DEVELOPMENT OF THREE YEAR OLD NIGERIAN NUMERICAL CHILD DUMMY HEAD AND VALIDATION IN FRONTAL IMPACT

[1]I. A. RAFUKKA, [2]B. B. SAHARI, [3]A. A. NURAINI, [4]A. MANOHAR

[1,2,3]Department of Mechanical and Manufacturing Engineering, University Putra Malaysia
[4]Department of Orthopedic Surgery, University Putra Malaysia
[1]Department of Mechanical Engineering, Bayero University, Kano, Nigeria
Email: [1]gs39956@mutiara.upm.edu.my

Abstract— Head injuries are the main cause of children fatalities and disabilities. The head finite element (FE) models remain the useful tool to investigate the injury risk of motor vehicle crash and fall scenarios. Adult head models have been developed by many researchers but child FE models need more attention. The models available in the literature were developed based on anthropometric data of some specific population. In this work a three year old child FE anthropomorphic test device (ATD) head has been developed by scaling down a Hybrid III 6 year old dummy head down to that of a three year old Nigerian child head size and weight using morphing technique, and the model was validated for frontal impact against the available data in the literature in head drop test. The peak resultant acceleration of the head in frontal impact was found to be within reported literature thresholds. The resultant acceleration was found to increase with increasing falling height. The acceleration obtained was 253.5g for the fall height of 376 mm and 126g for 130 mm falling height. The peak lateral acceleration and the peak acceleration after the main pulse for 376 mm fall height were as specified within the specification of 49CFR Part 572 Sub Part P for 3 year olds. The head model developed could therefore be useful in the vehicle safety assessment and height fall investigations of three year old children.

Keywords — anthropometry, ATD, child dummy, head drop test, morphing

I. INTRODUCTION

Finite element (FE) modeling has become the most efficient method of developing human and anthropomorphic test device models because of its repeatability and low cost compared to the physical crash dummies. Child FE models are scarce due to the complexity of material behavior and properties data, and limited experimental data to validate the models due to ethical issues associated with it. The only available models are validated by scaling the biomechanical response of the adult dummy as proposed by Irwin et al [1]. Head has been characterized as the most injured part of the body in a vehicle collision [2]. Traumatic brain injury usually from road traffic accident, fall and mishandling causes death and disability to children [3]. Child's centre of gravity is higher relative to their heights than adults which make them more vulnerable to sustain head-first fall [4]. Research interest now is in the pediatric injury biomechanics and few child head model have been proposed [5]. Therefore, there is need to develop a biofidelic head models that can be used to investigate injuries in car crash and child fall scenarios.

Child head FE models were developed by researchers for vehicle crash and forensic applications [5], [6], [7]. Roth et al. in 2008 [8] developed a 3 years old Head FE model and defined an injury criterion in terms of Von Misses stress in the brain for minor neurological injuries. Other researchers developed a complete 3 year old child dummy for vehicle crash and Child Restraint System assessment [9], [10]. Loyd [11] studied adult and paediatric cadaver head response in which they were compared with ATD heads response of matched age in head drop test with the aim of assessing their bio fidelity.

Using the exact anthropometry of the vehicle occupants in developing crash dummy models is necessary for the proper design of restrained system and vehicle body parts. The characteristics of the body such as weight and size have an effect on the kinematics of model [12]. The dummies used today are based on anthropometric data for a specific population which might not necessarily represent the weight and size of vehicle users in other populations. Happee et. al. [13] shows that the injury parameters of dummy models of various sizes and weight are beyond the range of standard dummies models because of the difference in weight and seat position. Jang in [14] scaled Hybrid III dummy to Korean average size and conducted occupant analysis using MADYMO. The results were compared to that of Hybrid III and various injury trends were formulated. Scaling have been used in crash safety studies, an example is the design of Hybrid III small female and large male dummies was based on scaling [15]. The anthropometry of Hybrid III 3 year old child dummy model was based on the child of United States [16], while the anthropometry of Q3 dummy was based on TNO child anthropometry database (CANDAT)[17]. The child FE model represents some specific population size and weight. There is therefore the need to develop child dummy head that will cover other populations that are not represented in order to enhance their crash safety. The aims of this work are therefore to develop a three year old child head numerical model using Nigerian anthropometry with 6 year old Hybrid III dummy head as a reference and validate the head model against the data from the literature for frontal impact as the first

priority for child occupant protection lies with frontal impact [12].

