ANALYSIS OF CHILD RESPONSES IN CRS USING CHILD HUMAN FE MODEL

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ABSTRACT

To investigate injuries to various body regions of a child in detail using a child restraint system (CRS), a finite element (FE) model of a 3-year-old child has been developed. Using this child FE model and Hybrid III FE model, the ECE R44 sled impact test simulations were conducted for three different types of CRS such as a 5-point harness, an impact shield and an ISOFIX CRS. For the child FE model, the whole spine flexed, whereas for the Hybrid III with stiff thorax spine, only the cervical spine and the lumbar spine flexed. As a result, in the 5-point harness CRS, the head down movement and its rotation were large for the child human FE model. The injury criteria of Hybrid III and child FE model were comparable in these CRS applications. In the impact shield CRS, the chest deflection was large. The head excursion was particularly small for the ISOFIX CRS.

The influence of belt slack of CRS on injury criteria was also examined from FE analyses. There was a relation between the ridedown efficiency and the chest acceleration. A slack seatbelt and harness in the 5-point harness CRS increased the injury risk. On the other hand, the injury criteria in the impact shield CRS with and without the seatbelt slack were comparable, which explains the low injury risks for children using the impact shield CRS in accidents.

INTRODUCTION

Accident data have demonstrated that a child restraint system (CRS) is effective for preventing injuries to children [1,2]. There are a variety of forward-facing CRS types, including those with a 5-point harness, tray shield and T-shield. Many studies have examined the differences in behavior and injury criteria of child occupants under various restraints. Melvin and Weber, for example, have shown from sled tests of CRS that the behavior of a child dummy depends on the CRS types [3]. Langwieder et al. [4,5] investigated German accident data and found that the injury risks of children were lower in an impact shield CRS than in a 4/5-point harness CRS.

In the JNCAP (Japan New Car Assessment Program), there are CRS dynamic tests, and forward facing CRS has been tested using three-year-old (3YO) Hybrid III. According to the number of units sold, CRSs are selected and subjected to a dynamic sled test using a minivan frame body [6]. In the JNCAP test, the injury criteria of Hybrid III in the 5-point harness CRS are inclined to be lower than those in the impact shield CRS with small chest deflection and low abdominal pressures. However, these results are inconsistent with the accident analysis by Langwieder et al. [4,5].

In CRS impact tests, crash dummies such as Hybrid III 3YO, TNO P3 and Q3 are widely used. Injury criteria are recorded by these dummies and CRS safety performance is evaluated. However, there are some differences in anatomical structure and mechanical properties between the human body and crash dummies. These differences can affect the responses of the child in CRS during impacts. Thus, to examine the behavior and injuries to a child by CRS types in detail, the dummy test results might be insufficient, especially for evaluating different types of CRS.

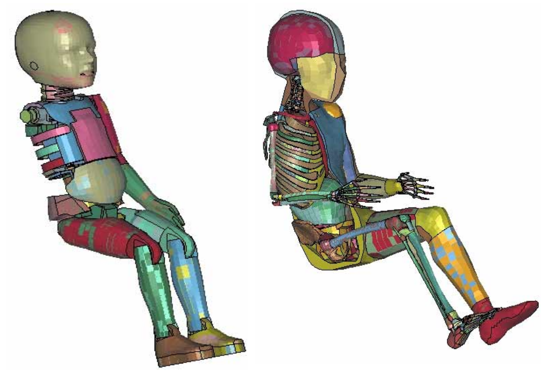
Many human finite element (FE) models of adults have been developed, and applied to the investigation of human responses in crash environments. Using these models, injury risks can be evaluated from stress and strain distributions, which cannot be measured in crash dummies. A child FE model will be useful when it is applied to evaluate the injury risk of a child using CRS. In the present research, a 3YO child FE model was used, which was developed by appropriate scaling of a THUMS (Total Human Model for Safety) AM50 (adult male 50 percentile) [7,8].

Many studies have demonstrated that the percentage of misuse is quite high in using CRS, and this misuse can limit the protective benefit of CRS [4,5,9]. There are several types of misuse in CRS. According to the CRS usage investigation by the JAF (Japan Automobile Federation) and the police in Japan, seatbelt slack (35%) and harness incorrect use (8.6%) were observed in investigated CRSs [10]. They also reported the CRS static displacement when a force of 100 N was applied in forward direction. The result was that 39.6% of CRS was relatively tight (within 30 mm), 40% was acceptable (30 to 100 mm) and 20.4% was loose (over 100 mm) installed on the car seat. An ISOFIX CRS is effective for the reduction of the frequency of incorrect attachment of CRS to the car seat. Several studies have demonstrated that the injury criteria for an occupant in the ISOFIX are smaller than or comparable with those in the conventional CRS [11,12]. In the present study, the child occupant responses in 5-point harness, the impact shield and ISOFIX CRS during impact were examined using Hybrid III and child FE model. For the 5-point harness CRS and the impact shield CRS, the influences of belt slack on the injury criteria were also examined.

