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Severity of cyclist head injuries caused by impacts with vehicle structure and road surface

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Abstract
For cyclist fatalities in 2014 in Japan, the head was the most frequently injured body region. In the present study, the authors analyzed the features of cyclist head injuries in real-world traffic accidents using the data of patients who were taken to the emergency room in Dokkyo Medical University Koshigaya Hospital in Japan, from 2011 to 2013. The results indicated that the percentage of skull fractures was the highest among cyclist head injuries. Assuming that a helmet can prevent head injuries sustained by cyclists in traffic accidents, the effect of wearing a helmet was investigated in impact tests against a vehicle and road pavement. In the tests, the severity of potential head injuries was determined from the Head Injury Criterion (HIC) obtained in an adult pedestrian head-form impactor with and without a helmet. The impact location selected for a vehicle was the A-pillar because the pillar had much higher stiffness than the vehicle bonnet or windshield. It was found that the HIC values for the head-form impactor wearing a helmet were much lower than the HIC values for the head-form impactor not wearing a helmet in both the head-versus-A-pillar impacts and head-versus-pavement impacts. The results suggest that wearing a helmet could reduce the possibility of skull fracture in cyclists.

Key words : Cyclist, Head injury, Skull fracture, Traffic accident, Vehicle, Helmet

1. Introduction

In 2014, there were 715487 injuries and fatalities in traffic accidents in Japan, of which 108539 (15%) were cyclists as shown in Fig. 1 (a) (ITARDA 2015). The number of traffic deaths decreased in Japan over a period of 20 years to 4113 in 2014. Among the various types of road accident injuries and fatalities in 2014, vulnerable road users of pedestrians and cyclists accounted for 50% (2038) of the 4113 fatalities as shown in Fig. 1 (b). The Japanese government began assessing the safety performance of car bonnet tops in 2005 in an effort to reduce the number of pedestrian deaths (Matsui and Tanahashi 2004), but in Japan, there are no effective regulation for cyclist protection at this time. Figure 2 shows the main body regions of cyclists that were injured in 2014 (ITARDA 2015). For cyclist fatalities, the head was the most frequently injured body region. The implementation of countermeasures that could decrease the severity of cyclist injuries and fatalities in traffic accidents requires a detailed understanding of the features of cyclist injuries in traffic accidents. The first purpose in this study is to clarify the features of cyclist head injuries in traffic accidents. In the current study, the authors investigated the features of cyclist head injuries by analyzing the data for patients who were taken to the emergency center of Dokkyo Medical University Koshigaya Hospital in Japan.

The analysis of impact situations for cyclists involved in car crashes showed that cyclists' heads generally impacted windscreens and A-pillars, and less frequently impacted the roof (Peng et al. 2012). One of the countermeasures proposed to reduce the severity of cyclist head injury is a helmet (Cummings et al. 2006). The results from accident analyses

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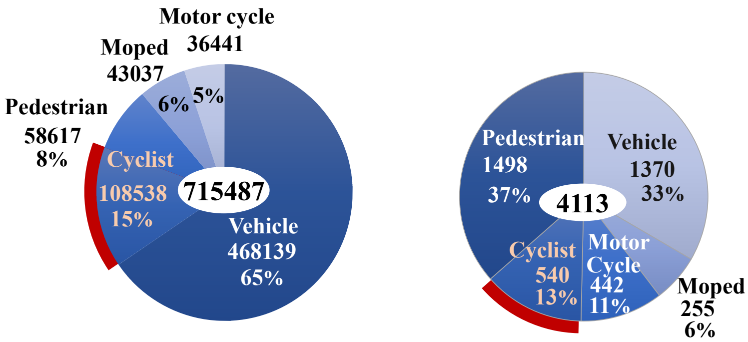
showed that the most frequent impact locations for a helmet were its side and front. Usually, there was little damage to the top or back of the helmet (Ching et al. 1997). The cause of injury to a victim's head and the severity of injury for different surfaces of impacts need to be investigated; i.e., the severity of fatal injuries to a cyclist's head that comes in contact with a vehicle and/or a road surface should be investigated in detail. The second purpose of this study is to assess the beneficial effect of wearing a helmet as indicated by the HIC level in a head-form impactor when the side of a helmet is impacted against the vehicle body and the road pavement.