II. REFERENCE DUMMY

Hybrid III 6 year old Finite Element Model Version: LST0.104.BETA which is currently the latest child model in LSTC was selected as the baseline model in this study. It was developed by Livermore Software Technology Corporation (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, Subpart N. The model contains 199,102 nodes, 127,154 solid elements, 45,032 shell elements and 142 beam elements [18]. The head assembly of this model comprises of skull, skin layer, transducers and instruments mount and head pivot pin.

III. ANTROPOMETRIC DATA/ MORPHING

The anthropometric data used for the dummy head was collected by direct measurement from 30 Nigerian children ages ranging from 2.5 to 3.5 year old and statistical analysis were carried out to obtain the desired dimensions. The mean dimensions of target anthropometry are presented in Table I. The main dimensions are head breadth, head height, head depth and head circumference. The definitions of these dimensions are shown in Fig. 1.

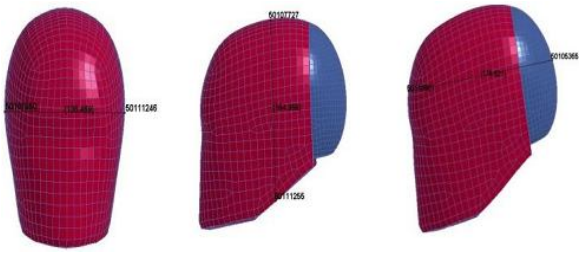

Fig. 1 Head Dimensions Definitions

Description	H III 6YO Measured	Data Collected (DC) (Mean)	Scaling Factors	FE Model 3YO (FEM)	Ratio (%) FEM/DC
Head Breadth (cm)	14.6	13.7	0.94	13.6	99.3
Head Height (cm)	17.3	18.3	1.06	18.4	100.5
Head Depth (cm)	17.2	17.7	1.02	17.6	99.4
Head Circumference (cm)	52.07	48.3	0.93	48.7	100.8
Head Weight (kg)	3.485	2.40	0.69	2.33	97

Table I. Head size dimensions

In developing the child dummy head it was ensured that the mass and dimensions of the head matched closely to the mean of each parameter of three year old Nigerian child head. The scaling was carried out using morphing technique by constraining the head in a morphing box constructed from box-solid of shape mesher of the LS Prepost as shown in Fig. 2.

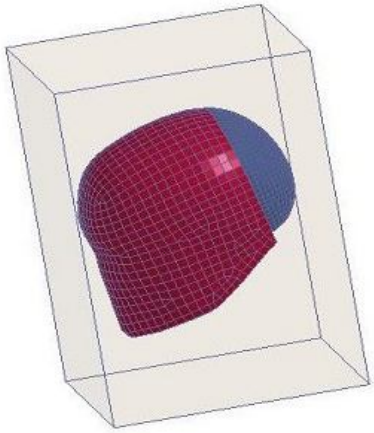

Fig. 2 Morphing Box

Scaling factors were applied in x, y and z direction for the head breadth, head depth and head height respectively. The differences between the FE model and measured parameters were within 1% which is considered not significant.

The percentage of the head weight to total body weight of master body form developed by Young et. al. [19], which represent 3 year old child in the United States in which the head weight was 19.3% of the total master body weight, was used as reference in determining head weight. Based on this percentage the head weight of 3 YO Nigerian child using the mean body weight of 12.23 kg was found to be 2.4 kg (Table I). The density of the head components was adjusted to obtain the required head weight of 2.33 kg with a difference of 3%. Head model generated by morphing has the same mesh quality comparable to baseline model. The head weight was calculated from the product of mass density, ρ, and the corresponding material volume of the head components. The values of ρ are given in Table III.

