Simulation for Creating Safety Knowledge from Injury Case

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***Abstract*— An injury case that skull fracture occurred when a little girl child fell from staircase of a slide was reconstructed by using the fall simulator for the injured child to analyze and identify the cause and countermeasure. The fall simulator consists of both multi-body model for the whole body to analyze and identify fall behavior in the accident and finite element model of the head to deeply investigate the head injury mechanism. The child fall simulator proved its usefulness that it compensates for lack of accident information corrected at an injury surveillance system and showed the accident scenario precisely. Moreover, the simulator made it possible to reveal latent danger in the environment which is much more dangerous than the case reported and evaluate the effectiveness of the countermeasure.**

***Index Terms*—Child injury prevention, Fall simulator, Head injury, Accident reconstruction**

I. INTRODUCTION

Leading cause of death for children from 1 to 14 years in Japan has not changed for 30 years, which is ‘accidental death’. Therefore, a national project named ‘safety-knowledge circulation’ has been carried out by Ministry of Economy, Trade and Industry Japan, in order to prevent ‘accidental injury’ [1]. The project aims to systematically correct children’s accident data at hospitals and utilize those to identify the cause and study how to cope with the accidents. Moreover, the project contains the delivery system of the information of the cause and countermeasure to the public, in order to prevent the recurrence. This paper focuses on to describe a part of the project, which is how to create general safety knowledge from injury cases by analyzing and identifying the cause of accidents.

In order that the accident analyses are to be effective, it is necessary to select more important accident cases by considering both frequency and severity. According to accident cases in 2007 corrected at hospitals participating the project, 54.4% of 2496 accidents cases was caused by ‘fall’ and 65.0% of the injury parts was ‘head’. Therefore, head injury in case of fall must be prevented.

Computer simulation is effective for analyzing accidents like falling because the analysis using digital human model makes it possible to reconstruct the accident situation. And, in addition, more dangerous situation can be analyzed only if the initial conditions are changed in the computer. Although an accident data corrected by injury surveillance system are used to define the simulation condition, the data does not include detailed information about accident circumstances at the time when the accident occurs. In fact, the corrected data only contains a few kinds of pre or post-accident data because the correction method depends on interview with injured child or the parents by physicians. Thus, accident circumstance lacked in the corrected data has to be inferred as inverse problem based on the little information. Moreover, an accident occurred and corrected in the environment is just the tip of the iceberg. Therefore, it is necessary to clarify and obviate other latent danger to realize safe environment for children. Computer simulation using digital-human models makes it possible to solve these problems.

Many digital-human models to analyze human behavior or injury in accidents have been developed for the purpose of prediction of injury. There are two types of the models; one of them is a multi-body model [2] and another one is a finite element (FE) model [3]. Multi-body model, composed of rigid links connected by joints, has an advantage for the short calculation time and ease of the posture change. Therefore, multi-body model is useful for carrying out a large amount of simulations to infer the accident situation. On the other hands, finite element model makes it possible to analyze tissue deformation exceeding tolerance level although the calculation time is longer. Therefore, it is effective for the analysis of head injury in falling to use a model combining the multi-body and finite element model depending on the accident circumstances.

Therefore, we constructed children fall simulator which consists of both the multi-body model for the whole body to analyze and identify fall behavior in the accident and finite element model of the head to deeply investigate the head injury mechanism by applying the head motion calculated in multi-body simulation. Moreover, a severe head injury case, which was corrected in the accident surveillance system, was reconstructed to analyze and identify the cause and countermeasure of the real accident.

II. OBJECTIVE INJURY CASE

A serious head injury in case of falling at the stair in a slide was reported to the injury surveillance system. The accident case is described here. A one year and eleven month girl child,

Fig.1 Slide with straight staircase where an serious head injury occurred

who was 81.6cm height and 10.0kg weight, was fallen from the 3rd or 4th stair of a slide in a certain public park, shown in Fig.1. The material of the surface where the head was hit was concrete. And the child grabbed the left rail by both hands. After falling, the head bounced on the concrete, and the child lied face down with the head being near the base of the left rail. Chief complaint was a headache and the state of consciousness was normal without vomiting. Although there is no intumescence in initial findings, X-ray picture showed linear skull fracture of right parietal bone and computed tomography (CT) showed an epidural hematoma under the impact site.