(a) Injury and fatality (b) Fatality

Fig. 1 Traffic injuries and fatalities by road users in Japan in 2014. (ITARDA 2015)

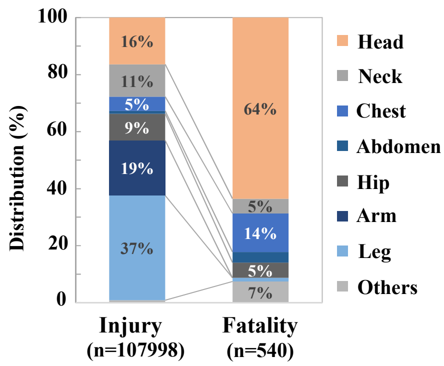


Fig. 2 Main injured body regions of cyclists in 2014. (ITARDA 2015)

2. Method
2.1 Analyses of cyclist head injuries

The present study analyzed the characteristics of cyclist head injuries using the emergency patient data (EPD) obtained from the medical emergency center of Dokkyo Medical University Koshigaya Hospital in Saitama prefecture of Japan. Dokkyo medical emergency center, one of the six medical emergency centers in Saitama prefecture, meets the needs of the population in the east area approximating 1.7 million. The EPD of Dokkyo medical emergency center from 2011 to 2013 were analyzed. The EPD contains the information on patient gender, age, external cause of injury, disease name, diagnoses, severity of injury and so on. The proportion of the EPD that involved exogenous disease is presented in Fig. 3. During the three year period from 2011 to 2013, Dokkyo medical emergency center had accepted 1083 emergency patients due to external causes. The highest proportion was emergency patients due to traffic accidents of 33% (358), where motor cyclists represented the highest percentage of 28% (101), followed by cyclists of 26% (92), as shown in Fig. 4. In traffic accidents, the proportion of male patients was much larger than female; 72% (258) of male and 28% (99) of female (Fig. 5 (a)). Among cyclists involved in traffic accidents also, the proportion of male patients was larger than female; 58% (53) of male and 41% (38) of female (Fig. 5 (b)). In the present study, the authors investigated the distribution of the age group and the types of head injuries caused in traffic accidents involving cyclists. The data used in the present study was approved by ethical committee of the Dokkyo Medical University Koshigaya Hospital.

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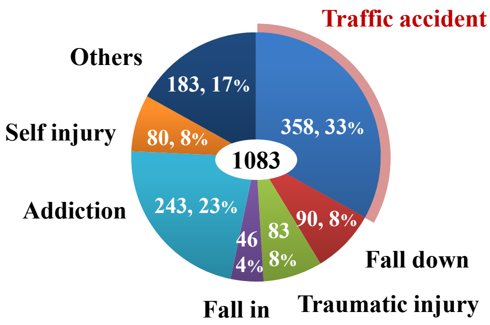


Fig. 3 Emergency patients by exogenous disease from 2011 to 2013.

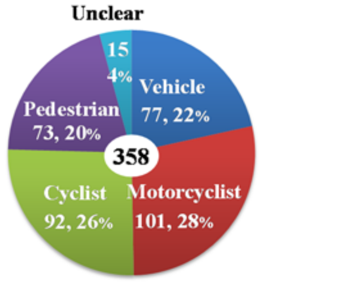
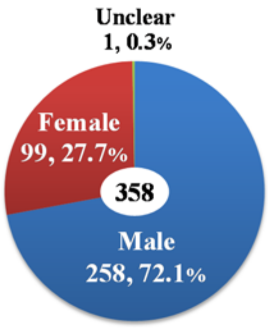
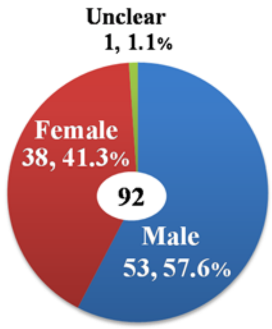


Fig. 4 Emergency patients in traffic accidents by road users.



(a) Overall emergency patients in traffic accidents



(b) Cyclists

Fig. 5 Ratio of male and female in emergency patients in traffic accidents.

