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Numerical Evaluation of Injuries to Unrestrained Six Year Old Child Passenger in Vehicle Frontal Crashes

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Abstract: Misuse and not using Child Restraint Seat (CRS) is a norm in some African countries. This work is aimed at evaluating crash injuries of unrestrained Six Year Old (6YO) child in frontal crash. Finite element (FE) crash simulation being valid and cost effective method of crash test of vehicles was employed. The unrestrained dummy model was positioned in car FE model and crash test was conducted in LS DYNA FE software at 48 km/h, in accordance with Federal Motor Vehicle Safety Standard (FMVSS). The results showed that unrestrained child experienced Head Injury Criteria (HIC36) and HIC15 that were 59% and 20% higher than National Highway Traffic Safety Administration (NHTSA) threshold respectively. Head acceleration (HA) and Chest Severity Index (CSI) were also high for the unrestrained dummy while Chest Deflection (CD) and chest acceleration (CA) were 40% and 8.3% lower than NHTSA limit which is attributable to dummy characteristics. It was found that unrestrained dummy's HIC36 and CA were 168% and 8.3% higher than experimental response of 6YO dummy restrained in Back Kid Backrest Booster from literature. This quantifies the injury sustained by child passenger seated in a car without CRS. Safety agents should come up with policies to prevent this vulnerable population from avoidable death.

1. Introduction

Vehicle crash has been a major cause of children mortality worldwide (Cunningham *et al*., 2018). Children's safety requirements are one important aspect in vehicle certification. Children involvement in motor vehicle accident has become a serious concern public health problem worldwide. Efforts have been made to mitigate this menace by introducing CRS for children up to 3 years old and a seat booster is recommended for 6YO children that are yet to use car seat belt (Wang *et al*., 2007; Jiang & Meng, 2022). Booster has been proven to provide reduction in injuries for children aged between 4 to 8 years (Jermakian & Edward, 2007). It is required to restrain the 6YO child in the booster to prevent serious injuries on crash. Misuse of the booster and not using it in the first place has been a practice in developing countries.

Great work has been done with regards to adult and children crash safety evaluation. Cruz-Jaramillo *et al*., (2018) conducted crash analysis using 6YO crash dummy model and found that belt restraint system placement is a factor that determines the performance of seat in protecting child injuries in frontal crashes. Jermakian and Edwards (2017) compared the Hybrid III (HIII) 6-Year-old with standard pelvis and modified pelvis with gel abdomen in booster sled tests. The results show that HIII 6YO dummy with modified pelvis and gel abdomen exhibited smaller torso rotations, larger knee-head excursions and other potential indicators of unfavorable kinematics associated with submarining when compared with the standard 6YO in paired tests. Zhang et al., (2023) proposes an efficient design framework of child booster seat based on a frontal collision which was found to significantly reduced injury parameters to 6YO child.

In some developing countries like Nigeria, though children are involved in vehicle crashes there was little attention to laws that regulates positioning the child passenger in cars. Many studies worked on retrained child and none investigated the injury outcomes of non-restrained child which is the situation we have in developing nations. The aim of this work is therefore to investigate the injury outcomes of non-restrained child with the aim of determining its severity. The study reveals the dangers associated with not using CRS for children in cars, so that relevant authorities will take appropriate measures.

2. Methodology

2.1 Finite Element Modelling

The dummy used in this work is Hybrid III 6 year old Finite Element Model Version: LST0.104.BETA, shown in Fig. 1, that is available on Livermore Software Technology Corporation (LSTC) website, which was developed by LSTC in cooperation with National Crash Analysis Centre (NCAC) and made available to LS-DYNA users. The dummy FE model was validated based on the certification tests contained in the Code of Federal Regulations, Title 49, Part 572, Sub-part N (LSTC, 2013). LS-DYNA specific “History” nodes and beam elements are provided in some specific locations of the body in order to provide value of responses required for the extraction of occupant injury criteria.

