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BIOMECHANICAL RESPONSE COMPARISON OF NIGERIAN CHILD ANTHROPOMETRIC TEST DEVICE (ATD) AND HYBRID III DUMMY

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Highlights:

- Crash dummy size affects injury outcomes in frontal crash tests.
- Finite element dummy model could be scaled to represent children of various anthropometries.
- Child anthropometry is crucial in safety certification.

Abstract: Anthropometric Test Devices (ATD) or crash dummies are used to simulate the response of human beings in crash tests of vehicles. There is concern about the difference in anthropometry of people from various locations of the world and current crash test dummies used in safety certification of vehicles. Three-year-old (3YO) Hybrid III dummy (D_{HIII}) may not represent Nigeria children because they were produced using United States child anthropometry. The aim of this work is to investigate how the size of 3YO Nigeria child dummy (D_{Nig}) affects crash injury outcomes in Finite Element (FE) crash analysis. FE dummy model that is scaled to Nigeria child anthropometry was used to simulate a sled test and the injury parameters such as head accelerations, chest acceleration and resultant upper neck moment and force were evaluated and compared with experimental results of D_{HIII} with the view to ascertain how good D_{HIII} can represent Nigerian child in crash test. The results show that D_{HIII} is different from D_{Nig} in head acceleration and chest acceleration by 29% and 6% respectively. Nigerian child resultant upper neck moment and force were 10% and 23% respectively lower than D_{HIII}. Difference in the injury outcomes means that D_{HIII} model cannot represent three-year-old Nigerian child in certification. Hence crash dummy of Nigerian child anthropometry is necessary in certifying vehicle safety performance for cars used in Nigeria.

Keywords: anthropometry; crash dummy; crash test; injury parameters; vehicle safety

1. Introduction

Road traffic injuries are the leading killer of children worldwide. Rates of road traffic deaths among children are about 3 times higher in low- and middle-income countries than in high-income countries (*Road Traffic Injuries: Children*, 2023). There has been interest in paediatric safety recently in the scientific community but there are limited data on injury threshold (Fraser et al., 2019). Designing safer vehicles for children has been a major challenge to automakers. Vehicles must satisfy safety performance regarding children before being put forward to market. Dummies used for crash certification of vehicles are made for a wide range of sizes to represent people of various ages to ensure that vehicles are safe for all occupants.

Nigeria has the highest road traffic accident rate in Africa, and second in the world (Atubi, 2010; Vitus, 2006). Developing child dummy to represent this population in vehicle crash tests is therefore important considering the reported mismatch between the child and the current crash dummies due to differences in anthropometries (Rafukka et al., 2016). Average three year old Nigerian child weight, for instance, was reported to be below WHO standard (Aina & Morakinyo, 2001). Thus their biomechanical response is expected to be different from the traditional child crash dummies. For a given vehicle design, the severity of injury in vehicle occupants is highly dependent on the physical size, age and weight of occupant. In the effort to keep vulnerable populations safe in vehicular crashes, human body models are modelled with their sizes, weight and material properties to represent the real human being. Though there are FE models of three-year-old (3YO) children developed by Livermore Software Technology Corporation (LSTC) and Humanetics, these models were developed based on anthropometry of some specific populations and for only 50th percentiles.

Efforts made by researchers in developing dummies to represent a given population are mainly on adults (Happee, 1998; S. J. Kim et al., 2003) with little attention to children, despite the studies reported differences in anthropometry between children of different populations and crash dummies (Rafukka et al., 2016; Serre et al., 2006). Injuries severity in vehicular crashes was shown to depend on the child's anthropometry (Kim et al., 2015). Wang et al. (2022) conducted car-to-pedestrian collision simulations using pedestrian multibody models representing anthropometric characteristics of Western European and Chinese populations on three typical vehicle shapes and impact speeds. The results indicate that the change of pedestrian model anthropometry (from Western European to Chinese) affects the head injury indices in the impact with road surface. Samad et al. (2021) investigated injury outcomes of scaled Hybrid III 50^{th} percentiles dummy to actual Malaysian anthropometric data integrated into the vehicle using the finite element method. The results showed that the neck forces and moments were slightly reduced while the other injury parameters remained similar. Hence there is a need to study the effect of dummy anthropometry on the injury sustained in a crash. The aim of this work is to compare biomechanical response of the standard 3YO Hybrid III dummy (D_{HIII}) with that of an FE dummy model scaled to Nigerian anthropometry with the view of assessing whether the vehicles certified using D_{HIII} will be safe for Nigerian children.

