



Improved Biofidelity of Child Crash Dummy Thorax Finite Element Model

Rafukka, I. A.

Department of Mechanical Engineering,
Bayero University, Kano,
Kano State

ABSTRACT

Crash dummies are measuring devices applied in safety certification of vehicles. They are used to imitate human response on crash. Biofidelity is the main requirement of dummies. Current Three Year Old (3YO) child crash dummies are validated using scaled adult data due to paucity of child volunteer and cadaver data. Hence there is need to validate their response against at least age mate cadaver response. This work modified the viscoelastic material properties of 3YO Finite Element (FE) child dummy thorax flesh and bib assembly and compare its response with two 3YO cadaver response data obtained from literature, with the purpose of improving its biofidelity. 6 m/s thorax impact test was conducted using FE simulation according to National Highway Traffic Safety Administration (NHTSA) 3YO Hybrid III (HIII) certification. It was found that adjusting the viscoelastic parameters: bulk modulus, K , long term shear modulus, G_1 , short term shear modulus, G_0 for thorax flesh and elastic modulus, E for bib assembly change the dummy response to that of cadaver with a difference of 10.4% and 17.5% for peak force and chest deflection respectively. Chest deflection-time history fits very well in the 3YO certification corridors. The biofidelic dummy will measure injury response more realistically than HIII dummy models.

ARTICLE INFO

Article History

Received: July, 2023

Received in revised form: November, 2023

Accepted: January, 2024

Published online: March, 2024

KEYWORDS

Child Crash Dummy, Chest Deflection, Biofidelity, Thorax

INTRODUCTION

Chest injuries in vehicle crashes are one of major causes of child fatalities worldwide. Crash dummies are used to evaluate safety performance of vehicles. They are used in design stage for virtual crash simulations. These dummies are used to measure the actual biomechanical response of human in crash event. The deformations and accelerations of dummies must correspond well with human beings for good injury predictions. The best way to ensure biofidelity of the dummies is to compare the biomechanics with real human beings or cadaver. Post-mortem human subjects (PMHS) provides biomechanical response used in dummy models validation, but children cadaver data is highly difficult to obtain (Yoganandan et al. 2013; Loyd 2011). Very few paediatric PMHS

biomechanical response data are available in the public literature. Thus, human and Anthropometric Test Device (ATD) child dummy models are only validated by certification corridors. Alternatively, accident reconstructions have been applied in the dummy validation and determination of injury criteria (Anderson et al. 2000; Meyer et al. 2014). Research is currently focused on implementing children cadaver response data to child physical and FE dummies for better biofidelity. For the child human and crash dummy models, lower extremities, pelvis and abdomen were not well validated because of lack of cadaver experimental data.

Improvement of biofidelity has been reported in the literature. Tot et al. (2008) compared head-neck of 3YO HIII dummy FE model with paediatric cadaver data, under

Corresponding author: Rafukka, I. A.

✉ ibrahimrafukka@yahoo.com

Department of Mechanical Engineering, Faculty of Engineering, Bayero University, Kano,

© 2024. Faculty of Technology Education. ATBU Bauchi. All rights reserved

flexion-extension bending and axial loading condition. A large difference was found in torsion and linear stiffness between 3YO HIII dummy and cadaver. Cadaver response was then executed in to 3YO HIII FE model by substituting the original material model of neck cable, material type 1 (MAT Elastic) with type 67 (MAT Nonlinear Elastic Discrete Beam) of LS-DYNA. The elastic bulk modulus, short and long-term shear modulus were also changed from their original values for the dummy neck response to simulate cadaver. Zhang et al. (2009) showed that 3YO HIII ATD neck is far from cadaver response in a sled test with peak acceleration of 17g. Cadaver biomechanical response was then implemented in to the paediatric neck under tensile and bending loading by modifying the material properties values of ligaments, intervertebral disks and facet joints. Sherwood et al. (2003) also showed that the 6YO HIII dummy neck flex more than that of 12-year-old cadaver in a sled tests conducted at 49 km/h under the same impact condition.

