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FINITE ELEMENT MODELLING OF THREE YEAR OLD NIGERIAN CHILD NECK FOR INJURY PREDICTION

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ABSTRACT

Child neck governs the head kinematic response on impact and therefore greatly influence the severity of head injury in motor vehicle crash. Biofidelic neck model developed using correct child anthropometry is crucial in evaluating head-neck associated injuries. In this work a six year old hybrid III (HIII) child dummy neck finite element (FE) model was scaled down to a three year old (3YO) Nigerian child anthropometry and inertial properties. The resulting neck model was coupled to three year old Nigerian child head model previously developed by the authors. Validation was carried out by pendulum test for flexion and extension test using acceleration pulse of Hybrid III 3YO certification specifications. Neck cable and neck rubber material parameters were determined for the neck response to correlate with the certification corridors of three year old child. The neck response was found to be within the certification corridors. Moreover, the new neck model was found to correlate well with 3YO model of Mizuno for flexion response and hybrid III dummy model for both extension and flexion responses as such it can be applied in evaluating neck injuries of 3YO Nigerian child on impact.

Keywords: child dummy, extension, finite element analysis, flexion, neck model, validation.

INTRODUCTION

Neck response on impact is of great importance as it determines head trajectory and loading conditions[1]. It governs head kinematics on head contact with vehicle interior in a crash. Accurate neck kinematics of child dummies is necessary in assessing the child restraint system (CRS) protection level. Neck response validation data is hindered by lack of experimental data due to difficulty in postmortem human subjects (PMHS) and volunteers' data.

Three year old pediatric head-neck models are very few in the open literature. Mayer *et al* [2]presented a proposal to develop 1 year old child (1-YOC), 3-YOC and 6-YOC head-neck models using real computer tomography (CT) scan geometry. Models were used to reconstruct accidents with the aim of identifying which parameter can predict bone fracture and loss of consciousness. Head acceleration was compared with Q dummy response in simulation to ensure correct head-neck kinematics. Dupuis *et al*[3] used scanner images of the subject to construct the neck model by segmenting the tissues and bones. Finite element model of 3 year old child neck was developed and intervertebral discs were modelled using nonlinear spring elements. The model was validated for kinematic response using the Q3 dummy response in frontal, rearward and lateral impact because of lack of available data. Head-neck response was also validated against certification corridor from a complete child dummy by some researchers [4],[5]. Zang *et al*[6] , implements a cadaver biomechanical response of the neck under tensile and bending loading to a 3 YOC model developed by Mizuno *et al* [7] in which altering mechanical behaviour of the child neck, made neck forces and moments to be within the corridor of pediatric cadaver tests. Dibb *et al.* [8] produced six and ten year old child head and neck computer model from a validated adult frame work. Models were validated against pediatric volunteer low speed frontal impact. Anthropomorphic test device (ATD) models of these ages were found to be stiffer than developed model; hence bio fidelity corridor has been established to guide future ATD designs. Biofidelic child neck is designed with joints that represent low resistance and wide range of motion at occipital condyles (OC) and atlas-axis (C1-C2) with remaining part that allow bending, twist, compression and elongation[9]. ATD necks are designed to mimic child neck response.

Following high rate of accident and its effect on vulnerable population around the world especially in the developing countries who have weak safety regulations it became imperative to develop finite element (FE) crash dummies that will represent this population to be used in evaluating CRS for enhancing safety of children in cars. As part of effort to develop this crash dummy for Nigerian three year old child, a FE dummy ATD head has been developed previously by scaling Hybrid III 6-YOC dummy[10]. In this phase of the work, a neck has been developed using Nigerian three year old child anthropometry by scaling Hybrid III 6-YOC dummy neck and the model is validated by comparing it with certification corridors and other 3YOC models response available in the literature. The first objective of this work is to morph the Hybrid III-6YOC neck to that of 3YO Nigeria child neck anthropometry. Second objective is to validate the model against certification corridors for flexion and extension and compare the neck kinematics with other three year old neck models in the literature.