IV. MATERIAL PROPERTIES

Material Properties of skull and skin was based on the data in the literature as shown in Table II. This was used as starting point for model validation.

Table II. Material Properties from the literature

Part	Mass density, ρ (kg/m^3)	Elastic Modulus, E (MPa)	Poisson's ratio, υ	Reference
Skull	3000	4700	0.2	Shuck et al.[20]
Scalp	1200	16.7	0.42	Zhou et al.[21] Deck et al [22]

Initial values are first assigned to the material parameters taking reference to literature values and then optimized to get proper correlation between simulation and threshold values. The material properties were adjusted to fit the mass and inertial properties of the 3 year old head. The skull was modeled using linear elastic material model and its mass density, ρ, was adjusted to fit the head mass. The head skin was modeled using linear viscoelastic material in which the long and short shear modulus was found to affect the stiffness and hence, was adjusted to get appropriate peak resultant acceleration. An increase in long/short shear modulus stiffens the material and the peak acceleration rises. All other head components were made as rigid (Material type 20). Table III shows the modified material properties.

A head version with rigid skull was also simulated and there was no significant difference in the peak resultant acceleration. For example, the difference for a 130 mm drop height is within 1%, hence the stiffness and viscosities of the skin were the main parameters for head calibration.

Table III. Modified Material Properties

Head Component	Material Model	ρ (kg/m^3) $X10^{-9}$	ν	E/K (MPa)	G_o (MPa)	G_1 (MPa)	β (1/sec)
Head Skull	Linear elastic isotropic	1.8	0.2	4700			
Skull Cap	Linear elastic isotropic	1.8	0.2	4700			
Head Front Skin	Linear Viscoelastic	1.2		16.7	4.5	3.5	250
Head Cap Skin	Linear Viscoelastic	1.2		16.7	0.5	0.3	250
Impacting Plate	Rigid	7.85	0.3	2.07 E5			

ρ: density, E: Elastic Modulus, K: Bulk Modulus, ν: Poison's Ratio, G_O: Short Time Shear Modulus, G_1: Long Time Shear Modulus, β : decay constant

Linear Elastic Isotropic*:* This is Material model 1 in LS Prepost for solids and fluids, and is applicable to brick, beams and sections [23]. The co rotational rate of the deviatoric Cauchy stress tensor, S_{ij}, and pressure are computed for elastic material by equations (1) and (2) respectively:

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

$$P^{n+1} = -klnV^{n+1} \quad (2)$$

Where G and K are elastic shear and bulk moduli respectively and V is the relative volume ie ratio of current volume to the initial volume.

Linear Viscoelastic*:* This is Material Model 6 in Ls Prepost, and allows the modeling of viscoelastic behaviour of beams, shells and solids [24]. Linear viscoelasticity is computed based on deviatoric stress tensor;

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

Where the shear relaxation behaviour is given by:

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

V. TEST CONFIGUARATION

In the drop test, the head model was oriented such that the head z-axis made an angle of 28.5° to the horizontal rigid plate while the mid sagittal plane is vertical [13]. The head model was given an initial velocity which was computed based on the drop height according to the relation:

$$v = \sqrt{2gh}, \quad (5)$$

Where h is the height of fall and g is gravitational acceleration. The simulation setup is sown in Fig. 3. Surface to surface contact with a friction coefficient of 0.2 is defined between head and rigid plate and the hourglass energy was set to be 10% of the total energy.