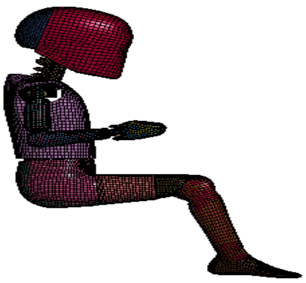

Fig. 1 6YO Hybrid III FE dummy model

The 6YO child dummy was positioned on rear seat of the vehicle using LS PrePost dummy positioning tool and constant downward gravity was applied in z-direction. AUTOMATIC_SURFACE_TO_SURFACE definition with static and dynamic friction coefficient of 0.3 and segment based soft contact option with a scale factor of 0.1 was defined between the dummy and car seat as shown in Fig. 2.

The vehicle finite element model of Ford Taurus that is publicly available in NCAC website (NCAC, 2015) for research purposes was utilized in the crash simulation. The model has been validated against physical crash test data. This model is used in this work because of its low computational requirements. Taurus model front-end structures were meshed with fine mesh because it is used for frontal impact assessment. The rear portion was meshed with coarse elements so as to reduce computation time without affecting the simulation results quality as shown in Fig. 2.

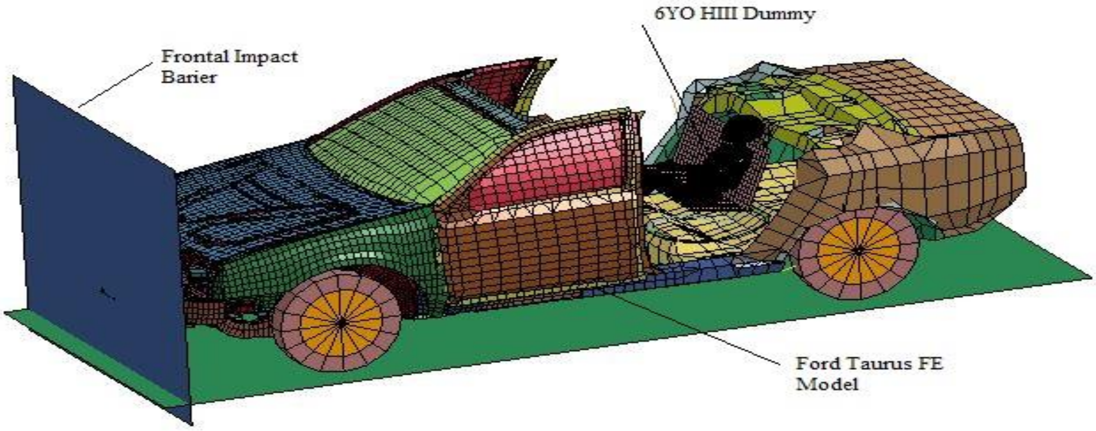

Fig. 2 Unrestrained 6YO child dummy model in Car FE model for frontal impact simulation

A frontal impact test was a conducted in LS DYNA solver at 48 km/h speed which was chosen based on FMVSS 208 requirement for full frontal impact test. This impact speed is also currently applied in full width frontal impact in Canada, Japan and Australia regulations (Crandall et al., 2012). The duration of simulation was taken as 140ms to enable the dummy response to complete. The control options in LS DYNA were set according to 6YO HIII dummy manual (LSTC, 2013). The time step scaling factor was reduced from default of 0.9 to 0.7 in *CONTROL_TIME_STEP card. This is because of instabilities when using 0.9 scaling factor which lead to the premature termination of the simulations. The simulation time was 10 hours. The injury parameters evaluated from the dummy FE model were then compared with NHTSA threshold as well as other experimental and simulation results of restrained 6YO HIII dummy from literature.