Current 3YO crash dummy models were validated using certification corridors that were scaled from adult data due to paucity of child data, without comparing their response directly with age mate cadaver. Biofidelic child crash dummies are crucial in designing vehicles that are safe for children population. While crash dummy head and neck modification for improved biofidelity has been reported in literature, little attention was given to the dummy thorax even though it is a human body part that must be certified in vehicle safety assessment. This work focused on modifying the material properties of 3YO dummy thorax FE model with the aim of improving its biofidelity to match well with biomechanical response of two child cadaver data in order to improve the dummy ability to predict injuries on crash.

MATERIALS AND METHODS

Crash Dummy FE Model

Hybrid III 6-year-old Finite Element Model Version: LST0. 104. BETA, available on LSTC website, which is currently the latest child model, was selected as the baseline model in

this study. It was developed by LSTC in cooperation with National Crash Analysis Centre (NCAC) and made available to LS-DYNA users. The model was validated based on the certification tests contained in the Code of Federal Regulations, Title 49, Part 572, Sub-part N. The baseline model is as shown in Figure 1. It contains 199,102 nodes, 127,154 solid elements, 45,032 shell elements and 142 beam elements (LSTC, 2013). LS-DYNA specific "History" beam elements and nodes are positioned in some specific locations of the body in order to provide value of response required for the extraction of occupant injury criteria.

The load cells and accelerometers are placed throughout the child dummy model in accordance with the coordinate system specified by the Society of Automotive Engineers (SAE). The dummy was intended to be used while properly restrained in CRS designed for sitting posture only. It was reclined and the pelvis angle reflects a child's seating position in a CRS. Also, the neck of the dummy was positioned at an angle such that the head is levelled when the dummy is seated. The FE model of the reference dummy in the present work was downloaded from (LSTC, 2011). Dummy FE model and the thorax used in the present study are as shown in Figure 1. The 6YO HIII dummy model was scaled to three-year-old anthropometry and validated before optimizing the material properties.

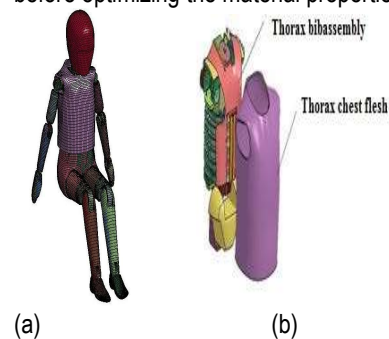


Figure 1: Hybrid III 6YO child dummy FE model (a) and Dummy thorax (b) (LSTC, 2011)

Federal Motor Vehicle Safety Standard (FMVSS) made it that for chest to be safe it must

Corresponding author: Rafukka, I. A.

✉ ibrahimrafukka@yahoo.com

Department of Mechanical Engineering, Faculty of Engineering, Bayero University, Kano,
© 2024. Faculty of Technology Education. ATBU Bauchi. All rights reserved

not be subjected to acceleration above 60g in a time interval of 3ms (CLIP3M).

Thorax material models

Linear elastic isotropic

This material model is applicable to solids and fluids, and can be used for brick, beams and sections (Hallquist 2006). It is material type 1 in LS-DYNA Software. For elastic material, the co-rotational rate of the deviatoric Cauchy stress tensor, S_{ij} , and pressure are calculated using equations (1) and (2) respectively:

$$S_{ij}^{n+\frac{1}{2}} = 2G \dot{\epsilon}_{ij}^{n+\frac{1}{2}} \quad (1)$$

$$P^{n+1} = -K \ln V^{n+1} \quad (2)$$

Where G and K are elastic shear and bulk moduli respectively. V is the relative volume that is ratio of current volume to the initial volume. In the present study, the material model is applied for neck cable and thorax bisassembly.

Linear viscoelastic

This is material model type 6 in LS-DYNA Software. It is useful in modelling the viscoelastic behaviour of beams, shells and solids (Hallquist 2006). The deviatoric stress tensor used for viscoelasticity computation is:

$$S_{ij} = 2 \int_0^t G(t-\tau) \frac{\partial \epsilon'_{ij}(\tau)}{\partial \tau} d\tau \quad (3)$$

Where the shear relaxation behaviour is given by:

$$G(t) = G_1 + (G_0 - G_1)e^{-\beta t} \quad (4)$$

Where G_1 , G_0 and β are the long term shear modulus, short term shear modulus and decay constant respectively.