METHODOLOGY

A 3YO child human finite element (FE) model has been developed by the authors for investigating injuries to children in impacts [13,14]. Taking the anthropometry and material properties of a 3YO child into account, the model was made by scaling from the adult human FE model THUMS (Total Human Model for Safety). The responses of this child human FE model were validated in various impact conditions, and they were included in the corridor of Hybrid III 3YO dummy certification tests. In the child FE model, the skull shape was modified and the pelvis model was developed with Y-cartilage to represent child anatomy [14].

A Hybrid III FE model provided by the First Technology Safety Systems (FTSS) was also used. The behavior and injury criteria were compared for various types of CRS using this child human FE model and Hybrid III 3YO FE model. Figure 1 shows the Hybrid III and child FE model.



(a) Hybrid III FE model (b) Child FE model

Figure 1. Hybrid III and child FE model.

In this study, three different types of CRS such as a 5-point harness, an impact shield and an ISOFIX CRS were analyzed. Figure 2 shows the child FE model in three types of CRS. Using the child and Hybrid III FE models, CRS sled tests based on the ECE R44 were simulated. An FE model of the ECE seat was created, and the CRS FE model was set in place on the ECE seat according to the ECE R44. The acceleration-time histories of the sled were included within the corridor of ECE R44, and the maximum acceleration was 25G with 50 km/h velocity change. Although the ECE R44 prescribes the use of a TNO P3 dummy, in the present study the Hybrid III 3YO was used because the Hybrid III 3YO has higher biofidelity.

For the 5-point harness CRS FE model, the CRS seat was modeled by shell elements, and the harness was modeled by membrane and seatbelt elements. In the impact shield CRS, the seat and shield made of styrene foam were modeled by solid elements. The material properties of these models were described in a previous study [13,14]. The ISOFIX CRS used in this study has a 5-point harness, a shell seat, a tether top and a base with two point ISOFIX attachments.

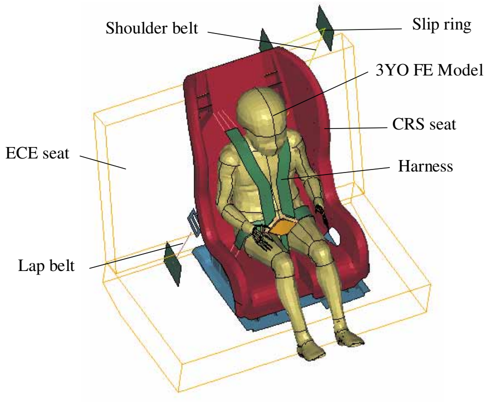
The sled tests were conducted using the Hybrid III 3YO for the 5-point harness, impact shield and ISOFIX CRS. Then, these sled tests were simulated using the Hybrid III FE model. By comparing the test and simulation results, the CRS FE models could be validated. The Hybrid III FE model also made it easier to understand the internal structural behavior of the Hybrid III model. Then, CRS sled simulations using the child FE model were conducted with validated CRS models, and the behavior was compared to that of the Hybrid III FE model. The stress distributions of the skeleton of the child FE model were also compared in three types of CRS. Injury criteria were examined for the Hybrid III and child FE model. The injury acceptance reference values (IARV) from the FMVSS 208 were used. The HIC15 is 570, the chest acceleration 539 m/s^2 and the chest deflection 34 mm. The head excursion of 550 mm was used from the ECE R44 since the ECE test setup was used.

In the FE simulation, two types of CRS misuse were examined. One was the loose installation of CRS by the vehicle seatbelt with slack. In the model, an initial seatbelt slack of 100 mm was added to a shoulder belt. The other error was the improper restraint of the child to the CRS. In this case, an initial slack of 100 mm was added to two shoulder harness straps of the CRS. Table 1 shows the matrix of the FE simulations. The seatbelt was modeled by the seatbelt elements, and the harnesses were modeled by the membrane with seatbelt elements in both ends. The initial slack was added as an option to the seatbelt elements.