The injury case was reconstructed by using simulation models to analyze and identify the cause and countermeasure for the accident.

III. CONSTRUCTION OF SIMULATION MODELS

Schematic view of the analysis method for the injury case is shown in Fig.2. Since the injury case described in previous section was based on the interview with injured child and the mother, only little pre-accident information was available. They did not remember details of the circumstances. Therefore, the lacked information of the circumstances, such as the initial posture and position, should be inferred and identified from the results of simulations which initial conditions were varied. Thus, injured child's whole body and actual slide was modeled by multi-body in order to infer the initial conditions consistent with the post accident circumstances. Moreover, the child head finite element model was constructed by using shape transformation from a generic adult model we had constructed. Finally, head impact simulations with the surface finite element model were carried out to estimate the effect of the surface stiffness to the occurrence of head injury. MADYMO ver6.4 (TNO Automotive) and RADIOSS ver5.1 (Altair Engineering co.) were used for the simulations.

A. Multi-body model for whole body

A multi-body model for the girl child, based on the dimensions of Japanese children, was constructed based on the method in Miyazaki et al.[2]. Fig.3 shows the process used to construct the model. And Fig.4 shows the model consisting of 17 ellipsoidal segments and 16 joints; the head, neck, thorax, abdomen, pelvis, thighs, calves, feet, upper arms, lower arms and hands. The shape, location of the center of gravity of each segment and the location of the joints were calculated from 39 different body dimensions estimated from the child's height and weight. The inertial properties were calculated from the body segment parameters of Japanese children [4].