Thorax impact test

Frontal thoracic test was conducted with the complete dummy FE model. Dummy model was seated in upright position on

horizontal plane as shown in Figure 2. The thorax was impacted by a cylindrical impactor with size and weight as specified in the standard (NHTSA, 2011). The impactor was positioned so as to strike the thorax at the 3rd rib at zero-degree angles. The Impactor struck dummy chest with initial velocities of 6 m/s.

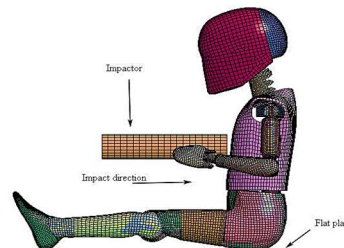


Figure 2: Thorax impact test set up

The impactor force was calculated by multiplying the x-acceleration measured by accelerometer located on the impactor by the impactor mass. The results were filtered using 108 Hz to remove the noisy signals as specified. The chest deflection was measured by potentiometer located in the dummy thorax. It was calculated by subtracting y-rotation of node no. 50433298 from y-rotation of node 50433301 (both filtered at 60 Hz), and then multiplied by distance between potentiometer head and base which is 93.23 mm (LSTC, 2013). The history nodes in the dummy model are shown in Figure 3.

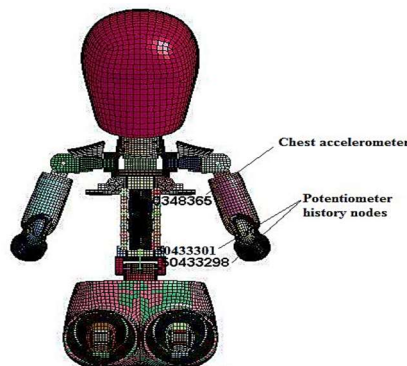


Figure 3: History nodes located in the dummy thorax

Corresponding author: Rafukka, I. A.

✉ ibrahimrafukka@yahoo.com

Department of Mechanical Engineering, Faculty of Engineering, Bayero University, Kano,

© 2024. Faculty of Technology Education. ATBU Bauchi. All rights reserved

The impactor force versus chest deflection curve is plotted and compared with certification corridor and cadaver results.

Frontal thoracic impact test was carried out with the complete dummy. The response of the dummy at some instances in the simulation is as shown in Figure 4.

RESULTS AND DISCUSSION



Figure 4: Response of Dummy at Some Instances in the Impact Test

Thorax chest flesh was modelled with linear viscoelastic material model (MAT_06) with fully integrated solid element. Fully integrated shell element with 3 through shell thickness integration points was used for thorax bib assembly. Thorax chest flesh with viscoelastic material properties and thorax bib assembly with elastic behaviour affect the thorax response. Chest deflection and peak impactor force are mainly affected by the viscoelastic material parameters of chest flesh and elastic modulus of thorax bib assembly parts. Initial values from reference dummy were applied and then optimized by several numbers of simulations for the force deflection curve to fit well in the certification corridors.

Viscoelastic parameters of thorax flesh: G_0 , and G_1 of MAT_06 in LS-DYNA and modulus of elasticity E, of thorax bib assembly were found to have effect in the response. Modified material parameters for good fitting of force-deflection curve in 3YO certification corridor are shown in Table 1.

It can be observed in Table 1 that viscoelastic material parameters values of chest flesh were decreased from their initial values to achieve the desired chest deflection, while the elastic modulus of thorax bib assembly was increased for better force-deflection response. **Error! Reference source not found.**

Table1: Thorax modified material properties

	ρ (Kg/mm ³)	K/E (MPa)	G_0 (MPa)	G_1 (MPa)	β (1/msec)
Thorax chest flesh (6YO HIII)	7×10^{-7}	0.032	0.045	0.033	0.25
Thorax chest flesh (3YO)	6.31×10^{-7}	0.02	0.01	0.005	0.25
Thorax bib assembly (6YO HIII)	1.4×10^{-6}	6	NA	NA	NA

Corresponding author: Rafukka, I. A.