2. Materials and Methods

2.1. Dummy Scaling

Different scaling factors are assigned to different body segments in x, y and z-direction. Baseline model geometry (6YO HIII) was adapted freely to the target anthropometry. Each dummy segment was constrained in morphing box in LS Prepost. Scaling factors were calculated by dividing target anthropometry values L_{ti} by corresponding reference anthropometry L_{ri} as shown in **Equation (1)**,

$$L_i = \frac{L_{ti}}{L_{ri}} \quad i = x, y, z \tag{1}$$

Anthropometry of Nigeria child was taken from the most recent anthropometric data of 3YO child that can be utilized for crash dummy design to the best of Author’s knowledge (Rafukka et al., 2016). Dimensions of 6YO HIII were measured from dummy model obtained from Livermore Software Technology Corporation (Mahadevaiah & Burger, 2013).

Scaling factors applied to various body segments are as listed in **Table 1**.

Table 1. Size scale factors used to scale 6YO HIII dummy model to 3YO Nigerian child anthropometry

Body segment	**Scaling factors**		
	λ_x	λ_y	λ_z
Head-neck	0.94	0.94	0.91
Torso	0.76	0.85	0.73
Upper arm	0.81	0.81	0.81
Lower arm	0.79	0.79	0.79
Upper leg	0.6	0.8	0.8
Lower leg	0.7	0.7	0.7

Table 2 shows the weight distribution of D_{Nig} (measured from the dummy after scaling) and D_{HIII} .

Table 2. Body mass distribution of morphed D_{Nig} and D_{HIII}

Body segment	**Scaled 3YO child (D_{Nig}) (kg)**	**3YO HIII (D_{HIII}) (kg) (Mizuno et al., 2005)**
Head	2.02	2.72
Neck	0.22	0.79
Torso	6.86	7.00
Upper arm	0.26	0.44
Lower arm	0.34	0.46
Upper leg	0.77	1.01
Lower leg	0.59	0.61
Foot	0.22	0.31
Total body weight	13.29	16.17

2.2. Sled Test Setup for Biomechanical Response Comparison

Experimental and simulation responses of physical 3YO HIII dummy (D_{HIII}) from Turchi et al. (2004) were utilized for comparison with response of D_{Nig} .

D_{Nig} was positioned in the CRS as shown in **Figure 1**. Last row of the five ends of the seat belt was constrained to a rigid seat using constrained extra node sets so that it follows the prescribed acceleration.

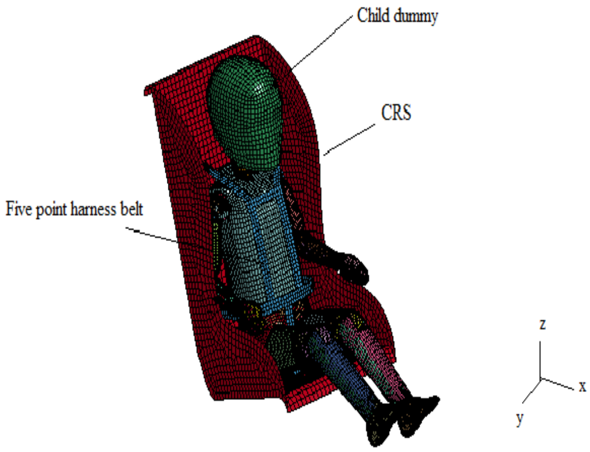


Figure 1. 3YO child dummy FE model ($\boldsymbol{D_{Nig}}$) in CRS

Constant downward gravity was applied to the dummy 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 both child seat and seat belt. The pre-and post-processing analyses were conducted with LS-PrePost (v4.2). Default time step scale factor of 0.9 was used, and hourglass control type 2 was applied which computes and includes hourglass in the energy balance.