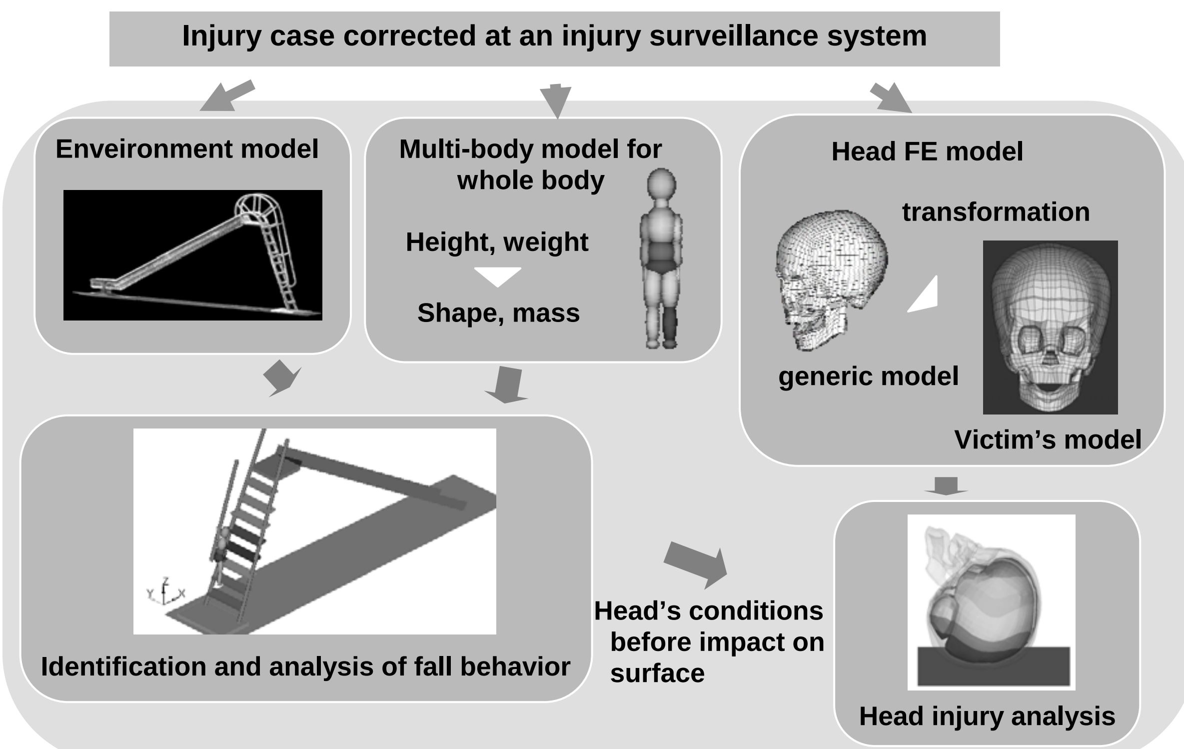


Fig. 2 Schematic diagram to analyze the injury case by using the child fall simulator

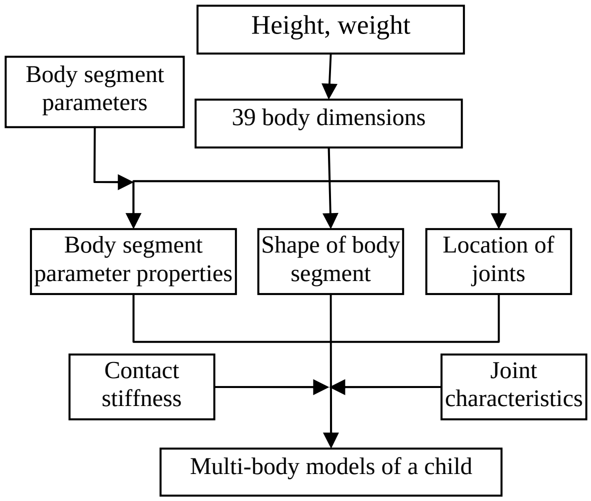


Fig. 3 Construction method for multi-body model of a child

Fig. 4 Multi-body model of a child

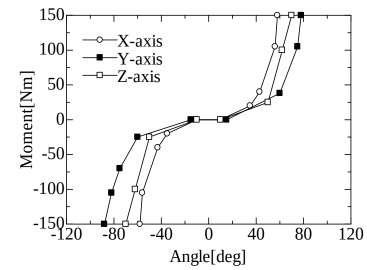


Fig. 5 Joint characteristics of the neck

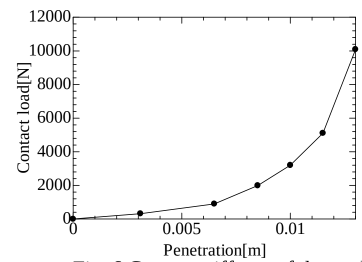
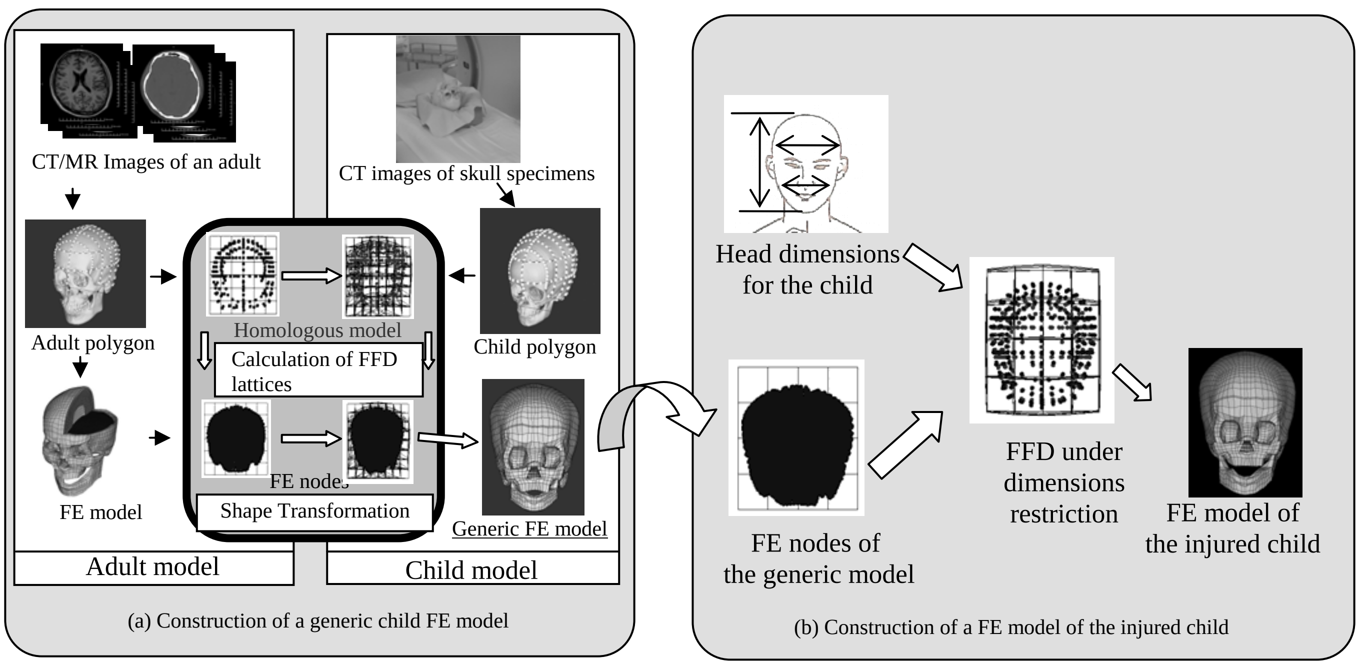