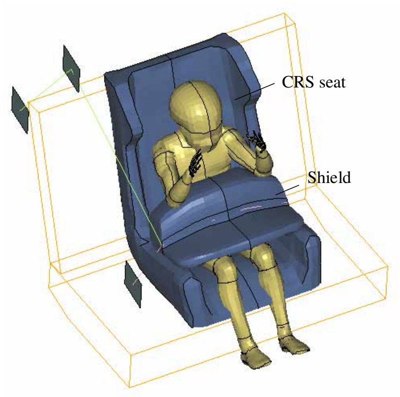
During impact, occupant kinetic energy is absorbed by the restraint energy and the ridedown energy. It is known that ridedown efficiency decreases as the restraint energy increases with restraint delay due to seatbelt slack [15]. Thus, the effect of restraint slack on the injury criteria can be evaluated numerically using the ridedown efficiency. Ridedown efficiency (μ) is defined as the ratio of maximum ridedown energy to the initial occupant kinematic energy as follows:

$$\mu = \frac{\int_0^{t_1} ma\,dX}{mv_0^2/2} = \frac{2\int_0^{t_1} a\,dX}{v_0^2} \qquad (1)$$

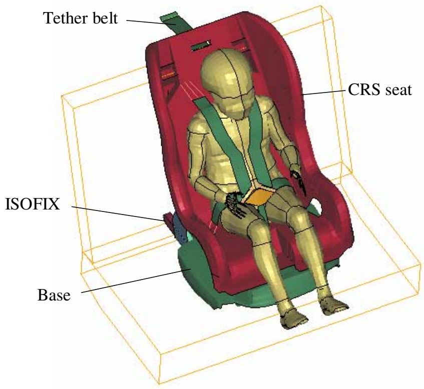
where a is the occupant deceleration, X the vehicle displacement, m the occupant mass, v_0 the initial occupant velocity and t_1 is the time when the vehicle velocity is zero. In Eq. (1), the chest acceleration was used for the calculation.



(a) 5-point harness CRS



(b) Impact shield CRS



(c) ISOFIX CRS

Figure 2. Child human FE model with three types of CRS.

Table 1. FE simulation matrix

CRS	Model	Slack
5-point harness	Proper use	No slack
	w/ seat belt slack	Seatbelt slack 100 mm
	w/ harness slack	CRS harness slack 100 mm
Impact shield	Proper use	No slack
	w/ seat belt slack	Seatbelt slack 100 mm
ISOFIX	Proper use	No slack

RESULTS

CRS Types and Occupant Responses

Three types of CRS, one with as the 5-point harness, the impact shield and the ISOFIX CRS, respectively, were examined based on FE simulations using the Hybrid III and child FE model under the conditions of proper use of the CRS with no belt slack.

<u>Occupant kinematics</u>

The behavior of the Hybrid III and child FE model in the 5-point harness CRS is compared in Figure 3. The pelvis and shoulders are restrained by the lap and shoulder harnesses. Due to head movement, the neck flexed and the chin made contact with the chest. As seen in Figure 3, whereas the thorax spine of the Hybrid III made of a steel box did not bend, the cervical and lumbar spine did. On the other hand, in the child FE model, as the whole spine flexed, the head moved downward. The accelerations of head, chest and pelvis are shown in Figure 4. In general, the acceleration tendencies of Hybrid III FE model are similar to that of the Hybrid III test. The head and pelvis accelerations of the child FE model are similar to those of the Hybrid III FE model. The chest acceleration curve of the child FE model has a plateau region when the shoulder harnesses compress the clavicles and the upper part of the rib cage. This plateau region continues after 100 ms where the inertial forces of the head, upper and lower extremities were applied to the chest.

The impact shield CRS used in the present study does not have harnesses, but the shield directly supports the chest of the child during the impact (Figure 5). In the Hybrid III FE analysis, though the chest of the Hybrid III was compressed by the contact with the impact shield, the thorax spine did not flex. Instead, the torso of the Hybrid III rotated upward around the impact shield. On the contrary, in the child FE model, the torso deformed along the impact shield and the whole spine continued to flex. The inertial forces of the head, upper and lower extremities continued to transfer to the torso, and a great force was applied to the chest by the contact with the impact shield. The chest deflections of the Hybrid III and child FE models were very large. In this type of CRS, extreme neck flexion was prevented by the chin contact with the top of the shield. Figure 6 shows the acceleration-time histories of head, chest and pelvis. The accelerations of the body are comparable in the Hybrid III FE and child FE models except for the chest acceleration. For the child FE model, there are two peaks in the chest acceleration at 65 and 90 ms. The first peak is due to the chest contact with the shield, and the second peak is due to the inertia force of the head and upper extremities.