2.2 Impact experiments

Assuming that a helmet could prevent cyclists receiving head injuries in traffic accidents, the effect of wearing a helmet was investigated in impact tests against vehicle frontal structures and road pavement. In the impact experiments using a vehicle, a pedestrian head-form impactor with and without wearing an adult helmet was impacted against the A-pillar of a light passenger car at a specific location. A-pillar impacts yield higher HIC values than other locations in a vehicle indicating a higher potential for more severe injuries than, for example, the windshield (Matsui 2004). In the current study, the lower part of the right side A-pillar of the car was selected for impacts, because the edge of the A-pillar has higher stiffness than that for its center part. In the impact against road pavement, a pedestrian head-form impactor wearing a helmet was dropped onto road pavement from a certain height to assess the potential for severe injury in contacts with the road surface. In both impact experiments for a vehicle and road pavement, the side of the helmet was impacted, since that was the region generally seen as the most frequently impacted region in the helmet in real-world traffic accidents.

2.2.1 Head-form impactor

An adult head-form impactor weighing 4.5 kg (Matsui and Tanahashi 2004) was used to measure the injury severity in impacts against A-pillars and road pavement. Such head-forms are typically used for regulatory and New Car Assessment Program (NCAP) testing in pedestrian safety evaluation in Japan. The head-form impactor consists mainly of a hemispherical part representing the head of human body and a base plate, both made of aluminum. The hemisphere is covered by a skin material made of polyvinyl chloride (PVC), as presented in Fig. 6. Three axial accelerometers are installed at the center of gravity of the head-form impactor. Three damped uniaxial accelerometers (Kyowa ASE-A-500) were installed in the adult head-form impactor. A cable-less head-form impactor was selected to eliminate noise in the data usually found when cable-equipped impactors were used (Matsui 2014). The cable-less head-form impactor has a built in, portable small-sized data acquisition system powered by a lithium-ion battery (Kyowa DIS-503A).

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2.2.2 Impact material and location of a helmet

In the impact experiments, FIGO G-1 (OGK Kabuto 2012), a bicycle helmet for an adult male was used (Fig. 7). The helmet has 16 ventilation holes, a chin strap, and padding made of soft polyurethane foam filling the gap between the head and the liner interior surface. The helmet has a maximum internal length of 220 mm and maximum width of 180 mm. The rear part of the helmet is not covered by a shell as shown in Figure 7. The mass of the helmet is 0.250 kg. Both impact tests against a vehicle and road pavement were conducted by impacts of the side area of a helmet as shown in Fig. 7.

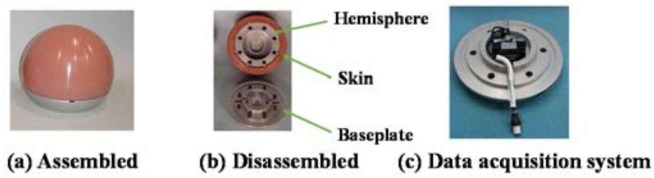

Fig. 6 Head-form impactor.

Fig. 7 Rear and bottom views of helmets.

2.2.3 Experimental conditions in impact tests against a vehicle

A 2003 model year light passenger car having the displacement of 660 cc or less was used since this type of a vehicle was popular in Japan. Figure 8 shows the light passenger car used in the experiment. It is reported that cyclists' heads are the most frequently impacted body regions against the windshields of vehicles in real world accidents (Peng et al. 2012). Based on the accident situation, a cyclist's head is impacted more frequently away from the center of a windshield (Otte 2015). Both the upper and lower edges of an A-pillar has higher stiffness than the center part of an A-pillar (Matsui 2004). In the current study, the lower edge of the right side A-pillar (Fig. 9) was selected as the impact location for the light passenger car. It should be noted here that the head-form impactor would contact both the A-pillar and rear end of the bonnet that was likely to reduce the impact severity level because of the relatively soft area of the bonnet. In this study, an impact point 70 mm away from the lower edge of the A-pillar was selected.

Fig. 8 Light passenger car used in the present study.

Fig. 9 Impact location.