BASELINE MODEL

Hybrid III 6 year old Finite Element Model Version: LST0.104.BETA which is currently the latest

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child model in Livermore Software Technology Corporation (LSTC) was selected as the baseline model in this study. It was developed by LSTC in cooperation with National Crash Analysis Centre (NCAC). Its validation was based on the certification tests described 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 [18].

Figure-1. Hybrid III 6YO child dummy FE model.

The neck model was based on the Hybrid III 6 YO dummy. It consists of 10 parts, from which two end plates are used to attach the head and torso to the neck. Steel cable is used to limit the axial loading of the neck. The head assembly of this model comprises of skull, skin layer, transducers and instruments mount and head pivot pin.

HEAD-NECK MODELLING

Neck dimensions were obtained by measurement Nigerian children from 2.5 to 3.5 year old. The principal dimensions of the neck are presented in Table-1.

Three year old child head weight was obtained by the equation of Mertz [14]which express head mass as a function of characteristic length (CL) using adult head mass:

$$M(CL) = 4.553kg\left(\frac{CL}{92.3cm}\right)^3 \quad (1)$$

Due to lack of Nigeria adult head weight value in the literature, the above equation was utilized to evaluate child head weight by substituting for CL of three year old Nigerian child:

$$CL = HL + HB + HC \quad (2)$$

Neck weight was also scaled from adult using scaling factors for neck breadth (NB), neck depth (ND) and neck length (NL). Neck breadth is assumed to be equal to neck depth since there is no significant difference between them, thus:

$$\lambda_x = \frac{NB_{3yo}}{NB_{adult}} \quad (3)$$

Neck Length scaling factor is obtained using erect height (EH) as the characteristic length:

$$\lambda_z = \frac{EH_{3yo}}{EH_{adult}} \quad (4)$$

For a constant density, mass scaling factor is given as:

$$\lambda_m = {\lambda_x}^2 \cdot \lambda_z \quad (5)$$

Table-1. Dimensions of the head-neck complex.

Erect Height Seated 3YO (cm)	51.7
Head Breadth (HB)(cm)	13.6
Head Length (HL)	17.7
Head Circumference (HC) (cm)	48.3
Head height (cm) from vertex to Occipital Condyle (OC)	12.6 [2]
Neck Length (cm)	9 [11]
Neck Breadth (cm)	8.3
Neck Circumference (cm)	23.1
Head-Neck height (cm)	21.6
Head Weight (kg)	2.909
Neck Weight (kg)	0.31
OC to CG Height (cm)	4.8[12]
Moment of Inertia (I_{yy} ($Kgcm^2$)	113[12]
Erect Height Seated adult (cm)	90.7[13]
Adult neck breadth (cm)	11.4[13]
Adult neck weight (kg)	0.965[13]

Neck length is the distance between occipital condyles and cervical vertebra (C7) and is difficult to measure from living human subject and as such it was obtained from the literature. Neck length in inferior superior was 90 mm for three year old [11]. Moment of Inertia about rotational axis is obtained from Loyd [12], using characteristic Length of three year old: Also from Loyd, the height of center of gravity (CG) from Occipital Condyle is -48.83mm for characteristic Length of 79.6 cm for three year old Nigeria child. Figure-2 shows the mid sagittal section view of head neck assembly.

Morphing operation was applied to scale down the head neck assembly to that of three year old child dimensions. 6YO HIII head-neck height of 238mm, and 3YO head neck height of 216mm, thus, scaling factor of 0.907 was used in z-direction to morph head-neck to 3YO child size. The morphing was carried out in Ls Prepost software by constraining the head- neck assembly in a solid element and scaling down to the appropriate dimensions.

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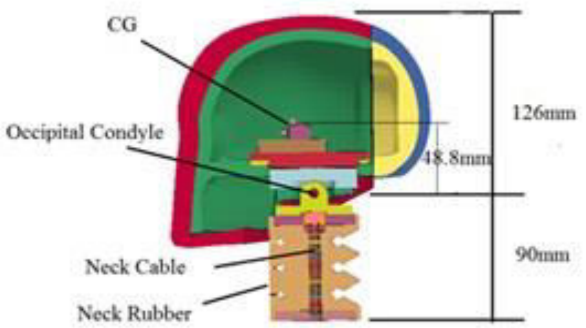

Figure-2. Head-neck assembly.