✉ ibrahimrafukka@yahoo.com

Department of Mechanical Engineering, Faculty of Engineering, Bayero University, Kano,

© 2024. Faculty of Technology Education. ATBU Bauchi. All rights reserved

Thorax bib assembly (3YO)	1.12×10^{-6}	7	NA	NA	NA
---------------------------	-----------------------	---	----	----	----

Dummy thorax response at 6 m/s impact speed

The force versus time history is shown in Figure 5. The first peak that appeared at the beginning of the impact within a short time is

attributable to the impactor-chest flesh contact. The peak at about 10ms is as a result of chest reaching the maximum deflection. This corresponds with maximum deflection of 33.4 mm which occurs about 10ms as seen in chest deflection history shown in Figure 6.

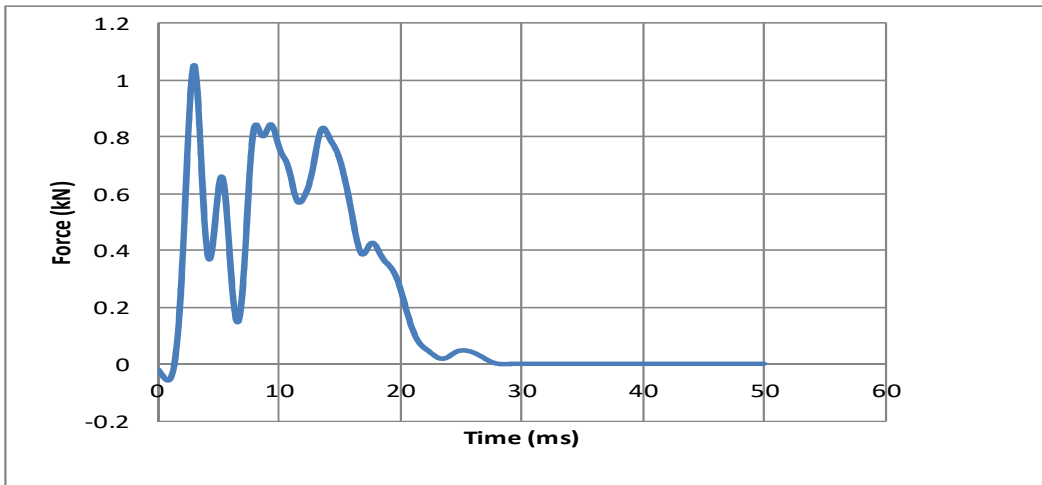


Figure 5: Impactor force-time graph for 3YO dummy at 6 m/s

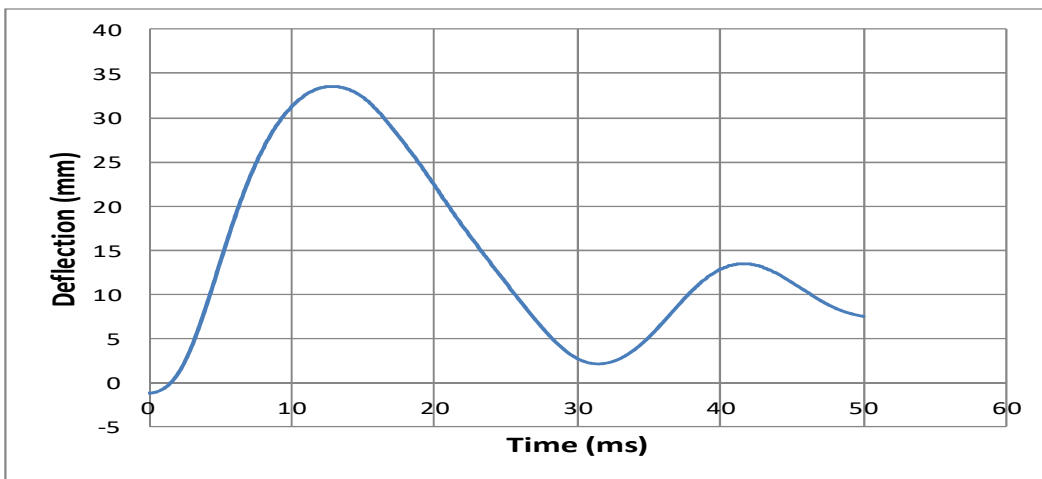


Figure 6: Thorax deflection-time graph for 3YO Dummy at 6 m/s impactor speed

Impactor force-deflection curve is shown in Figure 7 for an initial impactor velocity of 6 m/s. Significant part of the curve was within

3YO certification corridor and trend of curves look similar. The impactor force was below the lower limit of the corridor around 10mm and

Corresponding author: Rafukka, I. A.