The impact experiments against the lower edge of the A-pillar were conducted using the head-form impactor as shown in Fig. 10 (a). The target impact velocity and impact angle of the head-form impactor were set to 35 km/h and 65 degrees from the horizontal line, respectively, as shown in Fig. 10 (b). These test conditions were established on the basis of the results obtained from simulated vehicle-to-cyclist impacts using finite element models, when the vehicle impact velocity was 40 km/h. (Yamada et al., 2014). In this setup, the head-form impactor was connected to wires that limited the motion of the head-form impactor immediately following the impacts against the A-pillar in the experiments. Also, the head-form impactor was connected to a ground by a wire to avoid cumulative electricity in the head-form impactor. For the case of wearing a helmet, the side of a helmet was impacted against the lower edge of the A-pillar.

The result of the impact experiments against an A-pillar was evaluated in terms of the HIC values calculated from the resultant of the three measured accelerations in the x, y, and z directions. The time history of the resultant accelerations and the HIC values for the adult head-form impactor with and without a helmet were compared. The HIC values were

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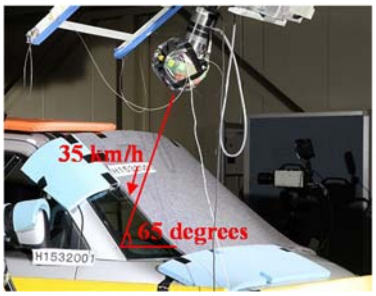
calculated using the following equation Eq. (1) (Eppinger et al. 1999).

$$HIC = \max \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t)dt \right]^{2.5} (t_2 - t_1) \qquad (1)$$

where $t_2 - t_1$ is an interval of any two arbitrary times, t_1 and t_2, in 15 ms.

(a) Not wearing a helmet



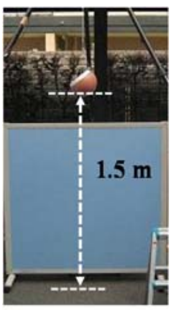
(b) Wearing a helmet

Fig. 10 Impact situation against the lower edge of the A-pillar by head-form impactor.

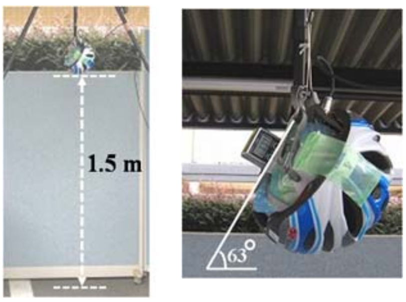
2.2.4 Experimental conditions in impact tests against road pavement

In the impact experiments against road pavement, the authors set a drop height of 1.5 meters measured as the distance between the side of the head-form impactor and the road surface ignoring the presence of the helmet. This distance was based on our previous study, in which a pedestrian head-form impactor was dropped onto a road surface to investigate the severity of injury to a pedestrian's head (Matsui et al., 2013). In the test conducted by Matsui et al. (2013), the drop height from the road surface was set as 1.5 m as shown in Fig. 11 (a). It is because the average eye height of Japanese males who are older than 13 years is 1.53 m according to the Research Institute of Human Engineering for Quality Life (HQL) (1997). In the present study, the authors investigated the differences in eye heights between a normal standing position (Fig. 12 (a)) and a riding position on a bicycle (Fig. 12 (b)). The test protocol employing volunteers in the present study was approved by the ethical committee of the National Traffic Safety and Environment Laboratory (NTSEL) in Japan. The maximum difference of eye heights was 0.03 meters for the five subjects studied as listed in Table 1. Therefore, it was assumed that the eye height of a pedestrian was the same as that of a cyclist. For the road surface, asphalt was selected as the material of the road pavement, because asphalt was the material most commonly used for road surfaces in Japan.

The side of the helmet (Fig. 7) was selected as the impact locations of the helmet in impact tests against road pavement. The angle of intersection between the bottom surface of the head-form impactor base plate and the line of the horizontal was determined to be 63 degrees, as shown in Figure 11.



(a) Headform impactor (Matsui et al. 2013)



(b) Head-form impactor wearing a helmet

Fig. 11 Impact tests against road pavement.

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Fig. 12 Measured eye heights for a normal standing position (a) and a riding position on a bicycle (b).

