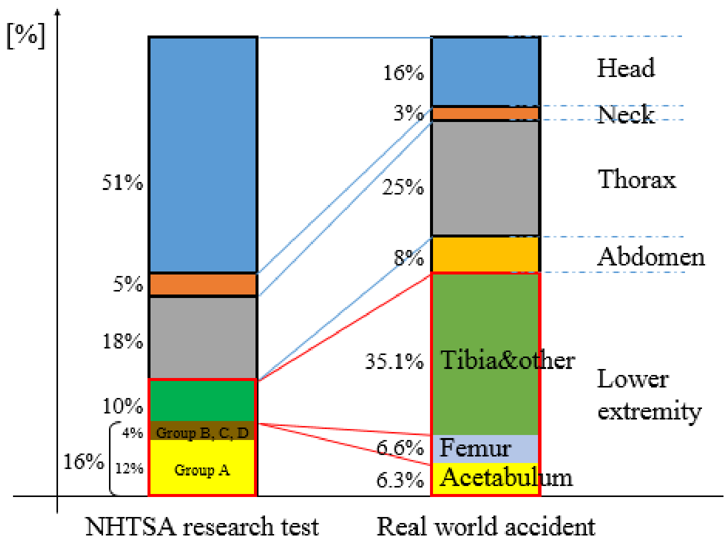


Figure 21. Percentage of acetabulum injury

CONCLUSION

Focusing on the direction (tension/compression) of acetabulum force Fx in the NHTSA research tests related to the US-NCAP revision proposal, the consistency of those research test results with real world accidents was investigated. As a result, the incidence in testing of the compression mode considered to be consistent with the real world accidents was 71%. On the other hand, the remaining 29% is a mode in which the injury value is determined by tension, and there is some possibility that it is not consistent with real world accidents.
Two of the possible main reasons are (i) the structual difference on the tension side of the human body and the hip joint of the THOR dummy and (ii) the judgement of acetabulum tensile load evaluated in the same way as compression mode when evaluating the injury value.
In future, further studies related to the above mentioned two factors are necessary in order to make the acetabulum injury risk evaluation method more appropriate.

ABBREVIATION

・FRB：Full Frontal Rigid Barrier
・IARV：Injury Assessment Reference Value
・LO：Left Oblique
・NASS-CDS：National Automotive Sampling System Crash worthiness Data System
・NHTSA：National Highway Traffic Safety Administration
・PMHS：Post Mortem Human Surrogate
・RO：Right Oblique
・THOR：Test device for Human Occupant Restraint
・THUMS：Total Human Model for Safety
・US-NCAP：The U.S. New Car Assessment Program

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Appendix A (NHTSA Research Test Data)

Selected cases is the following “○”. Acetabulum resultant force is above IARV in the following shading cases.

Selected data of LO

No.	Vehicle	Data(Driver)	Data(Passenger)
v07467	2011 BUICK LACROSSE	○	Not Available
v07851	2011 CHEVROLET CRUZE	○	NA
v07852	2011 CHEVROLET CRUZE	○	NA
v08475	2013 VOLVO XC60	○	○
v08476	2013 DODGE DART	○	○
v08477	2013 HONDA CIVIC	No data	○
v08478	2013 SUBARU FORESTER	○	○
v08488	2012 VOLVO S60	○	○
v08787	2014 MAZDA 3	○	○
v08788	2014 MAZDA CX-5	○	No data
v08790	2014 TOYOTA CAMRY	○	○
v08791	2014 HONDA ODYSSEY	○	○
v09043	2015 HONDA FIT	○	○
v09122	2013 NISSAN VERSA	○	○
v09123	2013 HYUNDAI ELANTRA	○	○
v09124	2012 TOYOTA CAMRY	○	○
v09125	2013 FORD TAURUS	○	○
v09126	2012 HONDA CR-V	○	○
v09127	2012 HONDA ODYSSEY	○	○
v09128	2012 CHEVROLET SILVERADO	No data	○
v09206	2011 CHEVROLET CRUZE	○	NA
v09208	2011 FORD EXPLORER	○	NA
v09212	2011 TOYOTA YARIS	○	NA
v09217	2011 DODGE RAM	○	NA

Selected data of RO

No.	Vehicle	Data(Driver)	Data(Passenger)
v08998	2014 MAZDA CX-5	○	○
v09042	2014 HONDA ACCORD	○	○
v09110	2012 NISSAN VERSA	○	○
v09121	2012 TOYOTA CAMRY	○	○
v09354	2015 SUBARU FORESTER	○	○
v09477	2015 CHEVROLET MALIBU	○	○
v09478	2015 FORD F-150	○	○
v09480	2015 TOYOTA HIGHLANDER	○	○
v09483	2015 VOLVO S60	○	○

Selected data of FRB

No.	Vehicle	Data(Driver)	Data(Passenger)
9333	Malibu	○	-
9334	Highlander	○	-
9336	MAZDA3	○	-
9337	FIT	○	-
9335	F-150	○	-

Appendix B

Number of injury above IARV (body region)

Injury	LO Driver	LO Passenger	RO Driver	RO Passenger	FRB Driver	SUM
Head	18	20	8	8	0	54
Neck	3	0	2	0	0	5
Thorax	12	3	0	3	1	19
Abdomen	0	0	0	0	0	0
Lower extremity	17	6	3	1	0	27

Number of injury above IARV (lower extremity)

Injury	LO Driver	LO Passenger	RO Driver	RO Passenger	FRB Driver	SUM
Acetabulum	8	6	2	1	0	17(12/5)*
Femur	0	0	0	0	0	0
Tibia	9	0	1	0	0	10

*Group A (compressive load) is 12 case, Group B~D (tensile load) is 5case.