To simulate Turchi et al. (2004) experiment, acceleration pulse was applied to the rigid seat in the negative *x*-direction, while constrained in *y* and *z* directions for translation and rotation and constrained in *x*-direction for rotation. The crash test was performed in accordance with Federal Motor Vehicle Standards (FMVSS 213) using acceleration pulse shown in **Figure 2**. The head and chest accelerations, resultant upper neck forces and moments were then measured in accordance with dummy manual (Mahadevaiah & Burger, 2013) and compared with literature experimental and simulation results.

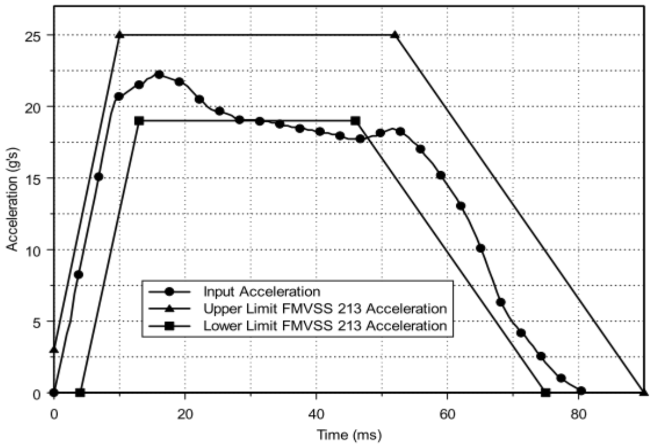


Figure 2. FMVSS 213 prescribed acceleration for sled test

Simulations were analysed for time duration of 150ms which is enough to observe the dummy response and interaction with child seat. The head and chest acceleration and upper neck moment and force were extracted from the dummy FE model through accelerometers and load cells located in the various dummy body segments.

2.3. Evaluation of Dummy Injury Parameters

From LS-PrePost, the head and chest acceleration were extracted from the nodout file option of ASCII command as resultant acceleration-time history of the accelerometer node. Neck upper force and moment were measured by the load cell located below the occipital condyle (Mahadevaiah & Burger, 2013).

The moment M_{yc} is given by **Equation (2)**:

$$M_{yc} = M_y - (D \cdot F_x) \quad (2)$$

Where, M_{yc} = Total moment about occipital condoyle in y-direction

M_y = Neck moment in y-direction; tendency of head and neck to bend towards chest (flexion) or towards back (extension).

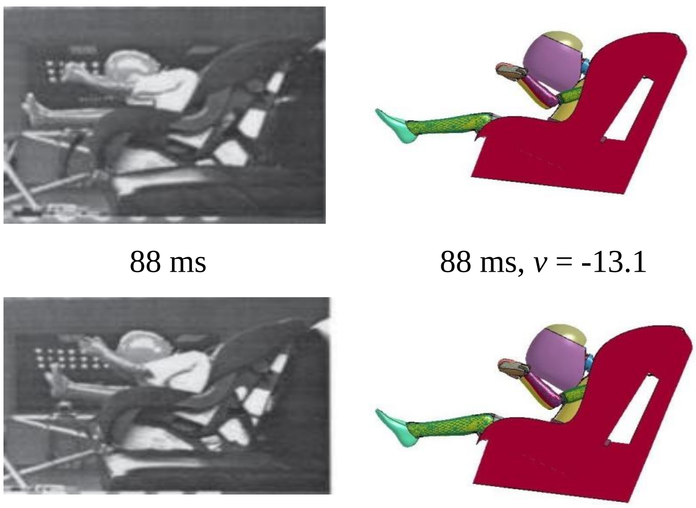
D = Distance between the load cell axis and the condyle axis

F_x = Neck force in x-direction

The simulation results were compared with experimental results of D_{HIII} from Turchi et al. (2004) and simulation results from Altenhof & Turchi (2004).

3. Results and Discussion

Figure 3 shows the response of D_{Nig} and D_{HIII} in some instances in the sled test. Qualitatively, D_{HIII} neck experienced high flexion at 88ms and 116ms comparable to D_{Nig}, which indicates the high neck moment and forces recorded, as seen in **Figure 3**.