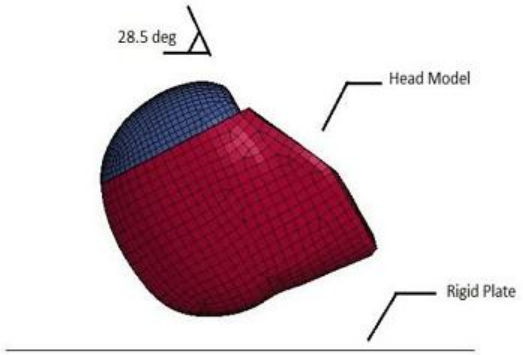

Fig. 3 Frontal Impact Test Configurations

The drop test was carried out for 2 values of drop heights of 130 mm and 376 mm on frontal impact.

In this analysis, head resultant acceleration was filtered using the SAE J211b Class 1000 filter specifications [25] to remove some noisy data. Sign conventions used are in accordance to SAE recommendations [26]. Simulations were conducted using LS-DYNA version 971.

VI. SIMULATION RESULTS AND DISCUSSIONS

Head acceleration is related to the head injuries because it causes intracranial pressures and brain tissue movements and distortions, hence it is considered as a parameter to predict head injury risk on impacts. The best way to validate human models is by conducting a post mortem on human subject (PMHS), but the child PMHS are very limited because of ethical reasons [27]. Available data from the literature were used to assess the bio fidelity of the head model.

The acceleration-time pulses measured by the accelerometer located approximately at the head centre of gravity have been the criteria used to validate the dummy head. The simulation result is as illustrated in Figures 4 and 5. Acceleration was peak at 3 ms which is common in head drop test.

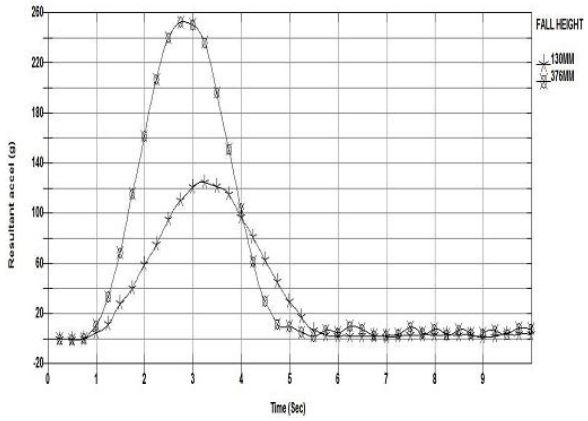

Fig. 4 Resultant Acceleration- Pulse time graph for 130 mm and 376 mm drop heights

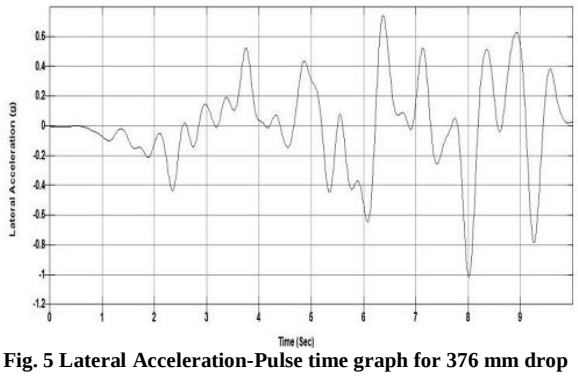

Fig. 5 Lateral Acceleration-Pulse time graph for 376 mm drop height

For the 130 mm drop height, the bio fidelity of the model was evaluated by comparing its response with the biomechanical target of the dummy based on the cadaver head drop test conducted by Hodgson and Thomas [28]. Though the data was based on scaling from adult PMHS, it remained the most reliable data for validating child head models due to limited quantitative data. For 376 mm drop height, the model was validated based on dummy certification corridors as specified within the specification of 49CFR Part 572 Sub Part P for 3-year-Old Child Crash Test Dummy, Alpha Version [29], since there were no experimental data for three year old available in the literature. The peak resultant acceleration for the two drop heights were within the threshold as shown in Table 4.