Fig. 6 Contact stiffness of the neck



(a) Construction of a generic child FE model

(b) Construction of a FE model of the injured child

Fig.7 Construction of a child head FE model using FFD method

Joint characteristics were expressed as a relationship between joint angle and passive torque, which the torque is zero within the range of the motion, as shown in Fig.5 [5]. Although the joint characteristics should be for the child, the characteristics of adult males were used due to a lack of data. However, the difference seems to have no practical impact on the results in this accident case because each joint motion did not reach the limit of the range in this case.

The contact stiffness of each segment was expressed as a nonlinear relationship between penetration and the contact force shown in Fig.6. The relationships for contact stiffness were defined by using the data of a Hybrid-III dummy.

B. Finite element model of the head

The method to construct finite element model for a child was developed, as shown in Fig.7. Although head shape of a child differs greatly from adult's one, child head's FE model with high shape fidelity has not been constructed yet.

Therefore, we constructed a child head FE model representing the precise shape based on CT images of the skull sample estimated 2 or 3 years old, provided by Tokyo University, and the model constructed was regarded as a generic model for a child head.

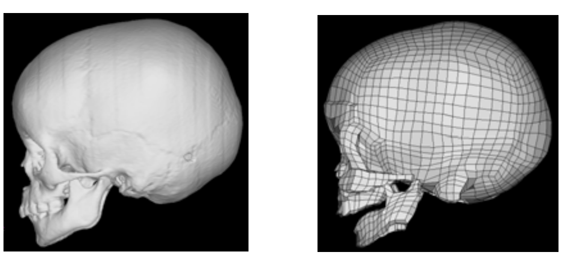
The method to construct a child's generic model is shown in Fig.7 (a). The child's generic model was constructed by transforming a FE model for an adult head which was constructed from the CT images in advance. The head FE model consists of the three layered-skull (outer table, diploe and inner table), face, mandible, CSF (Cerebral Spinal Fluid), meanings (dura, falx cerebri, tentorium, pia), cerebrum, cerebellum, and brainstem. The number of the elements is 22600.

Firstly, 3D polygon models for both the child's and adult's skull were created from 2D CT images by using 3D slicer. Secondly, 238 homologous points on each 3D polygon model were selected. And, the domain for free form deformation interpolating the sparse 238 shape points was created. The domain for the adult head was deformed so that the adult's 238 points correspond with the child's ones. Finally, the child's head FE model was constructed by transforming the adult FE model using the deformed domain.