88 ms — 88 ms, v = -13.1

116 ms — 116 ms

D_{HIII} — D_{Nig}

Figure 3. Qualitative comparison of $\boldsymbol{D_{Nig}}$ response and $\boldsymbol{D_{HIII}}$ experimental response from (Turchi et al., 2004)

For the head acceleration, D_{Nig} shows good correlation with experimental results in terms of curve trend and the occurrence of peak value as shown in **Figure 4**, there was large difference of 29% in terms of peak values. The differences can be attributed to the dummy anthropometry. Physical dummy was used in experimental studies which were made using US child anthropometry. For chest acceleration, however, the peak values differ by 6% as seen in **Figure**

5 and **Table 3**. Peak head acceleration was high for D_{HIII} which indicates the high risk of head injuries for heavy children because of high body weight. D_{Nig} are lighter in weight than D_{HIII} as shown in **Table 2**. The D_{Nig} acceleration curves for head and chest were noisier compared to D_{HIII} and this is because of the low total body weight of D_{Nig} as seen in **Figure 4** and **Figure 5**.

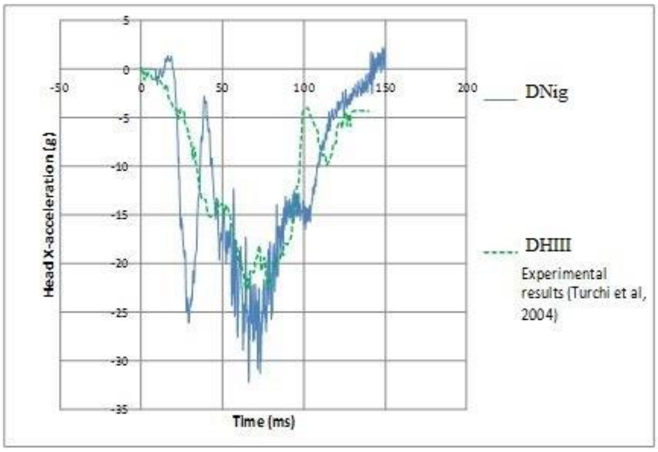


Figure 4. Head acceleration of $\boldsymbol{D_{Nig}}$ in comparison with $\boldsymbol{D_{HIII}}$ experimental results

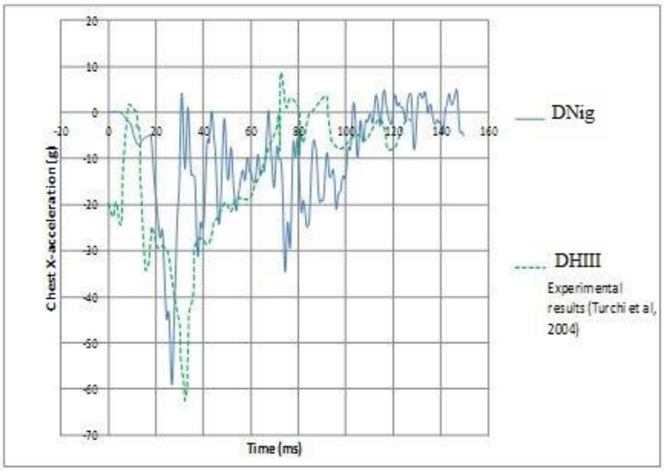


Figure 5. Chest acceleration of $\boldsymbol{D_{Nig}}$ in comparison with $\boldsymbol{D_{HIII}}$ experimental results

It is obvious from **Figure 6** and **Figure 7** that, D_{HIII} peak resultant upper neck moment was higher than that of D_{Nig}. This is expected, considering the weight and size differences between the two dummies and the fact that body weight of D_{HIII} is 16.17 kg (Mizuno et al., 2005) while that of D_{Nig} is 13.29 kg as shown in **Table 2**. Moment is a function of force, thus head with high weight will experience high neck moment compared to lighter one. In this case, D_{HIII} over predicts Nigerian child neck moment by 10% as shown in Table 3. D_{Nig} would sustain lower injuries when compared with parameters of D_{HIII}. Upper resultant neck force was also higher for D_{HIII} as expected because of its big size and high head weight as in the case of resultant upper neck moment as shown in **Figure 7**. This therefore shows that D_{HIII} overestimates the resultant upper neck force of three-year-old Nigerian child by 23% as stated in Table 3.