✉ ibrahimrafukka@yahoo.com

Department of Mechanical Engineering, Faculty of Engineering, Bayero University, Kano,

© 2024. Faculty of Technology Education. ATBU Bauchi. All rights reserved

20mm deflection. This is because the impactor pushes the torso back as it was hit: this moves the child FE model in backward direction (see

Figure 4), and result in subsequent contact force reduction.

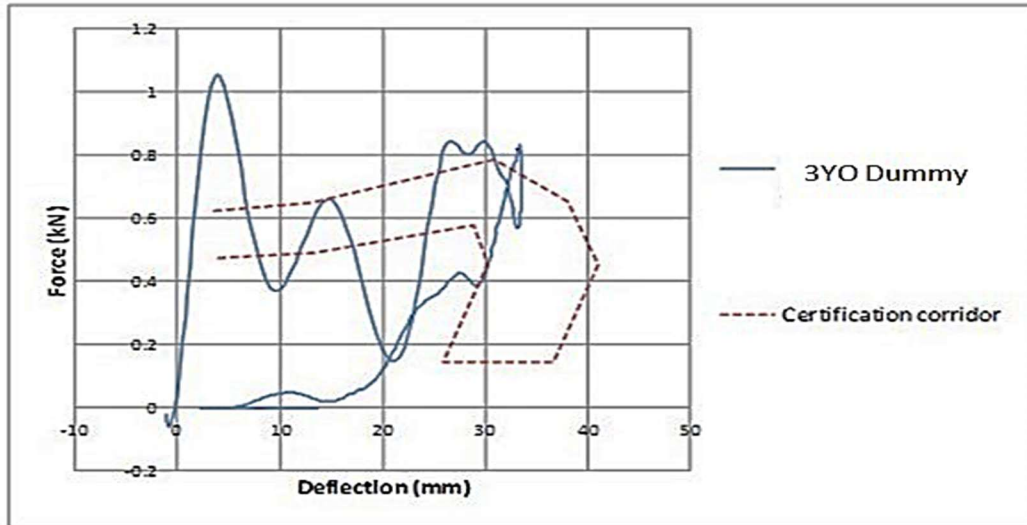


Figure 7: Force-chest deflection curve of 3YO dummy with respect to three-year-old certification corridor at 6 m/s impactor speed

Table 2 compares the 3YO Dummy model validation parameters with specifications

contained in 3YO HIII dummy requirements for thorax response of three-year-old.

Table 2: Comparison of 3YO Dummy thorax response with specifications of 3YO HIII dummy (NHTSA, 2011)

Parameters	Specification	3YO Dummy
Probe mass (<i>kg</i>)	1.70±0.02	1.71
Probe velocity (<i>m/s</i>)	6.0±0.1	6
Probe diameter (mm)	53.3	53
Peak force (kN)	0.68-0.81	0.83
Chest deflection (mm)	32-38	33.4

Apart from peak force that is slightly out of the range, all other parameters are within the specified values.

Comparison of thorax response with cadaver data

Validation in the previous sections was based on certification corridors which were derived from adult thorax response, due to scarcity of child cadaveric data. The 3YO Dummy thorax was further compared with three year old child cadaver thorax response data reported by

Ouyang et al. (2006). This is important in order to further show the level of biofidelity of the model in predicting 3YO thoracic injuries. To the best of author's knowledge, there are only two dynamic test data of paediatric thorax from Kent et al. (2009) and Ouyang et al. (2006). In this study, Ouyang data was utilized in validating thorax model. The test was conducted by subjecting 2 to 12 year old child's cadaver to frontal thoracic

Corresponding author: Rafukka, I. A.

✉ ibrahimrafukka@yahoo.com

Department of Mechanical Engineering, Faculty of Engineering, Bayero University, Kano,

© 2024. Faculty of Technology Education. ATBU Bauchi. All rights reserved

impact test using 2.5 kg impactor for 2 to 3 year old child cadaver. Table 3 compares the results

of thorax impact test of 3YO Dummy with child cadaver data of Ouyang et al. (2006).