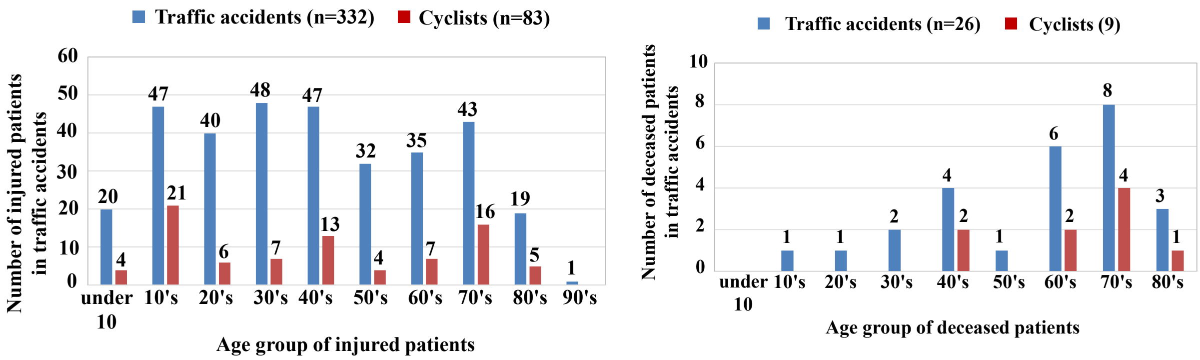
Table 1 Differences in eye heights between a normal standing position and a riding position on a bicycle.

Participants	Eye height (m)		
	(a) Standing position	(b) Riding position on a bicycle	Difference (b)-(a)
#1	1.625	1.625	0.000
#2	1.640	1.640	0.000
#3	1.590	1.570	-0.020
#4	1.470	1.490	0.020
#5	1.590	1.620	0.030

3. Results

3.1 Analyses of cyclist head injuries

The overall number of emergency patients involved in traffic accidents was 358 in the EPD from 2011 to 2013, which included 92 cyclists. Of the total of 358 emergency patients involved in traffic accidents, there were 332 injured patients and 26 deceased patients. Of the 92 cyclists involved, 83 were injured and 9 died in crashes. Fig. 13 presents the population by age groups for injured patients and deceased patients. Each of Fig. 13 (a) and (b) shows the number injured or deceased in traffic accidents by age groups along with the number of cyclists injured or deceased in those. Please be noticed here that each number of traffic accidents in different age groups includes each number of cyclists. The results indicated that the groups that had more patients injured in traffic accidents belonged to age 10's (47), 30's (48), 40's (47) and 70's (43). The largest number injured among cyclists was of age group 10's (21). On the other hand, the age group of deceased patients that had the highest count belonged to age 70's in traffic accidents and also among cyclists.



(a) Injured patients (b) Deceased patients

Fig. 13 Age group of emergency patients involved in traffic accidents along with cyclists.

Of the 92 cyclists involved in traffic crashes, 51 % (47) had head injuries as shown in Table 2. Some cyclists had multiple injuries. Counting the number of cyclist head injuries by types, the total number was 76 in 47 cyclists with head injuries. That is, the average number of cyclist head injuries by types per person was 1.6.

The distribution of 76 head injures by types among cyclists is presented in Fig. 14. The results found that skull fracture (19, 25%) was the most frequent, followed by subarachnoid bleeding (12, 16%) and subdural hematoma (9, 12%).

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Table 2 Number and ratio of cyclists with head injury and average number of head injuries by types per person.

Items	Cyclists
Number of cyclists in emergency patients (a)	92
Number of head-injured cyclists (b)	47
Ratio of head-injured cyclits (b) / (a)	51%
Number of head injuries by types (c)	76
Average number of head injuries by types per person (c) / (b)	1.6

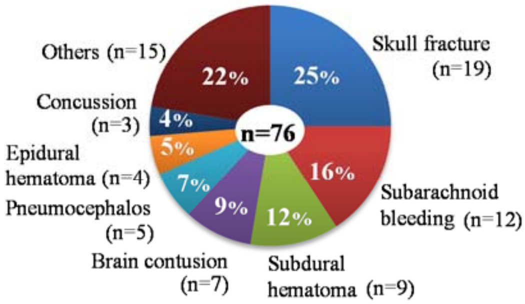

Fig. 14 Component rates of cyclist head injuries by types.