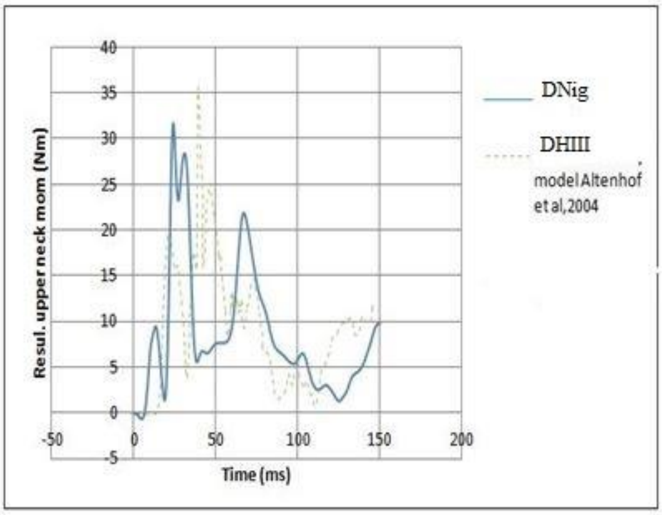


Figure 6. Resultant upper neck moment of $\boldsymbol{D_{Nig}}$ in comparison with $\boldsymbol{D_{HIII}}$ results from (Altenhof & Turchi, 2004)

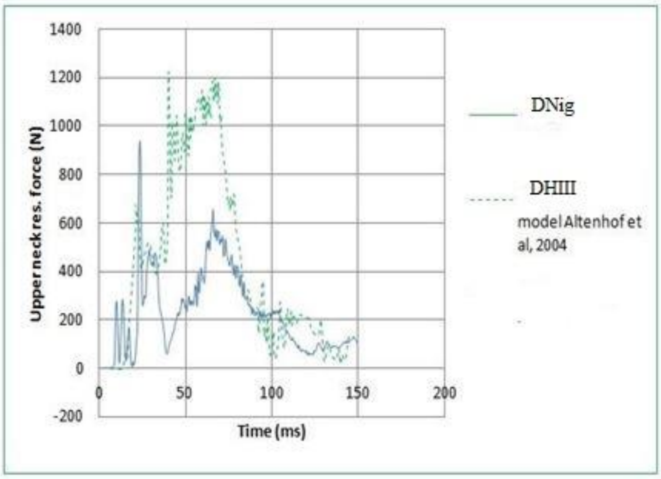


Figure 7. Resultant upper neck force of $\boldsymbol{D_{Nig}}$ in comparison with $\boldsymbol{D_{HIII}}$ results from (Altenhof & Turchi, 2004)

It is clear from **Table 3** that D_{Nig} experienced injury values that are different from that of D_{HIII} for all the parameters compared. This proves the fact that D_{HIII} could not represent three year old Nigerian child in vehicle certification.

Table 3. Peak Values Comparison for D_{HIII} and D_{Nig}

Dummy Biomechanical response	$\boldsymbol{D_{HIII}}$	$\boldsymbol{D_{Nig}}$	% difference
Head acceleration	-32	-22.5	29
Chest acceleration	-63	-59	6
Resultant upper neck moment	35.6	32	10
Upper neck resultant force	1223	940	23

4. Conclusion

This work compares the biomechanical response of crash dummy scaled to 3YO Nigerian child anthropometry with that of 3YO HIII dummy. A sled test simulation was conducted with D_{Nig} based on FMVSS specification in LS DYNA and response was compared with that of standard D_{HIII}.

D_{HIII} was different from D_{Nig} in head acceleration, chest acceleration and resultant upper neck moment and force. A largest difference was noticed in head acceleration which is due to the difference between the two dummies in size and weight. D_{HIII} was found to experience higher upper neck moment and force than D_{Nig}. The mismatch in biomechanical parameters is a result of difference in anthropometry between the two dummies. D_{HIII} gives injury parameters that are different from 3YO Nigerian child. Differences in anthropometry are an indication that 3YO Nigerian child is not sufficiently represented by the 3YO Hybrid III dummy. This has deleterious effect on the safety certification with respect to Nigerian child. The study uncovers the need to consider crash dummy that represents anthropometry of particular people using the vehicle in safety certification.

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Credit Author Statement

Modelling, simulation and writing of original draft, Rafukka, I.A.; Supervision and correcting paper writing, Sahari, B.B.; Supervision, Nuraini, A.A.; Supervision, Manohar, A.

Conflicts of Interest

The authors declare that there is no conflict of interest in the study.

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