Fig.8 shows comparison between 3D polygon model of the child's skull sample, which was constructed from CT images, and the FE model reconstructed by using the method. As shown in the figure, the method precisely reconstructed the feature of local shape for child's head.

Moreover, the generic model was transformed to the model which has average dimensions of the injured child's age. In this case, 2years average dimensions were available. Therefore a generic child FE model was transformed to the injured child's model under dimensions restriction. The errors of the dimensions were about 1mm as shown in Table1.

Although adult's material properties were used for almost those for 2years model because of lack of the data, skull Young's modulus, which is most important for the direct impact analysis, were based on Irwin's grow curve that is a relationship between skull Young's modulus and age[6].



(a) Polygon model **(b)** FE model

Fig.8 Comparison of head shapes between a FE and polygon model

Table1 Comparison of target and the head FE model dimensions

Item	Target dimension [mm]	FE model [mm]	Difference [mm]
head width	122.3	122.3	0.4
head height	178.5	185.1	1.2
head length	162.3	169.2	0.1
Pileum-root of the nose height	101.9	101.6	0.3
bizygomatic breadth	93.2	92.0	1.2

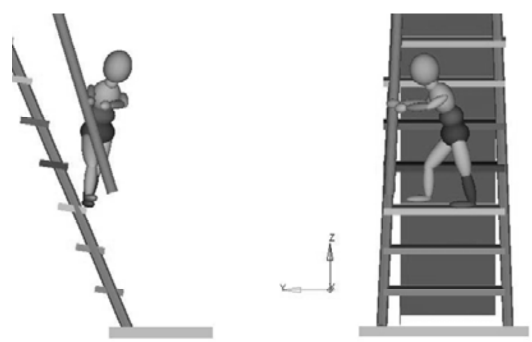
C. *Model of the environment*

The shape of the slide where the accident occurred was measured by using 3D terrestrial laser scanner system (LMS-Z420i, RIEGL), as shown in Fig.2. Moreover, the stair model was constructed by using CAD software (Rhinoceros4.0, Apricraft) .

IV. ANALYSIS OF THE ACCIDENT

A. *Accident reconstruction based on the injury case*

As described before, pre-accident circumstances determined from the ury case report were only that the injured child was standing on 3rd or 4th stair with grabbing the left rail by both hands. Therefore, more than 200 cases changed standing position, direction and postures were simulated using the multi-body model so as to reconstructing post accident situations described in chapter II. As the results, pre-accident position and posture of the injured child was estimated as shown in Fig.9. The falling behavior estimated, shown in Fig.9, showed that the body was rotated along midsaggital axis in a clockwise direction due to slipping the right foot on the 3rd step. After that, the right shoulder firstly impacted onto concrete surface, and then, right side of the head collided onto the surface around the base of the left rail. Impact velocity of the head onto the surface is shown in Table2. The z velocity was much slower than that in case of free fall, which is 5.0m/s due to the right shoulder impact before head's impact.



(a) Initial posture estimated

Fig.9 Falling behavior in case of the accident reconstructed

Table2 Impact velocity of the head onto concrete surface

	Linear Velocity[m/s]	Ang velocity [rad/s]
x	-0.14	-8.77
y	-0.36	11..39
z	-1.74	-3.63

In addition, head injury analysis in the impact case was carried out using FE model of the head by applying the rigid body posture and velocity obtained from the multi-body analysis as initial condition.

Von Mises stress on skull, pressure in brain and HIC value were selected as evaluated value for occurrence of head injury. Tolerance value of Von Mises stress to evaluate skull fracture was defined as 27MPa, converting failure stress in tensile test described in Ref.[7] to bending stress. Tolerance value of brain pressure relating to brain contusion which is fatal brain injury was defined as 237kPa for compression and -100kPa for extension[8]. And HIC value, calculated from linear acceleration responses at the head COG, is tolerance value for skull fracture or brain concussion and the tolerance value corresponds to 1000.