2.2 Injury Parameters

Injury in the head can cause brain concussion or affect some sensory organs (Ji, 2015). HIC is the main criteria used in assessing the head injury risk on impact. It is the standardized maximum integral of head acceleration measured at the head center of gravity within a specified time windows. It is calculated based on the equation (Henn, 1998; Du Bois et al., 2004):

$$\boldsymbol{HIC} = \left[\frac{\mathbf{1}}{\boldsymbol{t_2 - t_1}}\int_{t_1}^{t_2} \boldsymbol{a_{result.}} \cdot \boldsymbol{dt}\right]^{\mathbf{2.5}} \cdot (\boldsymbol{t_2 - t_1}) \qquad \textbf{[1]}$$

Where t_1 and t_2 are the initial and final times of intervals within which HIC reaches a maximum value (Liu et al., 2016). Acceleration is measured in unit of acceleration of gravity (g) and time in seconds. The resultant acceleration of the dummy model is measured by accelerometer located at the head centre of gravity which provides the components of acceleration in $x, y, and\ z$ directions and the resultant acceleration is evaluated as:

$$a_{result.} = \sqrt{\left(a_x^2 + a_y^2 + a_z^2\right)} \qquad \textbf{[2]}$$

The maximum time interval can be limited to 36ms or 15ms which yields HIC_{36} and HIC_{15} respectively.

Chest severity index gives the degree of chest injuries. It is determined same way as HIC, only that the accelerometer used to measure chest resultant acceleration is located in the dummy spine. This parameter though can be determined using finite element software such as LS-DYNA, it is not being considered in current certification standards. Chest deflection was measured by potentiometer located in the dummy thorax. It was calculated by subtracting y-rotation of node no. 51433298 from y-rotation of node 51433301 (both filtered at 60 Hz), and then multiplied by distance between potentiometer head and base which is 93.23mm (LSTC, 2013).

3. Results and Discussion

The dummy response at some points of simulation is shown in Fig 3. The biomechanics of the head and neck indicates more about the high acceleration and HIC values especially at 90ms.

120ms **90ms** **70ms**

Fig. 3 The response of the dummy at instances in the crash simulation

The results extracted from simulation are shown in Fig. 4 to 7. The peak values were recorded as presented in Table 1. HIC36 and HIC15 are shown in Fig. 4 and 5. Peak head resultant acceleration is 100g which is too high for a child occupant. It is required that child head acceleration should be low on impact, since, if peak acceleration last for 15ms to 35ms it causes high injury criteria. High HIC is an indicator of serious brain injuries. HIC36 and HIC15 are 1594 and 840.7 as indicated in Fig. 4 and Fig. 5 respectively.