The kinematics and acceleration of the occupant in the ISOFIX CRS are shown in Figures 7 and 8, respectively. In this type of CRS, the occupant restraint starts earlier than in other types of CRS. The ISOFIX attachment and the top tether secure the CRS effectively on the car seat. Accordingly, the torso flexion angle and the head excursion were small. The head flexion angle of the child FE model was larger than that with the Hybrid III FE model. At 100 ms, the chin made contact with the sternum, which led to relatively high acceleration of the chest.

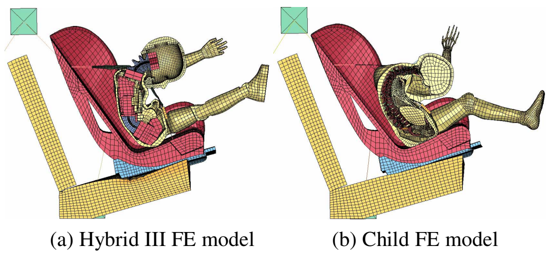


Figure 3. Occupant kinematics in 5-point harness CRS at 120 ms.

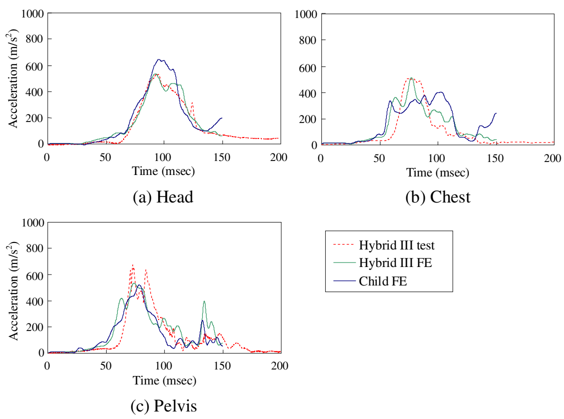
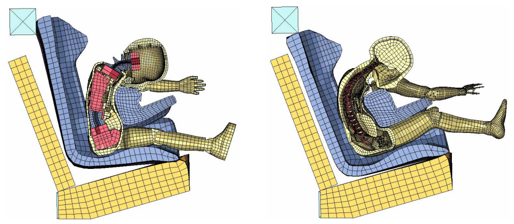
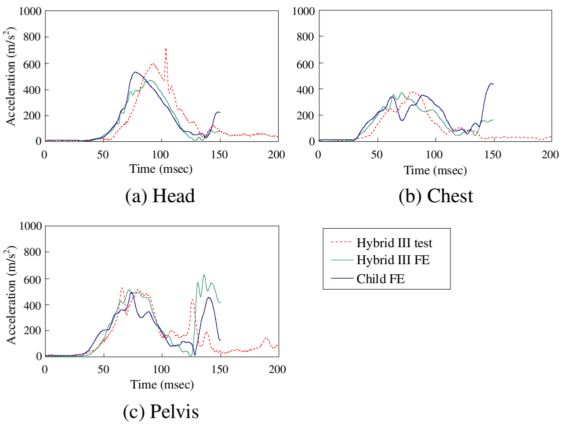


Figure 4. Resultant acceleration of occupant in 5-point harness CRS.



(a) Hybrid III FE model (b) Child FE model

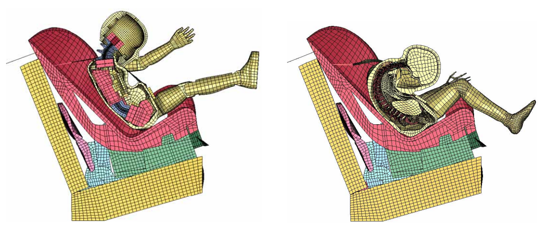
Figure 5. Occupant kinematics in impact shield CRS at 120 ms.



(a) Head (b) Chest

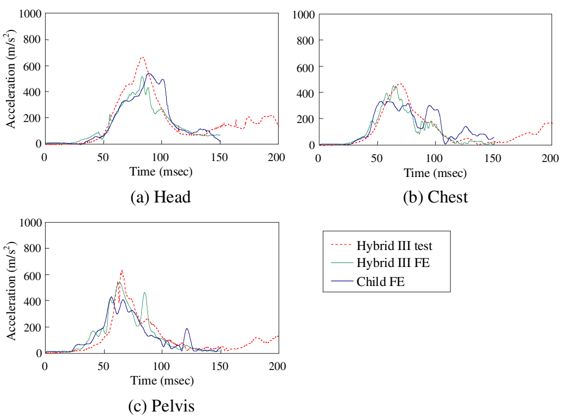
(c) Pelvis

Figure 6. Resultant acceleration of occupant in impact shield CRS.