MATERIAL MODELLING

The neck cable beam was modelled with linear elastic isotropic material model (MAT_001) in Ls Dyna Software, and neck rubber with nonlinear viscoelastic material: material viscous form (MAT_062) in Ls Dyna. All other components were modelled as rigid materials.

Strength of the neck cable beam and parameters of neck rubber were considered as base line in dummy neck validation. Neck cable elastic modulus E, determines the head angle of rotation in both flexion and extension test. Increase in cable stiffness decreases the angle and vice versa, thus, E was adjusted for the head rotation angle to be within the specified values. It was found in a parametric studies that initial Young's modulus E_1, exponent in power law for Young's modulus N_1, and elastic modulus viscosity E_2, affect both the moment about OC and head angle of rotation. Initial parameters were first assigned and some adjustments were made in these parameters in order to get moment and head angle of rotation within the certification corridor. Table-2 shows the initial and adjusted parameters for the neck model.

Table-2. Model material properties.

		$\rho(\times 10^{-9})$ Kg/m^3	E_1/E MPa	N_1	V_2 MPa	E_2 MPa	N_2	v
Neck mold	Initial Parameters	1.1	4	0.02	0.86	10	0.92	0.48
	Optimized Parameters	1.1	1.8	0.018	0.86	15	0.92	0.48
Neck Cable	Initial Parameters	7.89	96000					0.3
	Optimized Parameters	7.89	90000					0.3

$\rho =$ mass density, E = elastic modulus, $E_1 =$ initial Young's modulus, $N_1 =$ exponent in power law for Young's modulus, $V_2 =$ viscous coefficient, $E_2 =$ elastic modulus of viscosity, $N_2 =$ exponent in power law of viscosity

Linear Elastic Isotropic*:* This is Material model 1 in LS Dyna for solids and fluids, and is applicable to brick, beams and sections [15]. The update of the force resultants, F_i, and moment resultants, M_i, includes the damping factors:

$$F_i^{n+1} = F_i^n + \left(1 + \frac{DA}{\Delta t}\right)\Delta F_i^{n+1/2} \quad (6)$$

$$M_i^{n+1} = M_i^n + \left(1 + \frac{DB}{\Delta t}\right)\Delta M_i^{n+1/2} \quad (7)$$

For fluid option, the bulk modulus, K, and pressure rate, p, are computed for elastic material by equations (7) and (8) respectively:

$$K = \frac{E}{3(1-2\vartheta)} \quad (8)$$

$$\dot{p} = -K\dot{\varepsilon}_{ij} \quad (9)$$

And the deviatoric stress tensor is given by:

$$S_{ij}^{n+1} = VC \cdot \Delta L \cdot a \cdot \rho\dot{\varepsilon}'_{ij} \quad (10)$$

Where ΔL is the characteristic length element, a is fluid bulk sound speed, ρ is the fluid density and $\dot{\varepsilon}'_{ij}$ is the deviatoric strain rate. Material Viscous Form: It was developed to model EuroSID side impact dummy. It is used for solid elements and consists of a nonlinear elastic stiffness in parallel with a viscous damper E_2 to overcome time step problem and is applied when E_1^t is less than E_2 [15]. Quantities $E_1$and V_2 are non linear with crush as described by the following equations:

$$E_1^t = E_1(V^{-n}) \quad (11)$$

$$V_2^t = V_2\big(abs(1-V)\big)^{n_2} \quad (12)$$

Viscosity generates a shear stress τ:

$$\tau = V_2\dot{\gamma} \quad (13)$$

Where $\dot{\gamma}$ = engineering stress, V= relative volume

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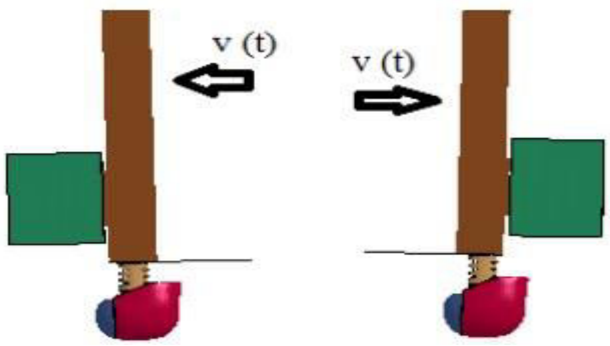
SIMULATION SET UP