3.2 Impact experiments

Figure 15 shows the resultant acceleration–time history along with the calculated HIC values for impacts against the lower edge of the A-pillar measured by the adult head-form impactor with and without a helmet. In the impact against the lower edge of the A-pillar, the maximum resultant accelerations were 2275 m/s^2 and 4189 m/s^2 with a helmet and without, respectively, while the calculated HIC values were 2644 and 6529 for the same. Measured accelerations by the head-form impactor and calculated HIC values with and without a helmet are summarized in Table 3. The result found 60% reduction in the HIC values when a helmet was worn. Please note that the HIC value for wearing a helmet was over 1700, which is considered to be the threshold level of HIC for the "rigid parts of a car bonnet" established in the Japanese regulation for pedestrian head protection (JASIC 2013). To understand the reproducibility of the test device, we investigated the HIC values (2644 and 2790) by two impact test results under the same impact test condition, such as the adult head-form impactor with a helmet against the lower edge of the A-pillar. The ratio of the difference in the two tests to their average was 5%, showing that the measurements of HIC was reproducible.

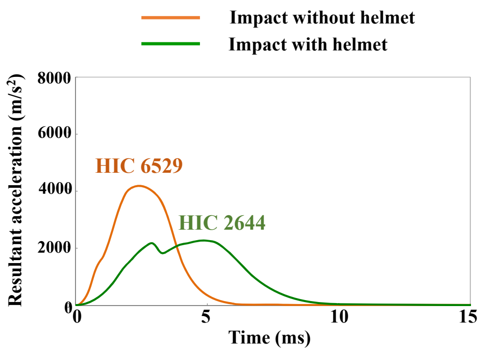

Fig. 15 Histories of resultant acceleration in the impacts against the edge of A-pillar by a head-form impactor with and without a helmet.

Table 3 Measured maximum resultant accelerations and HIC in the impacts against the edge of A-pillar.

Items / Conditions	Max resultant accelerations	HIC	Reduction of HIC {(a) - (b)} / (a) * 100
Without helmet (a)	**4189 m/s^2**	**6529**	**60%**
With helmet (b)	**2275 m/s^2**	**2644**	

For the impact experiments against road pavement, the resultant acceleration along with the calculated HIC values was obtained using the adult head-form impactor with and without a helmet. The maximum resultant accelerations were 1571 m/s^2 and 6434 m/s^2 for the conditions with and without a helmet, respectively. The HIC values were 885 and 6525 for the same two conditions, namely, with the helmet and without. Table 4 presents the measured accelerations and the HIC values using the head-form impactor under the two conditions stated above, in impact experiments against road pavement. These results showed an 86% reduction in HIC values when the helmet was used. The HIC value (885) for the adult head-form impactor wearing a helmet was 48% below the threshold level of 1700. To understand the reproducibility of the test device, we investigated the HIC values (865 and 860) by two impact test results under the same impact test condition, such as the adult head-form impactor with a helmet against the road pavement. The ratio of the difference in the two tests to their average was 3%, showing that the measurements of HIC was reproducible.

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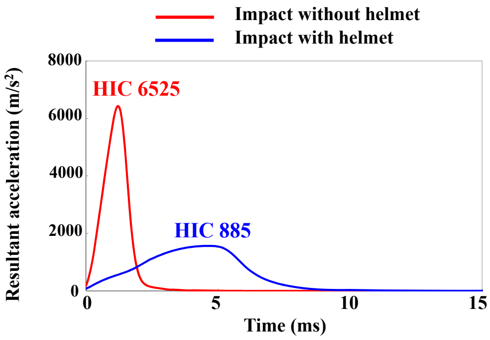

Fig. 16 Histories of resultant acceleration in the impacts against a road pavement by a head-form impactor with and without a helmet.

Table 4 Measured maximum resultant accelerations and HIC in the impacts against a road pavement.

Items / Conditions	Max resultant accelerations	HIC	Reduction of HIC {(a) - (b)} / (a) * 100
Without helmet (a)	6434 m/s^2	6525	86%
With helmet (b)	1571 m/s^2	885	

4. Discussion and Conclusions

This study was conducted to investigate the characteristics of cyclist head injuries in traffic crashes by analyzing the data of emergency room patients including cyclists. The result revealed that skull fracture (19, 25%) was found to be the most frequently involved. The HIC criteria has a historical basis related to the Wayne State Tolerance Curve (WSTC) that was developed from the early research work that determined the tolerance level of the head to skull fracture loads and its relationship to brain injury (Eppinger et al. 1999). Considering the background of the HIC, the HIC values in impact experiments were obtained in order to find the beneficial effect of wearing a helmet to prevent cyclist head injuries, possibly due to application of loads that could cause skull fracture.