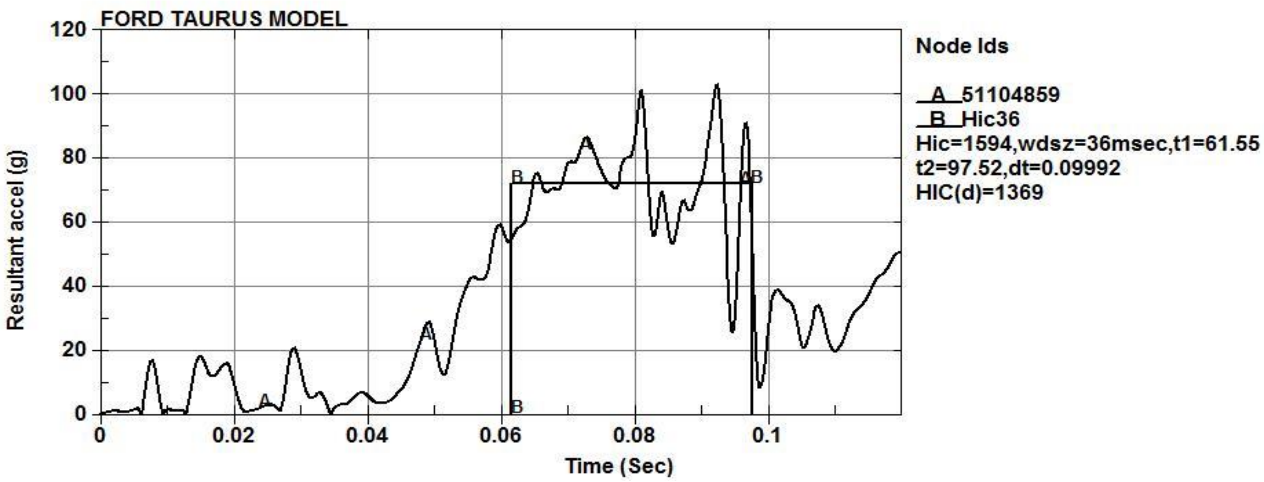

Fig. 4 HIC36 for unrestrained 6YO HIII dummy model

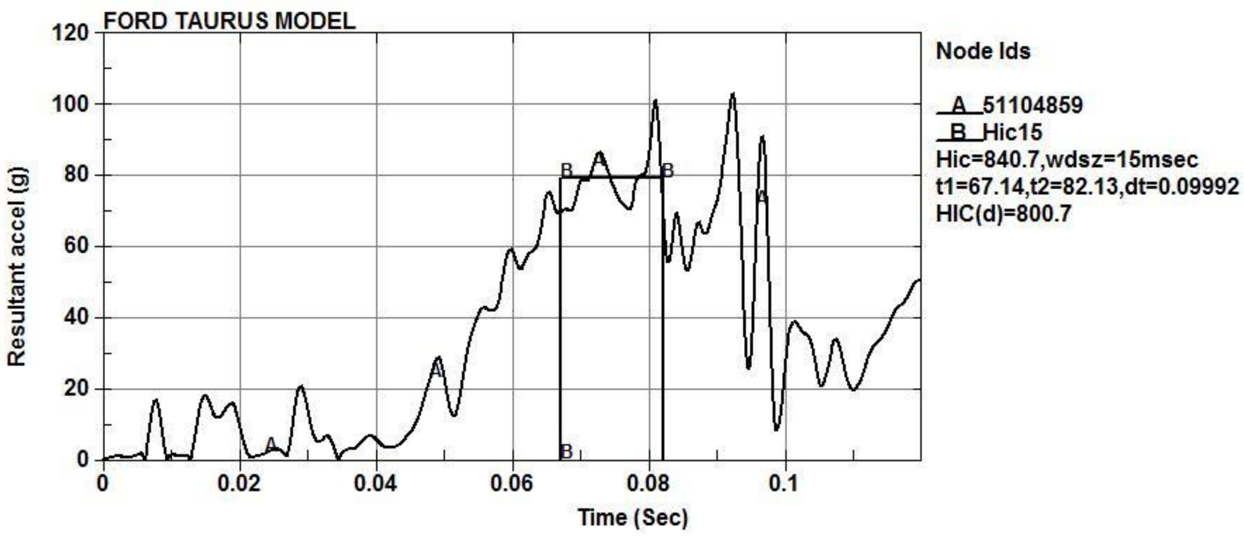

Fig. 5 HIC15 for unrestrained 6YO HIII dummy model

HIC formula is used for CSI replacing head centre of gravity acceleration with thoracic spine acceleration. As shown in Fig. 6, the peak chest acceleration is 55g. NHTSA requires 6YO child thorax acceleration not to exceed 60g as shown in Table 1. CSI is 325.9 in 15ms windows which is considerably high even though not specified in NHTSA limit.