The pendulum was modelled using the dimensions and inertial properties as specified in Part 572.33(c) (3) of the regulation[16]. Pendulum stick is 1867mm length and was constrained to rotate about y-axis only. Neck pendulum test is included in the certification tests of 3YO and 6YO finite element model neck calibration test[17][18]. In the test, the head-neck assembly was rigidly attached to the pendulum on the mounting plate and the pendulum impact energy is absorbed by an aluminium honeycomb block which decelerates the pendulum to pre-defined velocity ranges. Pendulum impact velocity was achieved by adjusting pendulum to honeycomb block distance. Figure-3 shows the simulation set up for extension and flexion test.



(a) (b)

Figure-3. Pendulum test configuration for extension (a) and flexion (b).

The pendulum was released and allowed to fall freely to achieve an impact velocity (v) of 5.50 ±0.10 m/s and 3.65 ±0.1 m/s for flexion and extension tests respectively. Figures 4 and 5 show the pendulum velocity – time graph for flexion and extension tests measured by accelerometer located at 1657 mm distance from pivot center.

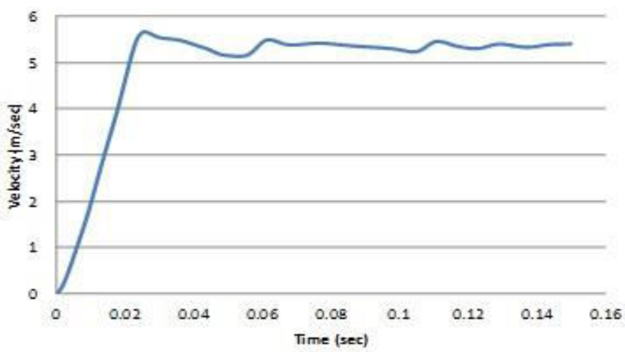


Figure-4. Pendulum velocity-time graph for flexion test.

Simulations were conducted in Ls Dyna solver version 970. The termination time of the simulation was 150 ms and contact between head and pendulum was not defined in order to allow maximum head excursion to take place. Pendulum was stopped by honeycomb block with an acceleration vs time pulse which meets the velocity changes as contained in the specification. Table-3 compares the simulation pendulum velocity and specification values.

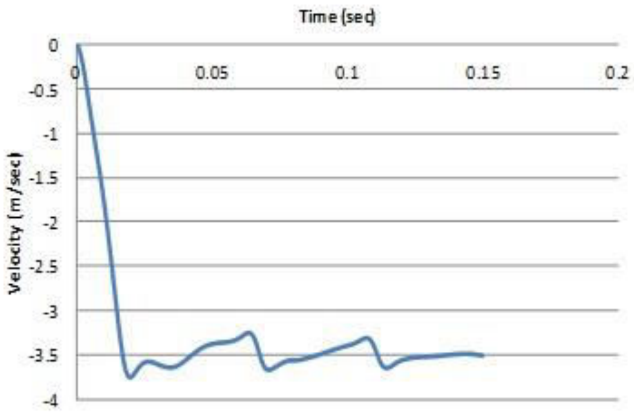


Figure-5. Pendulum velocity-time graph for extension test

Table-3. Pendulum response validation as specified in part 572.143.

Parameter	Time (ms)	Specification	Simulations results
Pendulum impact velocity for flexion (m/s)		5.50 ±0.10	5.60
Pendulum impact velocity for extension (m/s)		3.65 ±0.1	3.73
Pre impact velocity Flexion (m/s)	10	2.0–2.7	1.9
	15	3.0–4.0	3.3
	20	4.0–5.1	4.6
Pre impact velocity Extension (m/s)	6	1.0-1.4	1
	10	1.9–2.5	1.8
	14	2.8–3.5	2.8

RESULTS AND DISCUSSIONS

Neck moment and head angle of rotation are the metrics used to calibrate dummy neck. Head rotation which is the same with D-plane rotation stated in the specification was measured with reference to the pendulum longitudinal centerline.

