HEAD INJURY ANALYSIS IN CASE OF FALL FROM PLAYGROUND EQUIPMENT USING CHILD FALL SIMULATOR

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Child fall simulator was constructed to reconstruct and analyze falling accident cases occurred in playground equipment. 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. An injury case that skull fracture occurred when a little girl child fell from staircase of a slide was reconstructed by using the simulator to analyze and identify the cause and countermeasure. The child fall simulator proved its usefulness that it compensates for lack of accident information recorded 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.

1 Introduction

Playing in playground equipment is a perfect sport for children, because it is good for exercise and cultivates their creativity and teamwork. However, many accidents have occurred because potential fatal hazard exists in playground. In Japan, leading cause of death for children from 1 to 14 years has not changed for 30 years, which is ‘accidental death’. Therefore, a national project named ‘safety-knowledge circulation’ has been carried out. The project aims to correct children’s accident data at hospitals and utilize each case to identify the cause and study how to cope with the accidents. According to accident cases in 2007 recorded at hospitals participating this 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.

However, each accident data recorded by injury surveillance system does not include detailed information about accident circumstances at the time when the accident occurs, because the correction of information depends on interview with injured child or the parents by physicians. Moreover, an accident occurred and recorded 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 is effective for analyzing accidents like falling because the analysis using digital human model makes it possible to reconstruct the accident situation.

Therefore, the purpose of this study is to construct 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 due to fall, which was recorded in the accident surveillance system, was reconstructed to analyze and identify the cause and countermeasure of the real accident.

2 Construction of Simulation Models

Schematic view of the analysis method for injury cases is shown in Figure 1. Firstly, injured child's whole body and the environment such as playground equipment were modeled by multi-body in order to infer the initial conditions consistent with the post accident circumstances. The environment model where the accident occurred was constructed based on 3D shape measured by terrestrial laser scanner system (LMS-Z420i, RIEGL)

Moreover, the child head finite element model was constructed by using shape transformation from a generic model. Finally, head impact simulations with the surface finite element model were carried out to estimate the cause and the effects of the countermeasure. MADYMO ver6.4 (TNO Automotive) and RADIOSS ver5.1 (Altair Engineering co.) were used for the simulations.

2.1. Multi-Body Model for Whole Body

A multi-body model for the injured child shown in Figure 1was constructed from the height and weight. The model consists of 17 ellipsoidal segments and 16 joints; the head, neck, thorax, abdomen, pelvis, thighs, calves, feet, upper arms, lower arms and hands.

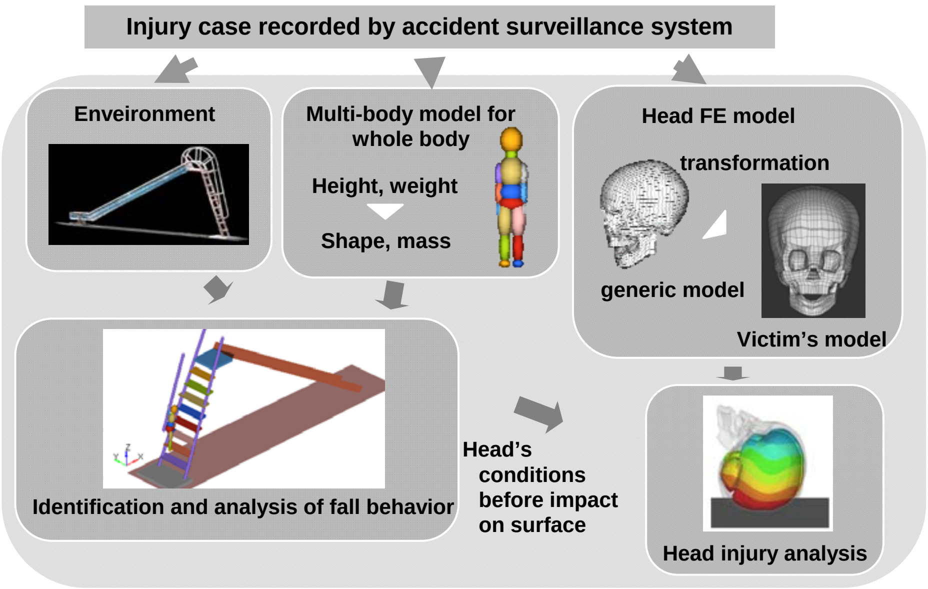


Figure 1. Schematic diagram to analyze the injury case by using children fall simulator

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 (Yokoi *et al.*, 1986). Joint characteristics were expressed as a relationship between joint angle and passive torque (Yang & Lovsund, 1997). 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 most of fall cases from playground equipment because each joint motion might 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. The relationships for contact stiffness were defined by using the data of a Hybrid-III dummy.

2.2. Construction of the Head Finite Element Model

The child model was constructed by transforming a generic FE model using Free Form Deformation (FFD) method. A generic head FE model was constructed from CT images of a subject, which 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.