Table 3: Comparison of 3YO Dummy with cadaver thorax response from Ouyang et al. (2006)

Subject	Impactor mass (Kg)	Impactor diameter (cm)	Impact speed (m/s)	Age/gender	Weight (kg)	Height (cm)	Cause of death	Chest Defl. (mm)	Force (kN)
1	2.5	5	6	3/M	13.5	93	Brain tumour	44.8	0.83
2	2.5	5	6	3/F	10.5	85.0	Heart disease	40.0	0.75
3YO Dummy (present study)	2.5	5	6	3/NA	12	87	NA	33.4	0.83

M-male, F-female

It is observed from Table 3 that the peak force of 3YO Dummy is equal to the value reported for cadaver No.1. However, 3YO Dummy appeared stiff than the two cadavers, hence the simulation results underestimated the cadaver chest deflection by about 10mm. This may be due to possible mismatch between the test setup of cadaver and dummy model. The

difference could also be attributed to small difference in weight and height of the dummy relative to cadaver as seen in Table 3. In addition, cadavers are also not living human. Figure 8 compares 3YO Dummy impactor force versus external chest deformation curve with Ouyang cadaver test data.

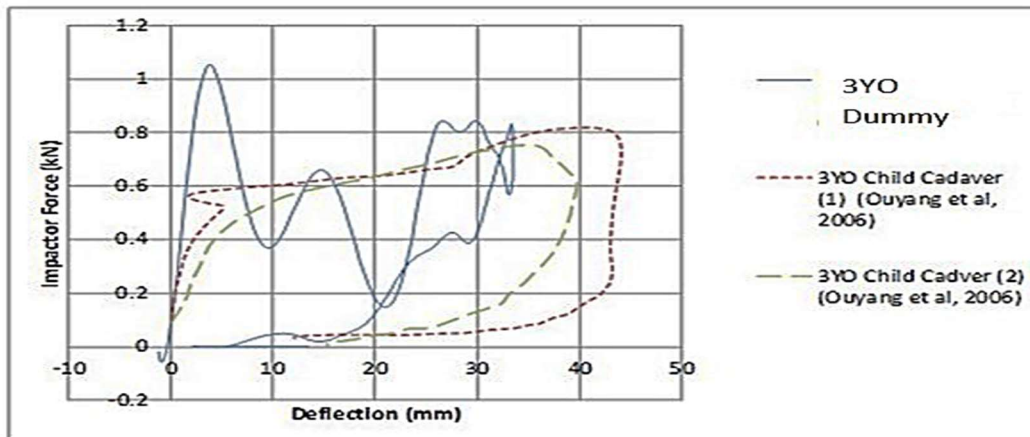


Figure 8: Comparison of 3YO Dummy response with cadaver response from Ouyang et al., (2006)

The noisy nature of 3YO Dummy curve shown in Figure 8 is due to the structure of crash dummy thorax which was made of parts of steel and aluminium properties with hollow inner, unlike human which contain flesh, muscles cartilages and bones. In addition, accelerometer

was placed in the thorax of the 3YO dummy model, which is difficult for human cadaver. A high peak occurred at about 5ms which was not captured by the cadaver results. This is the characteristics of crash dummy thorax response (FTSS, 2008; Saul et al. 1998). Table 4 shows

Corresponding author: Rafukka, I. A.

✉ ibrahimrafukka@yahoo.com

Department of Mechanical Engineering, Faculty of Engineering, Bayero University, Kano,

© 2024. Faculty of Technology Education. ATBU Bauchi. All rights reserved



that peak force at maximum chest deflection of the 3YO Dummy correlates well with the two cadavers compared. The difference in maximum chest deflection is fairly good, considering the

differences in maximum chest deflection between the two cadavers even though they were of the same age.