Moment about occipital condyle (M_{oc}), is corrected by shear force F_x, thus according to Hybrid III 6YO manual [18]:

$$M_{OC} = M_y - 0.01778F_x \quad (14)$$

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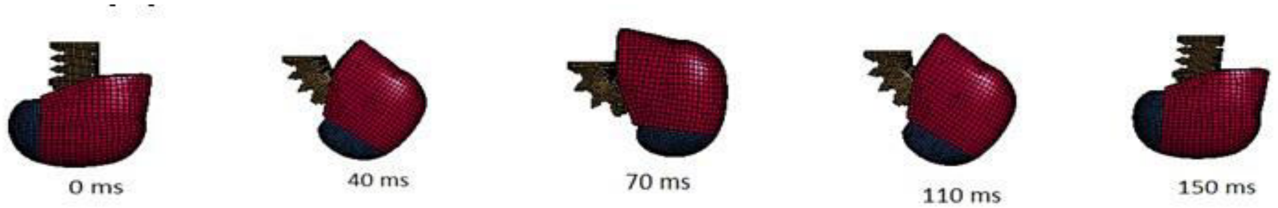

Figure-6. Head-neck kinematics for flexion test.

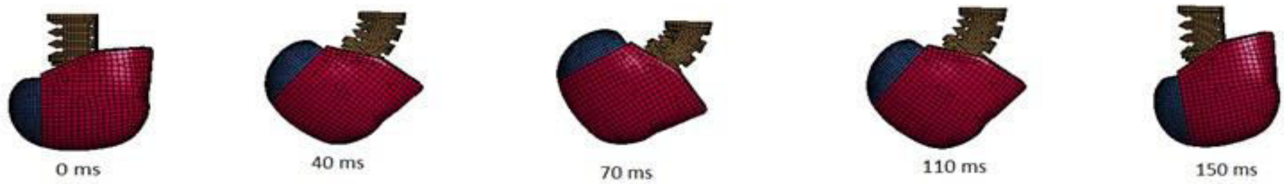

Figure-7. Head-neck kinematics for extension test.

Z-axis scaling factor applied in morphing HIII 6YO head-neck assembly down to 3YO Nigeria child dimension was used to scale perpendicular distance between shear fore F_x, to OC centre of rotation, thus, the modified moment equation became:

$$M_{oc} = M_y - 0.01613F_x \quad (15)$$

Figures-6 and 7 qualitatively show the head-neck response for flexion and extension test. Neck response at 70 ms simulation time indicates that maximum head rotation was higher in flexion than in extension test, and this can be attributed to the dummy neck structure and pendulum impact velocities.

Moment about occipital condyles (OC) takes negative value as indicated in Figure-8. This is because extension load is applied to the neck during the translational movement of the head at the early phase of motion. Moment about OC vs angle of rotation curve was within certification corridors in the loading phase before 60^0 head rotation. Though, the curve was out of corridor beyond that angle, the trend of the curves looks similar.

Neck model was compared with neck response of Mizuno model in order to further test its biofidelity. Response of 3YO neck approximately correlate with 3YO Mizuno *et al* [4] model because large proportion of the curve on both loading and unloading phase was within Mizuno neck response curve. The model was considered biofidelic even though larger portion of the curve was out of corridor because its response is similar with Mizuno model which is considered biofidelic 3YO child model scaled from adult human model. Both models have a maximum neck bending moment about OC of 20 Nm.