Table3 shows summary of the simulation results and Fig.10 shows Von Mises stress distribution of the skull where deepest gray region exceeds the tolerance value. High risk region was distributed on upper area of the right parietal bone. On the other hands, maximum positive brain pressure was 148kPa and negative one was -72kPa, which did not exceed the tolerance value. Those results mean that skull fracture occurs but the possibility of occurrence of fatal brain injury is low. According to injury information of the accident, skull fracture and epidural hematoma occurred but fatal brain injury such as brain contusion was not observed. Since the results obtained from the accident reconstruction by using the children fall simulator corresponded with the injury information from the actual accident, simulation by using the child fall simulator proved its usefulness that it compensates for lack of accident information corrected at the surveillance system and shows the accident scenario precisely.

Table3 Summary of the results in the accident reconstruction case

Injury estimation parameter	Simulation results	Possibility	Actual injury information
Skull Von mises stress	Over 27MPa in right parietal bone	High	Right parietal bone fracture
Max. Brain pressure	Positive:148 kPa negative:-72 kPa	Low	None
HIC	482	?	Skull fracture

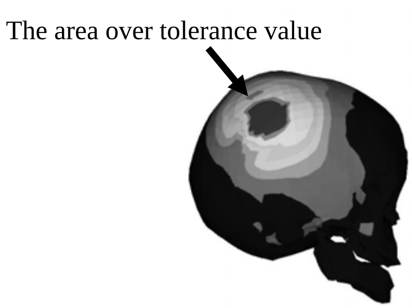


Fig.10 Contour map of skull Von Mises stress in the accident reconstruction case

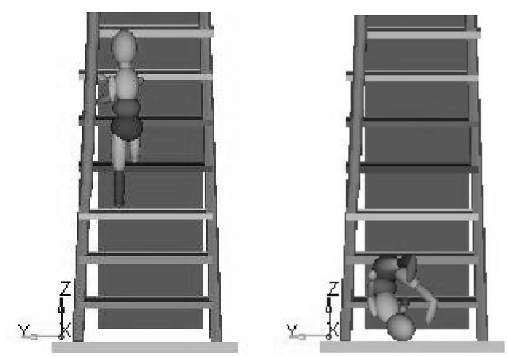
B. *Worst case analysis*

It is expected that more dangerous situations than the accident case exist in the environment. It is important to reveal latent danger in the environment to design the safe environment for children.

Therefore most dangerous case when the child falls from 3rd or 4th step of the staircase was extracted from the simulation results. Fig.11 shows pre and post accident circumstances in case of the most dangerous case in the simulations. As shown in the figure, the case falling backward and directly impacting the head on the surface was most dangerous. The head impact velocity resulted 4.4m/s which is 2.5 times higher than the actual accident case.

Table4 shows summary of the simulation results and Fig.12 shows Von Mises stress distribution of the skull. As shown in the figure, skull Von Mises stress exceeding tolerance value distributed much wider area than the reconstructed case. Moreover, maximum pressure exceeded the tolerance value in this case, which means fatal brain injury might occur. In HIC value, the value was almost 20 times higher than the case.

Thus, it is highly likely that fatal brain injury such as brain contusion occurs even falling from 3rd or 4th step.



(a) Pre-accident (b) Post-accident

Fig.11 Fall behavior in the worst case

Table4 Summary of the results in the worst case

Injury estimation parameter	Simulation results	Possibility
Skull Von mises stress	Over 27MPa in much wider area	High
Max. Brain pressure	Positive:603 kPa negative:-211 kPa	High
HIC	9255	High

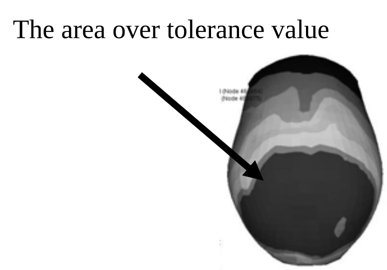


Fig.12 Contour map of skull Von Mises stress in the worst case

C. *Effect of rubber surface*

The concrete surface was changed to a rubber surface with 6cm thickness as countermeasure for the accident. The material properties of the rubber surface were defined based on Shorten et al[9].