Table 4. Frontal Impact Validation

Parameters	Simulation Result (g)	Threshold Values	
Peak Resultant Acceleration (g) (130mm)	125.8	121±32	[30]
Peak Resultant Acceleration (g) (376 mm)	253.5	250-280	[29]
Peak Lateral Acceleration(g) (376 mm)	-1.01	-15 to +15	[29]
Peak Acceleration after main Peak pulse	4.2%	<10%	[29]

As can be seen from Fig. 4 and Table 4, the peak resultant acceleration was 125.8g for frontal impact at a falling height of 130 mm. The pulse duration was about 5 ms, which is comparable to that of 3 year old Q3 dummy as shown by Loyd [11]. Head impact from a height of 376 mm has a peak resultant acceleration of 251.4g, and the peak acceleration after the main pulse for 376 mm drop height was 4.2% of the main pulse peak resultant acceleration which is within specified threshold (<10%). The peak resultant acceleration was -1.01g which was in good agreement with specification. The peak resultant acceleration was found to increase with increasing fall height which is an indication of increasing head injury risk to the child's head on falling from higher height.

CONCLUSIONS

A three year old child ATD head FE model has been developed by scaling down a Hybrid III 6 year old dummy head to Nigerian anthropometry. The model was validated for two drop heights tests in frontal impact using the available threshold values for three year old child head response in the literature. The peak resultant acceleration which is related to head injuries was found to increase with falling height because of added energy and non-linear stiffness response. The head meets the specification of three year olds, thus could be used for crash safety assessment.

AKNOWLEDGEMENT

The authors wish to thank Universiti Putra Malaysia for the facilities and Bayero University Kano, Nigeria for the financial support of the first author. In addition, this work was also supported by Fundamental Research Grant Scheme with Reference Number: FRGS/2/2013/TK01/UPM/01/1, vot 5524355, Ministry of Education (MOE), Malaysia, and was carried out in Universiti Putra Malaysia (UPM). The authors therefore would like to record their thanks to the MOE and UPM for the supports.

REFERENCES

[1]. H.J. Mertz (1984), A procedure for normalizing impact response data, SAE 840884.
[2]. A.R. Burdi, D.F. Huelke, R.G. Snyder, G.H. Lowrey (1969), Infant and children in the adult world of automobile safety design: pediatric and anatomical considerations for design of child restraints, J Biomechanics, Vol 2, Pp 267-280.
[3]. D. Viano, H. VonHolst, E. Gordon (1997), Serious brain injury from traffic related causes: priorities for primary intervention, Accid. Anal. Prev. 29, Pp 811–816.
[4]. Z. Lia, J. Zhanga, J. Hub (2013), Surface material effects on fall-induced paediatric head injuries: a combined approach of testing, modelling and optimisation, International Journal of Crashworthiness, Vol. 18, No. 4, 371–384.
[5]. S. Roth, J.S. Raul, B. Ludes, R. Willinger (2007), Finite element analysis of impact and shaking inflicted to a child, Int. J. Leg. Med. 121 (3) 223–228.