(a) Hybrid III FE model (b) Child FE model

Figure 7. Occupant kinematics in ISOFIX CRS at 120 ms.



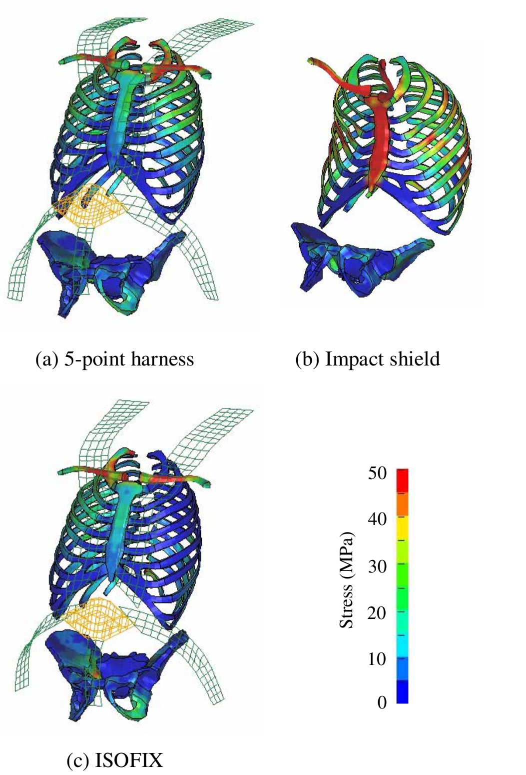
(a) Head (b) Chest

(c) Pelvis

Figure 8. Resultant acceleration of occupant in ISOFIX CRS.

Stress distributions of skeleton

Von Mises stress distributions of the skeleton are presented in Figure 9. In the 5-point harness CRS, stresses are high at the clavicles and the upper part of the rib cage because great forces were applied from shoulder harnesses which control flexion of the torso. In the impact shield CRS, the middle of the rib cage deformed along the shield. Due to compression and bending of the rib cage, high stresses in the sternum and whole ribs were observed. In the ISOFIX CRS, the overall stress levels are smallest among the three types of CRSs. The stresses at the clavicle are high where the shoulder harness interacts. In general, the stress in the pelvis is small for all CRS types.



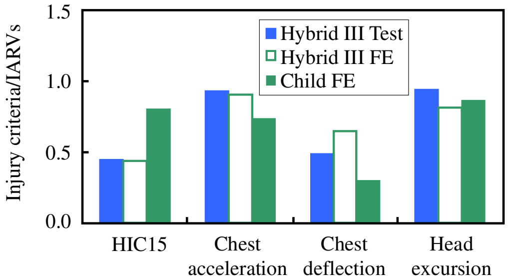
(a) 5-point harness (b) Impact shield

(c) ISOFIX

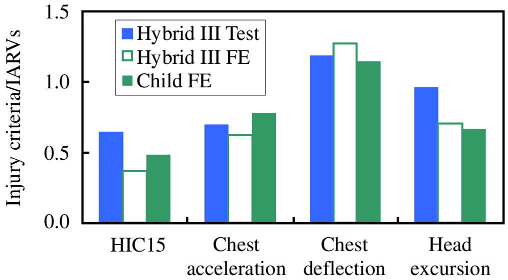
Figure 9. Von Mises stress distribution of skeleton in 5-point harness CRS (90 ms), impact shield CRS (100 ms) and ISOFIX CRS (75 ms).

Injury criteria

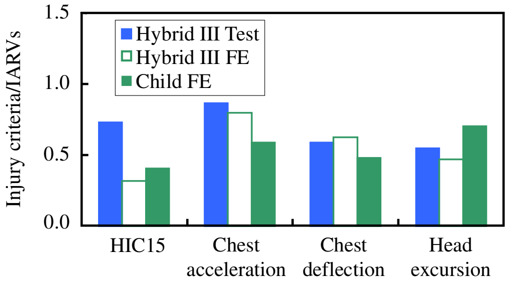
The injury criteria for the Hybrid III test, Hybrid III FE model and child FE model were examined for three types of CRS (Figure 10). Generally, the injury criteria of Hybrid III FE model and child FE model are comparable, and they are less than the IARVs except for chest deflection in the impact shield CRS. For the 5-point harness CRS, the chest acceleration and the deflection of child FE model are smaller than those of the Hybrid III FE model. The head excursion is similar between the Hybrid III FE and child FE models, because the head longitudinal direction does not change although the head of the child FE model moves downward. The chest deflection of both the Hybrid III FE and child FE model in the impact shield CRS is large as the force concentrates in the chest area. In the ISOFIX CRS, the head excursion is smallest among the three CRS types. In this CRS, the head excursion of the child FE model is larger than that of the Hybrid III FE model due to head rotation difference.