Furthermore, Figure-9 compares 3YO child neck response with HIII 3YO model in certification corridor. Initial extension moment can be noticed for both 3YO child and HIII dummy response. Large portion of 3YO curve for loading phase was within HIII dummy curve. This shows response similarities between the two models

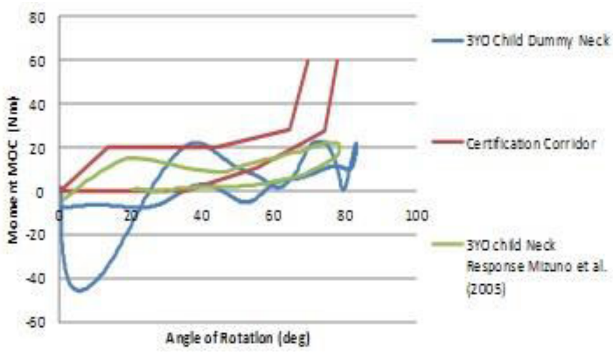

Figure-8. Comparison of neck response of 3YO child neck model and 3YO child neck from Mizuno with respect to certification corridor for Neck Flexion.

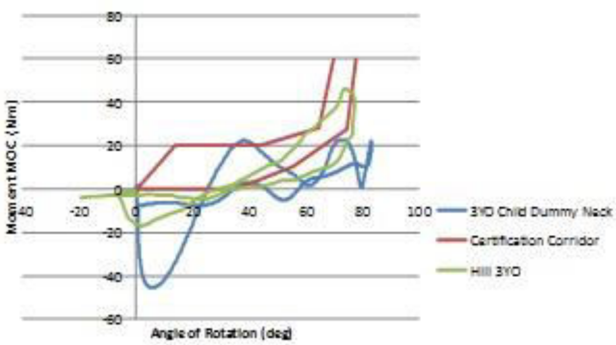

Figure-9. Comparison of 3YO child neck model and H III 3YO neck response with respect certification corridor for neck flexion.

Maximum moment was high in HIII 3YO dummy because it was designed to represent physical dummy which was shown to have a stiff neck because of mechanical material properties limitations [19]. The 3YO neck model show better biofidelic response than HIII 3YO dummy in terms of maximum moment because such material limitations were eliminated.

It can be seen in Figure-10 that an initial flexion response appeared in the neck extension test. This is due to translational motion that occurs before head rotation begins. Such an initial response in the opposite direction was reported in human cadaver test but not represented by certification corridors [19]. Large portion of the curve was within certification corridor during loading, while it is interesting to note that approximately all the curve is within corridor for unloading phase. Both models show initial flexion at the beginning which is not represented by the corridor. HIII 3YO neck show high moment at maximum angle of head rotation of about 48 Nm because of mechanical material limitations in the physical crash dummies which the model represents. It is important to note that, this problem was rectified by the new 3YO child model. However, 3YO child neck show lower maximum angle of head rotation than Hybrid III 3YO dummy.

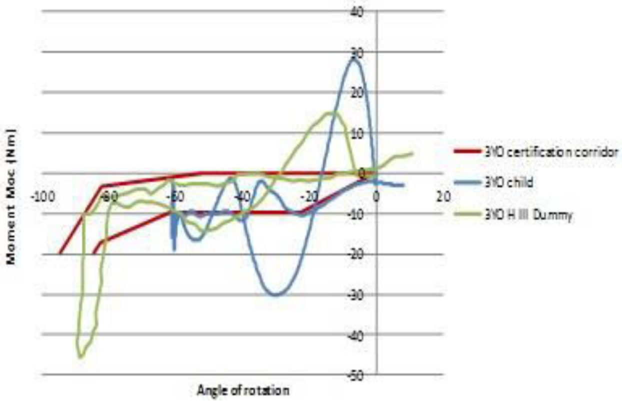

Figure-10. Comparison of 3YO child neck model response and H III 3YO with respect to certification corridor.

CONCLUSIONS

A 3YO finite element neck model has been developed by scaling a 6YO hybrid III dummy neck to anthropometry and inertial properties of three year old Nigerian child. The head-neck assembly was then validated against 3YO certification corridors by pendulum flexion and extension tests. Moment about occipital condyles vs angle of rotation curves of 3YO child neck model was found to be in agreement with hybrid III dummy neck biomechanical response. The new neck model show similar response with three year old child dummy neck developed by Mizuno *et al* in flexion test. The neck model is useful in developing new child dummy model to predict injury in vehicle crashes for 3 YO Nigerian child.

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