Table 4: Comparison of 3YO Dummy thorax response with 3YO cadaver

	Cadaver 1	3YO Dummy	% diff.	Cadaver 2	3YO Dummy	% diff.
Peak force (kN)	0.83	0.83	0	0.75	0.83	10.4
Deflection (mm)	44.80	33.40	25	40.0	33.4	17.5

CONCLUSION

This work modified the materials properties of 3YO crash dummy FE model for improved biofidelity. The viscoelastic material properties of the dummy chest flesh were fine tuned to get better material parameter values. K , G_0 and G_1 of 0.02MPa, 0.01MPa and 0.005MPa respectively were found to yield best thorax response that simulate cadaver response. Elastic modulus, E of thorax bib assembly that yield better biofidelity was found to be 7MPa. Modified dummy model showed better biofidelity than 3YO HIII with respect to certification corridors. The peak force and deflection of the thorax correlates with 3YO cadaver data with a difference of 10.4% and 17.5% respectively. The dummy thorax therefore mimics real human response on impact than traditional HIII dummy. Modified dummy model is useful in measuring child chest injuries on car and domestic accidents with better biofidelity.

REFERENCES

Anderson, R., Streeter, L. & Mclean, J. (2000). Estimation of impact severity in pedestrian accidents using accident investigation, computer simulation and physical reconstruction. In *Road Safety Research, Policing and Education Conference*. pp. 285–290.

FTSS. (2008). *FTSS Hybrid III 3 Year Old Dummy Model – LS-DYNA*.

Hallquist, J.O. (2006). *Theory manual*, Livermore Software Technology Corporation.

Kent, R., Salzar, R., Kerrigan, J., Parent, D., Lessley, D., Sochor, M., ... Maltese, M. R. (2009). Pediatric thoracoabdominal biomechanics. *Stapp Car Crash Journal*, 53(November), 373–401.

Loyd, A.M. (2011). *Studies of the Human Head from Neonate to Adult: An Inertial, Geometrical and Structural Analysis with Comparisons to the ATD Head*. Duke University.

LSTC. (2011). Download LSTC Dummy and Barrier Models for LS-DYNA. Retrieved July 2, 2016, from http://www.lstc.com/download/dummy_and_barrier_models

LSTC. (2013). *LSTC Hybrid III 6 year old Finite Element Model Documentation*.

Meyer, F. et al. (2014). Development of a 3-year-old child head–neck finite element model and derivation of novel head injury criterion. *International Journal of Crashworthiness*, 19(3), pp.233–243.

NHTSA. (2011). *National Highway Traffic Safety Administration-part 572.144-subpart P-3-year-old child crash test dummy, alpha version*.

Ouyang, J., Zhao, W., Xu, Y., Chen, W., & Zhong, S. (2006). Thoracic impact testing of pediatric cadaveric subjects. *The Journal of Trauma*, 61(6), 1492–500.

Yoganandan, N., Derosia, J. & Humm, J. (2013). An improved method to calculate paediatric skull fracture threshold. In *23rd International Technical Conference on the Enhanced Safety of Vehicles (ESV)*. pp. 1–8.

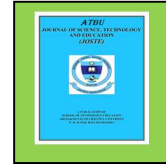
Saul, R. A., Pritz, H. B., Backaitis, S. H., & Hallenbeck, H. (1998). Description and performance of the hybrid III three year

Corresponding author: Rafukka, I. A.

✉ ibrahimrafukka@yahoo.com

Department of Mechanical Engineering, Faculty of Engineering, Bayero University, Kano,

© 2024. Faculty of Technology Education. ATBU Bauchi. All rights reserved



- old, six year old and small female test dummies in restraint system and out-of-position air bag environments. In *Proceedings: International Technical Conference on the Enhanced Safety of Vehicles* (pp. 1513–1531).
- Sherwood, C.P. et al. (2003). Prediction of cervical spine injury risk for the 6-year-old child in frontal crashes. *Traffic injury prevention*, 4(3), pp.206–213.
- Tot, M. et al. (2008). Implementation of child biomechanical neck behaviour into the hybrid III crash test dummy. *SAE Technical Paper*.
- Zhang, W. et al. (2009). Implementation of Child Biomechanical Neck Behaviour into a Child FE Model. In *SAE International Conference*.

Corresponding author: Rafukka, I. A.

✉ ibrahimrafukka@yahoo.com

Department of Mechanical Engineering, Faculty of Engineering, Bayero University, Kano,

© 2024. Faculty of Technology Education. ATBU Bauchi. All rights reserved