(a) 5-point harness



(b) Impact shield



(c) ISOFIX

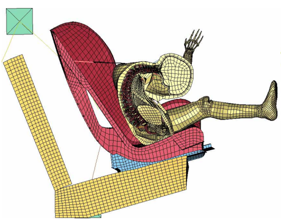
Figure 10. Ratio of injury criteria to injury assessment reference value (IARV) for three types of CRS.

Misuse of CRS

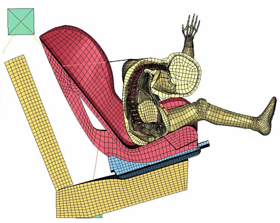
It is known that belt slack leads to delay of restraint starting time, and can result in high injury criteria. The relations between the belt slack and the occupant responses for various types of CRS were examined with respect to the occupant kinematics, injury criteria and ridedown efficiency.

<u>**Occupant kinematics**</u>

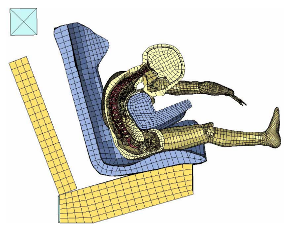
The kinematics of the child FE model with the addition of slack for various CRS types are presented in Figure 11. In the 5-point harness CRS with seatbelt slack, the CRS moved forward whereas the kinematics of the occupant is similar to the case with no slack. In the case of harness slack for the 5-point harness, because of the time delay of the restraint by the shoulder harness, the occupant torso flexed with a large head rotation angle. In the impact shield CRS with seatbelt slack, the occupant kinematics is similar to that with no slack. Accordingly, the occupant flexion behavior is affected more by the harness slack than the seatbelt slack.



(a) 5-point harness (seatbelt slack)



(b) 5-point harness (harness slack)

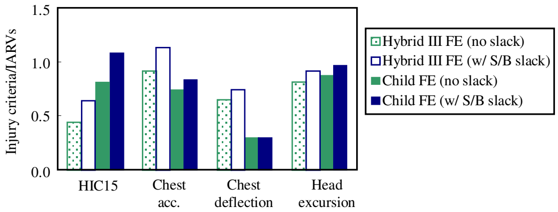


(c) Impact shield (seatbelt slack)

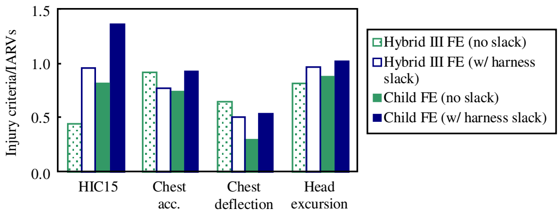
Figure 11. Occupant kinematics in various CRS with slack at 120 ms.

Injury criteria

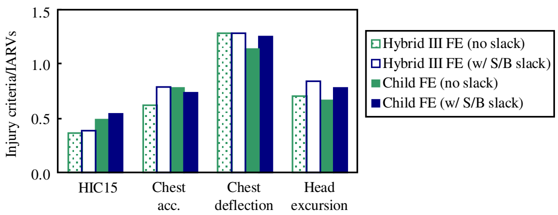
Injury criteria of Hybrid III FE and child FE models in 5-point harness and impact shield CRS for belt slack are shown in Figure 12. In all CRS types, the head excursions increase consistently due to belt slack. In the 5-point harness CRS, both the seatbelt slack and the harness slack result in high HIC or chest acceleration. Compared to 5-point harness CRS, injury criteria of the occupant in the impact shield CRS do not change so much by the seatbelt slack.