The emergency patient data (EPD) did not have any information on the status of helmet wearing among the cyclists who were treated in emergency rooms. Therefore, the authors could not evaluate the differences in the types of head injuries seen in the data on the basis of helmet use by the victims. Additional studies should be conducted to examine whether there would be differences in the types of cyclist head injuries on the basis of helmet use seen among patients coming to emergency rooms in the future. By noting the status of helmet use among cyclists with head injuries that arrive in hospital emergency rooms, it would be possible to analyze future data to understand real-world benefits of helmet use.

The authors investigated the effect of wearing a helmet in impact tests against a vehicle and road pavement by using an adult pedestrian head-form impactor in both cases, with and without a helmet. In tests, the severity of potential head injuries was determined using the Head Injury Criterion (HIC) as an injury assessment criterion for possible evaluation of skull fracture. The impact location for a vehicle was the A-pillar because the pillar had much higher stiffness than the vehicle bonnet or windshield. It was found that the HIC values for the head-form impactor wearing a helmet were much lower than those for the head-form impactor not wearing a helmet in both the head-versus-A-pillar impact and head-versus-pavement impact. The results suggest that wearing a helmet could reduce the possibility of skull fracture in cyclists.

Figure 17 shows the sides of helmets after the impacts against the lower edge of A-pillar and road pavement. It was observed that the helmets had visible cracks in both experiments. From these results, the mechanism of the reduction of HIC values by wearing a helmet is considered that the form material in the helmet could absorb impact energy. In future work, the mechanism of absorbing impact energy of a helmet should be clarified by the computer simulations with an appropriate helmet model.

(a) Against A-pillar

(b) Against road pavement

Fig. 17 Observed cracks after the impact tests.

The lower edge of the A-pillar was selected for the impact location in the experiment, because this region of the pillar had a much higher stiffness than the vehicle bonnet or windshield. Considering actual accidents involving cyclists,

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the effect of wearing a helmet should also be investigated in the impact with other parts having lower stiffness in a vehicle.

In the impact experiment against the lower edge of A-pillar, the target impact velocity and impact angle of the head-form impactors were set at 35 km/h, and 65 degrees from horizontal line, respectively, based on impact analyses studies using finite element models. In the model analyses conducted by Yamada et al., an AM50 dummy finite element model (FE model) on a bicycle model was impacted by the center of a sedan FE model at 40 km/h. The relative head impact velocity with respect to the vehicle was 36.8 km/h and its direction was 66 degrees, (Yamada et al. 2014). They were close to the impact condition adopted in the present study. Generally, the impact conditions, such as impact velocity and impact angle, might be influenced by several factors, such as bicycle velocity, the riding posture of a cyclist, or the impact location of a vehicle under deceleration by the brake. The impact conditions in the present study represented only one scene where a cyclist was impacted by a vehicle at 40 km/h. The real-world traffic accident cases involving cyclists could have much higher or lower vehicle travel velocities. Therefore, further experiments are required to see the effect of different conditions of impact for cyclists' heads with vehicle travel velocities over or less 40 km/h.

Also, in the impact experiment against the lower edge of A-pillar, the HIC value for wearing a helmet was over 1700. In order to reduce the HIC value much more, the additional energy absorbing padding or inflatable padding would be necessary for the A-pillar while ensuring proper visibility for a driver.

In impact experiments against road pavement, the drop height was determined on the basis of only the potential energy of the head. However, in general vehicle-to-cyclist accidents, the kinetic energy is imparted to the cyclist from the horizontal velocity of the vehicle. This could result in a rotational velocity component of the cyclist head causing injuries to the head, which might be more severe. In future work, the severity of injury to the cyclist's head caused by the rotational velocity should also be investigated, which could evolve into the assessment of brain injury by the rotational acceleration of cyclists' heads.

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