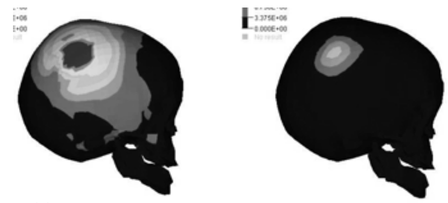
Fig.13 shows comparison of skull Von Mises stress distribution in case of the rubber surface with concrete one with respect to the accident case. Any region where skull stress exceeds the tolerance value was not observed. And, the comparison of brain pressure and HIC are shown in Fig.14. Those values were drastically reduced in case of rubber surface; brain pressure was reduced by 77% and HIC was by 88%. From those results, the accident was highly possible to prevent if the rubber surface is equipped instead of concrete one.

Moreover, the comparisons incase of the worst case are shown in Fig.15. Skull Von Mises stress did not exceed tolerance value in any region even in the worst case. In addition, brain pressure was reduced by 73 % over and did not exceed tolerance value either. Rubber surface enables to prevent both skull fracture and fatal brain injury in any case when the child falls from 3rd or 4th step on the staircase.

V. Conclusion

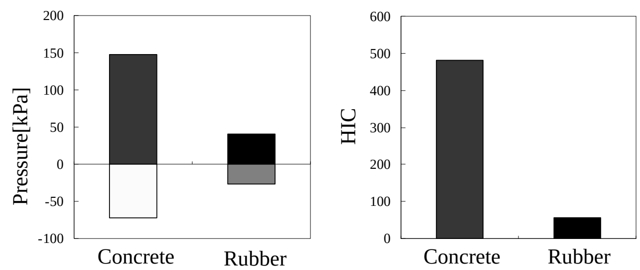
Children fall simulators were constructed to reconstruct an accident case corrected to the injury surveillance system and analyze the cause and countermeasure of the accident. The model consists of both multi-body model for the whole body to analyze and identify fall behavior in the accident and finite element model of the head to deeply investigate the head injury mechanism by applying the head motion calculated in multi-body simulation as boundary condition.

Moreover, an injury case that skull fracture occurred when a little girl child fell from staircase of a slide was reconstructed by using the fall simulator for the injured child to analyze and identify the cause and countermeasure of the real accident. Since the results obtained from the accident reconstruction corresponded with the injury information from the actual accident, simulation by using child fall simulator proved its usefulness that it compensates for lack of accident information corrected at the injury surveillance system and shows the accident scenario precisely. Moreover, the simulator made it possible to reveal latent danger in the environment which is much more dangerous than the case reported and evaluate the effectiveness of the countermeasure, which is the change of the concrete surface to rubber one in this case.



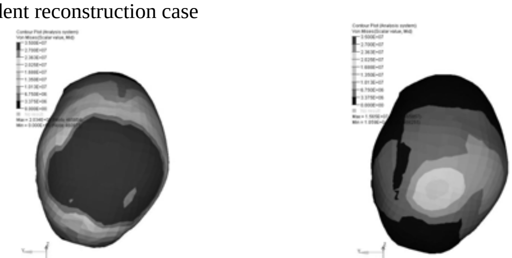
(a) concrete (b) rubber

Fig.13 Comparison of skull Von Mises stress in case of the accident reconstruction case



(a) Brain pressure (b) HIC value

Fig.14 Comparison of max brain pressure and HIC value in case of the accident reconstruction case



(a) Concrete (b) Rubber

Fig.15 Comparison of skull Von Mises stress in case of the worst case

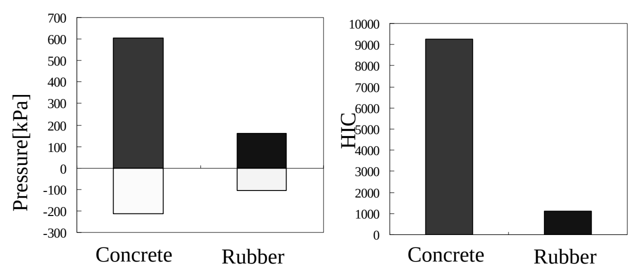


Fig.16 Comparison of max brain pressure and HIC value in case of the worst case

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