(a) 5-point harness CRSwith seatbelt slack



(b) 5-point harness CRS with harness slack

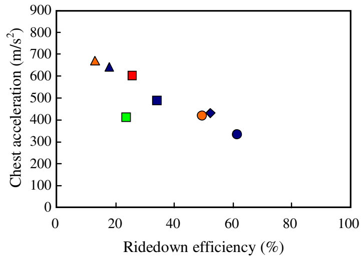


(c) Impact shield CRS with seat belt slack

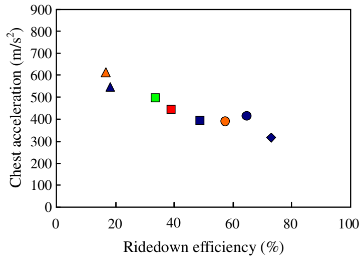
Figure 12. Injury criteria of Hybrid III and child FE model with and without belt slack.

Ridedown efficiency

The ridedown efficiency was calculated by the chest acceleration and is plotted in Figure 13 for all types of CRS with and without slack. The FE analysis of the vest-type CRS [14] is also included in this Figure. The chest acceleration tends to decrease as the ridedown efficiency increases. The ridedown efficiency of the child FE model is about 18%, 48%, 65% and 72% for the vest, the 5-point harness, the impact shield and the ISOFIX CRS with no belt slack, respectively. When slack is added to the shoulder belt of the impact shield CRS, the ridedown efficiency is still high and the chest acceleration is less than the injury acceptance level.



(a) Hybrid III FE model



(b) Child FE model

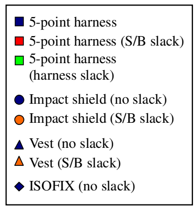


Figure 13. Ridedown efficiency and chest acceleration in Hybrid III FE and child FE model.

DISCUSSION

The analysis has shown that the global flexion behavior is comparable between the Hybrid III and the child human FE models in the three types of CRS. However, there are significant differences in thorax spine flexibility. Surprisingly, the spine flexibility and anatomical structure did not significantly affect the injury criteria in the 5-point harness CRS. This is because most of the injury criteria reached the maximum value before there was any observable difference in behavior between the Hybrid III and child FE models. Furthermore, the head downward movement of the child FE model did not increase the head excursion. In the 5-point harness CRS, the harnesses apply force to the clavicle, upper ribcage and pelvis, which are relatively strong locations in the skeleton. The stresses in the pelvis were low when the forces from the lap harnesses were applied to the pelvis because this child FE model has a Y-cartilage that allows relative displacement of the ilium, pubis and ischium [14].

A local difference in chest anatomy between the Hybrid III and child FE model can also affect injury criteria. In the CRS types in which the pelvis is not restrained, e.g., the impact shield CRS, a large force was applied directly to the chest, which could lead to local deformation in the ribcage. With the child FE model, these local deformation modes and injuries can be estimated. In the impact shield CRS, the chest deformed along the shield. Therefore, the shape and energy-absorbing characteristics of the impact shield will be important to control the chest deformation during impact.

In the 5-point harness, as the chin made contact with the chest in the child FE model, deflection and stresses of the sternum were observed. This sternum deflection will not be realistic compared to the cadaver tests or real-world accidents in which sternum injuries due to chin contact are not frequently reported. In the present child FE model, the face, including the mandible, mandibular joint and teeth, has not been modeled in detail. The detailed model of face and neck of child should be included when examining the head flexion behavior which affects the chin-chest contact and neck loading. In the child FE model, the occipital condyle/C1 is not a simple kinematic joint but is modeled by bone contact and ligaments with a large deformation during impact, which makes it difficult to measure the force and moment of the neck. However, in the present study, the head accelerations of the Hybrid III FE and the child FE models were comparable, suggesting that the neck loading was similar between the two FE models. This indication might be inconsistent with the analysis by Sherwood et al. [16], who indicated that 6-year-old (6YO) Hybrid III neck loadings in the dynamic test could be overestimated due to the stiff thorax spine. It is possible that the great neck force was generated by the chin and sternum contact in the Hybrid III, and this contact interaction could change when the thorax spine became flexible. Further research is warranted to investigate the neck loadings and its injury threshold in a child with various CRS.

The seatbelt slack and harness slack can increase the injury criteria for the 5-point harness CRS. In the impact shield CRS, the influence of seatbelt slack on the injury criteria was small. In the accident analysis by Langwieder et al. [4,5], injury risks to children using the impact shield CRS were lower than using the 5-point harness CRS. In general, CRS tests are based on the proper use of CRS with tension added in the seatbelt and harness. The injury criteria of the crash dummies in the 5-point harness CRS can be smaller than those in the impact shield CRS in many tests. It is likely that the misuse of the CRS can explain the differences in the occupant injury risks observed in the accident and laboratory test. In the impact shield CRS, the chest deflections of the Hybrid III FE model and child FE model were over the IARV (34 mm). It is known that the ribcage of a child is flexible, and rib fractures are not frequent in real-world accidents. It may be still difficult to use this threshold for rib fractures of children.