[6]. Y.Guan, J.Zhang, N. Yoganandan, F.A. Pintar, C.A. Muszynski, T.A. Gennarelli (2006),Automating 3D meshing method for patient-specific modeling, Biomed. Sci. Instrum. 42 pp 199–204.
[7]. S.S. Margulies, K.L. Thibault (2000), Infant skull and suture properties: measurements and implications for mechanisms of pediatric brain injury, J. Biomech. Eng. 122 (4) pp.364–371.
[8]. S. Roth, J. Vappou, J.S Raul, R. Willinger (2008), Child head injury criteria investigation through numerical simulation of real world trauma, Computer Methods and Programs in Biomedicine, Volume 93, Issue 1,Pages 32-45.
[9]. K. Mizuno, K. Iwata, and T. Deguchi, T. Ikami, M. Kubota (2005), Development of a three-year-old child FE model, Traffic Injury Prev. 6 (4), pp. 361–371.
[10]. T. Koizumi, N. Tsujiuchi, Y. Uchida (2005), Impact Injury Rating of child FE human model for 3 year old, IMAC –XXIII: Conference and Exposition on structural Dynamics.
[11]. M. Loyd, (2011). Studies of the Human Head from Neonate to Adult: An Inertial, Geometrical and Structural Analysis with Comparisons to the ATD Head. Retrieved from http://dukespace.lib.duke.edu/dspace/handle/10161/4986\nhttp://dukespace.lib.duke.edu/dspace/bitstream/10161/4986/1/Loyd_duke_0066D_11141.pdf
[12]. M.R. van Ratingen, J. Wismans (1998), Modelling Pediatric Kinematics. 42nd Annual Proceedings Association for the Advancement of Automotive Medicine October 5-7, Charlottesville, Virginia pp139,
[13]. Zhou, T.B. Kahlil, and L.J. Dragovic (1996), Head injury assessment of a real world crash by finite element modelling, in Proceedings of the AGARD Conference, ARGAD, USA, pp. 81–97,
[14]. Y.H. Jeong (1999), Passenger Safety Analysis using MADYMO with Scaled Korean Dummy Models, Master thesis, Hanyang University.
[15]. H.J. Mertz., A.L Irwin, J.W Melvin., R.L Stalnaker., M.S. Beebe (1989), Size weight and biomechanical impact response requirements for adult size small female and large male dummies. SAE-890756,
[16]. A.L. Irwin, H.J. Mertz (1997), Biomechanics Bases of for CRABI and Hybrid III child dummies, SAE 973317,
[17]. Twisk (1994), Anthropometric Data of Children for the Development of Dummies. TNO report 75061275-B,
[18]. U. Mahadevaiah, M. Burger, C. Maurath (2013), LSTC Hybrid III 6-year-old Finite Element Model Documentation.
[19]. J.W. Young, H.M. Reynolds, J.T. McConville, R.G. Snyder, R.F. Chandler (1976), Development and evaluation of masterbody forms for 3- and 6-year-old-child dummies, FAA-AM-76-9, UMTRI
[20]. L.Z. Shuck, S.H. Advani (1972), Rheological response of human brain tissue in shearing, ASME J. Biomech. Eng. 94(4) pp. 905–911,
[21]. Zhou, T.B. Kahlil, and L.J. Dragovic (1996), Head injury assessment of a real world crash by finite element modelling, in Proceedings of the AGARD Conference, ARGAD, USA, pp. 81–97
[22]. C. Deck, R. Willinger (2008), Improved head injury criteria based on head FE model, Int. J. Crashworthiness. 13(6), pp. 667–678
[23]. LS Dyna Keyword users manual, volume 1, version 971,livermost software technology corporation (LSTC), (2007)
[24]. O. John, L.S. Hallquist (2006), DYNA theory Manual, livermost software technology corporation (LSTC),
[25]. SAEJ222-1. SAE J211/1- Instrumentation for impact test part 1: Electronic Instrumentation Society. Society of Automotive Engineers, (1995)
[26]. LS-DYNA Model Version 4.0 - User Manual, LS-DYNA Model of the Hybrid III 3-Year Old Child Dummy User Manual, Version 4.0 August,(2008)
[27]. M.T. Prange, J.F Luck, A. Dibb, C.A Van Ee, R.W. Nightingale, and B.S Myers (2004), Mechanical Properties and Anthropometry of the Human Infant Head, Stapp Car Crash Journal 48, pp. 279-99
[28]. V.R Hodgson, L.M Thomas (1975), Head Impact Response, VRI 7.2 SAE,
[29]. Code of Federal Regulations, 49, Part 572 Subpart P (2014) 3-year-old Crash Test Dummy, Alpha Version
[30]. M.R Van Ratingen, D.Twisk, M.Schrooten, M.C.Beusenberg, , A.Barnes, G. Platten (1997), Biomechanically Based Design and Performance Targets for a 3-Year-Old Child Crash Dummy for Frontal and Side Impact. Proc. 2nd Child Occupant Protection Symposium, pp. 243-260. Society of Automotive Engineers,Warrendale, PA

★★★