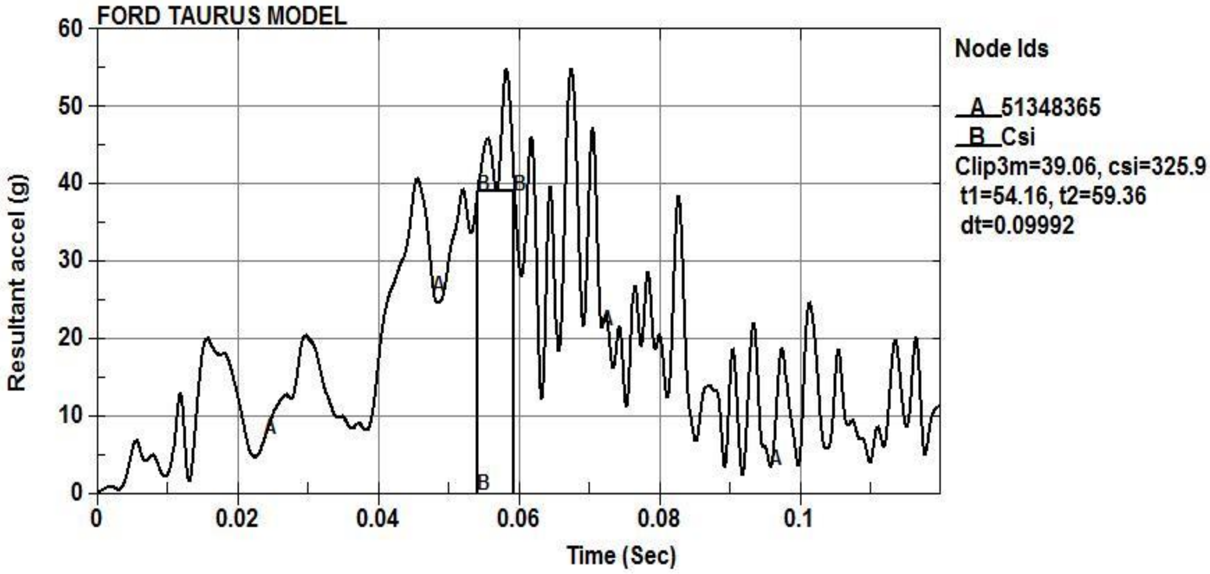

Fig. 6 CSI of unrestrained 6YO HIII dummy model

Chest deflection-time history extracted from the dummy is shown in Fig, 7 and the maximum deflection is 24mm as shown in Table 1. This value is lower than recommended values of 40mm for 6YO. Low deflection is attributable to the dummy inherent characteristics coupled with absence of restraint belt which sometimes exerts force to the chest if it is not well controlled.