The ISOFIX is effective for preventing poor installation of the CRS on a car seat. The ridedown efficiency of the ISOFIX CRS was so high, and the injury criteria of the Hybrid III and child FE model were smaller than the IARVs. In this CRS, though the head excursion of the child FE model is larger than that of the Hybrid III FE model due to head rotation difference, the head excursion was considerably less than the IARV.

CONCLUSIONS

The child responses in three types of CRS with and without belt slack were examined using Hybrid III FE model and child FE model. The conclusions are summarized as follows.

1. From the analysis of sled tests with three types of CRS, the global flexion behavior was comparable between the child FE model and Hybrid III FE model. Close examination revealed differences in behavior due to thorax spine flexibility and thorax deformation mode. Using the child FE model, injury risks to occupants using CRS can be examined in detail.
2. In the case of slack in the harness or seatbelt, the injury risks were high for the 5-point harness CRS. The impact shield CRS was robust for the injury criteria when slack was added to the seatbelt. The influence of slack of the harness and seatbelt on the chest acceleration can be summarized by the ridedown efficiency.

3. The injury criteria, especially head excursion, were small in the ISOFIX CRS for the Hybrid III and child FE model.

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REFERENCES

[1] Kahane, C., “An evaluation of child passenger safety: the effectiveness and benefits of safety seats”, National Highway Traffic Safety Administration, DOT HS 806 890, 1986.

[2] Arbogast, K., Durbin, D., Cornejo, R., Kallan, M., Winston, F., “An evaluation of the effectiveness of forward facing child restraint systems”, Accident Analysis and Prevention, Vol. 36, pp. 585-589, 2004.

[3] Melvin, W., Weber, K., “Abdominal intrusion sensor for evaluating child restraint systems”, SAE Paper 860370.

[4] Hummel, T., Langwieder, K., Finkbeiner, F., Hell,W., “Injury risks, misuse rates and the effect of misuse depending on the kind of child restraint system”, SAE Paper 973309.

[5] Langwieder, K., Hummel, T., Finkbeiner, T., “Injury risks of children in cars depending on the type of restraint”, Child Occupant Protection in Motor Vehicle Crashes, 1999.

[6] Ono, Y., Komiyama, Y., Takatori, O., “Method of evaluating abdominal injury in Japan’s child-restraint-system assessment Program”, Paper Number 05-292, 19th ESV, 2005.

[7] Iwamoto M, Kisanuki Y, Watanabe I, Furusu K, Miki K, Hasegawa J., “Development of a finite element model of the Total Human Model for Safety (THUMS) and application to injury reconstruction”, Proc. 2002 IRCOBI International Conference, pp. 31-42.

[8] Oshita F, Omori K, Nakahara Y, Miki K., Development of a finite element model of human body, 7th International LS-DYNA Users Conference, 2002.

[9] National Transportation Safety Board, “The performance and use of child restraint systems, seatbelts, and air bags for children in passenger vehicles”, NTSB/SS-96/01, 1996.

[10] National Police Agency, Japan Automobile Federation, “Investigation on child seat usage”, 2006 (in Japanese).

[11] Lowne, R., Roy, P., Paton, I., “A comparison of the performance of dedicated child restraint attachment systems (ISOFIX)”, SAE Paper 973302.

[12] Langwieder, K., Hummel, T., Roselt, T., “ISOFIX – possibilities and problems of a new concept for child restraint systems, International Journal of Crashworthiness, Vol. 8, No.5, pp. 443-454, 2003.

[13] Mizuno, K., Iwata, K., Deguchi, T., Kubota, M., “Development of a three-year-old child FE model”, Traffic Injury Prevention, Vol. 6, Issue 4, pp. 361-371, 2005.

[14] Mizuno, K., Iwata, K., Namikiri T., Tanaka, N., “Comparison of human FE model and crash dummy response in various child restraint systems”, ICRASH 2006, Athens, Greece.

[15] Huang, M., *Vehicle Crash Mechanics*, CRC Press, 2002.

[16] Sherwood C.P., Shaw C.G., Van Rooij L, Kent R.W., Crandall J.R., Orzechowski K.M., Eichelberger M.R., Kallieris D., “Prediction of cervical spine injury risk for the 6-year-old child in frontal crashes”, Traffic Injury Prevention, Vol. 4, No.3, pp. 206-213, 2003.