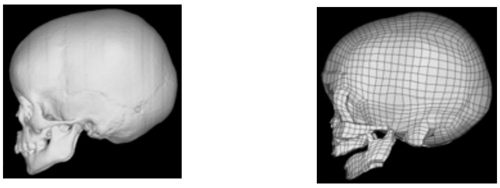
In order to construct a head FE model of a specific individual child by using FFD method, domain for FFD, which interpolates 238 homologous points on 3D polygon model of the heads with B-spline function, were created. The domain for the generic head was deformed so that 238 points of generic model correspond with the child's one. Finally, the child head FE model was constructed by transforming the generic FE model using the deformed domain.

Figure 2 shows comparison between 3D polygon model of the child's skull, which was constructed from CT images, and the FE model constructed by the method. As shown in the figure, the method precisely reconstructed the feature of local shape for child's head. 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 (Irwin & Mertz, 1997).

3 Analysis of an Accident Recorded in Injury Surveillance System

3.1. 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 as follows. A one year and eleven month girl child, who was 81.6cm height and 10.0kg weight, was fallen from the 3rd or 4th stair of a slide in a public park. The material of the surface where the head 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. X-ray picture showed linear skull fracture of right parietal bone and



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

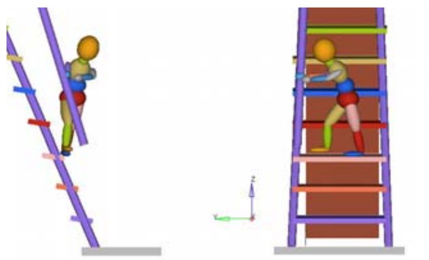
Figure 2. Comparison of head shapes between a FE and polygon model

computed tomography (CT) showed an epidural hematoma under the impact site.

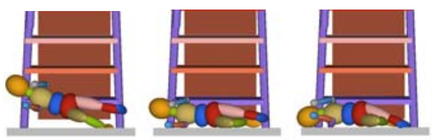
3.2. Accident Reconstruction Based on the Injury Case

As described before, pre-accident information determined from the injury 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. As the results, pre-accident position and posture of the injured child was estimated as shown in Figure 3. The falling behavior estimated 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 Table1. 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.

In addition, head injury analysis in the impact case was carried out using FE model of



(a) Initial posture estimated



(b) Falling behavior at impact on the surface

Figure 3. Falling behavior in case of the accident reconstructed

Table 1. 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

The area over tolerance value

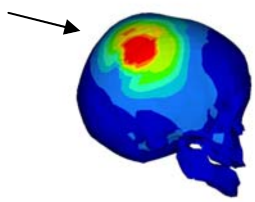


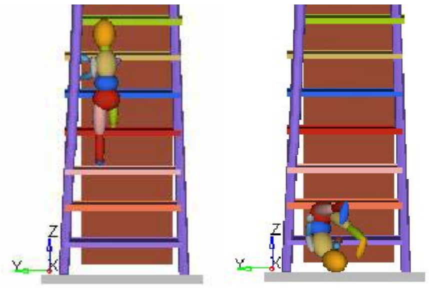
Figure 4. Contour map of skull von Mises stress in the accident reconstruction case

the head by applying the rigid body posture and velocity obtained from the multi-body analysis as initial condition. Figure 4 shows von Mises stress distribution of the skull where red region exceeds the tolerance value which is 17.6MPa (Ommaya *et al.*, 2002). High risk region was distributed on upper area of the right parietal bone. Therefore, the results obtained from the accident reconstruction by using the children fall simulator corresponded with the injury information from the actual accident.

3.3. 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. Figure 5 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. Figure 6 shows von Mises stress distribution of the skull. As shown in the figure and Table2, skull von Mises stress exceeding tolerance value distributed much wider area than the reconstructed case. Moreover, maximum brain pressure relating to fatal brain contusion exceeded the tolerance value defined as 237kPa for compression and -100kPa for extension(Ward *et al.*, 1980). Thus, it is highly likely that fatal brain



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

Figure 5. Fall behavior in the worst case

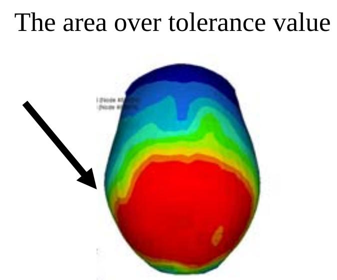
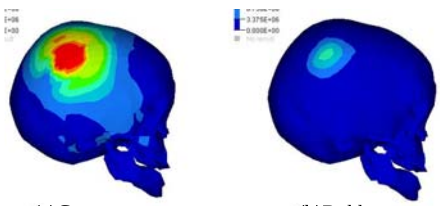


Figure 6. Contour map of skull von Mises stress in the worst case

Table 2. Summary of the results in the worst case

Injury estimation parameter	Simulation results	Possibility
Skull von Mises stress	Over Tolerance value in much wider area	High
Max. Brain pressure	Over Tolerance value Positive:603 kPa negative:-211 kPa	High



(a)Concrete (b)Rubber

Figure 7. Comparison of skull von Mises stress in case of concrete surface with that in rubber one

injury such as brain contusion occurs even falling from 3rd or 4th step.

3.4. Estimation of the Effect of the Countermeasure

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 & Himmelsbach (2002).

Figure 7 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. From the results, the accident was highly possible to prevent if the rubber surface is equipped instead of concrete one.

4 Conclusion

Children fall simulators were constructed to reconstruct an accident case recorded 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. 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 recorded 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.

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