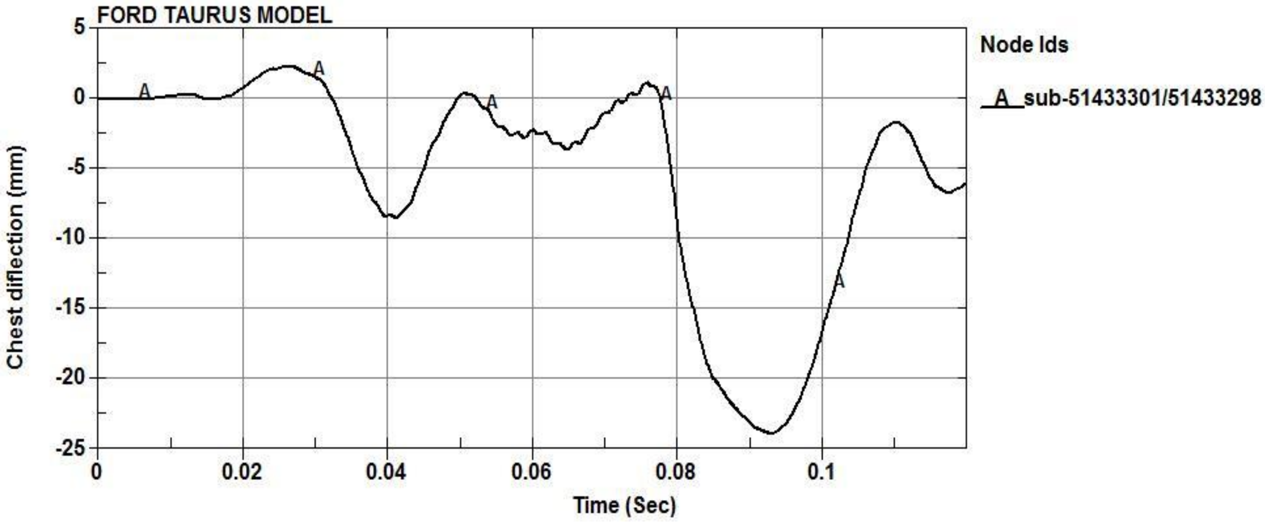

Fig. 7 Chest deflection of unrestrained 6YO HIII dummy model

HIC, CSI and peak values of HA, CA and CD are shown in Table 1. Injury values were first compared with the maximum allowable values required in FMVSS No. 213 (NHTSA) for 6YO HIII dummy (Hagedorn & Stammen 2015). HIC36 and HIC15 are 59% and 20% higher than NHTSA recommended limits as shown in Table 1. This is an indication of high injury sustained by unrestrained child. Also form Table 1, HIC36 is 168% higher than that of 6YO HIII dummy restrained in Back Kid Backrest Booster (BKB) reported by Wu et al., (2023) . High HIC shows that, unrestrained child is at risk of serious head injury on impact at 48 km/h. Head peak acceleration experienced by dummy head is 37% higher than simulation results reported by Cruz-Jaramillo et al., (2018). Higher acceleration indicates the tendency of brain concussion which can lead to death or permanent head damage. It is clear that HIC values of unrestrained child do not satisfy the minimum safety standard of NHTSA which requires HIC36 and HIC15 not to be greater than 1000 and 700 respectively for 6YO child. CSI value is also 15.6% higher than Simulation results using Low Back Booster presented by Cruz-Jaramillo et al., (2018). Chest acceleration is 8.3% higher than CA of 6YO child in Back Kid High Back though it is 8.3 lower than NHTSA limits. Higher acceleration was transmitted to the chest which explains the tendency of high chest injuries sustained by the unrestrained child.

Crash test at 48 km/h using 6YO HIII dummy supposed to have injury values below the NHTSA limits as evidenced by experimental results by Wu et al., (2023). HIC36 and CA for restrained dummies from literature were generally within the threshold as shown in Table 1, thus satisfying the child protection requirement of FMVSS. Lower chest deflection that is 40% lower than NHTSA threshold is the characteristics of the dummy stiff thorax and can't therefore measure the deflection well.

The results obtained in this study is in par with what was reported by Hagedorn and Stammen (2015) where the 6YO HIII experienced an unexpected failure of the lumbar bracket, causing the dummy to separate between the torso and pelvis for lap seat belt configuration.

Table 1 Comparison of Injury Parameters of Unrestrained 6YO HIII model with NHTSA Threshold and Experimental/Simulation Results of Restrained 6YO HIII from Literature

Injury parameters	**Simulation results from**	**NHTSA** (Hagedorn &	**% difference**	**Experimental Results using Back kid**	**% difference**	**Simulation result using Low back**	**% difference**

	Present study	Stammen 2015)		Backrest CRS (Wu et al., 2023)		booster (Cruz-Jaramillo et al., 2018)	
HIC36	1594	1000	59	594	168	554.3	
HIC15	840.7	700	20				
HA (g)	85					62	37
CA (g)	55	60	-8.3	50.8	8.3	44.4	23.9
CSI	325.9					281.9	15.6
CD (mm)	24	40	40				

Conclusion

In this work, unrestrained 6YO HIII dummy model was subjected to crash test in car FE model with the aim of analyzing injury outcomes of unrestrained 6YO child it's representing. The dummy was positioned on rear seat of the vehicle and crash simulation was carried out at 48 km/hr. HIC36, HIC15 and head acceleration, chest acceleration, CSI and chest deflection were recorded and compared with NHTSA threshold as well as experimental and simulation results of restrained 6YO HIII dummy from literature. HIC36 and HIC15 were 59% and 20% higher than NHTSA recommended limits. HIC36 was 168% higher than that of 6YO HIII dummy restrained in Back Kid Backrest Booster. This is an indication of serious head injury for unrestrained child. The dummy exhibited high HIC15 and HA values while CD was lower than recommended values by 40% and this is attributable to the dummy characteristics. The study highlights the dangers of not restraining 6YO child in vehicle and quantifies the level of injuries sustained in frontal crash. Developing countries should therefore enforce restraining child in CRS for improved safety.

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Conflict of Interest: The authors declare that there is no conflict of interests regarding the publication of this paper.

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