On the Development and Validation of 12MO Numerical Child Head Dummy Model for Automotive Crashworthiness Assessment

J.M. Nursherida, B.B. Sahari, Nuraini A.A, A.Manohar, and M.S.A Samad

Abstract**—**Finite element analysis using finite element model (FEM) are often used as a substitute for human experimental head injury studies especially in predicting automotive collision analysis and to intensify our understanding of injury mechanism and develop prevention strategies. The use of FEM in crash test dummies is beneficial over physical dummies because of the lesser cost and repeatability. Various adult FEM of the head have been developed, but there are comparatively few paediatric FEM due to insufficiency of material property data for children. Therefore, there are not enough models representing twelve-month-old (12MO) child dummy models. Child head injury is a very costly problem, both in terms of morbility and direct medical costs. In fact, it is the leading cause of death and disability for children around the world under age 18-years-old. Given its importance and effect on the population, the study of pediatric head injury is greatly obstructed by the lack of available pediatric post mortem human specimen (PMHS) data. As a substitute for PMHS testing, anthropometric test devices (ATDs) and finite element models (FEMs) have been developed to model the head. However, there is a scarcity of data for the design and validation of these models. This paper presents the development and validation of a 12MO finite element dummy head model and simulated results compared with the child cadaver experimental data under drop condition tests. The model was developed by using both deformable and rigid body materials. The anthropometric data were collected from published literatures and journal articles that focused on 12MO head data. Using recent published material property data of infant skull, skin and scalp, a FE model of the 12MO ATD head was developed to study head responses in head drop tests. The head assembly was validated by using frontal/forehead set-up of head drop tests. The simulation of a frontal head drop test was done and compared with the experimental cadaver data. The test with drop height of 130 mm is the certification procedure.

Keywords**—**12MO head dummy model, crashworthiness assessment, finite element analysis, head drop test.

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I. Introduction

HEAD injury is leading cause of paediatrics fatality and disability in the United States [1-3], in which drop/fall is one of the most frequent causes [4-5]. Finite element modelling is a widely used tool to investigate the dynamic response of the adult head under impact. Nevertheless, compared to adult models, there are very few three dimensional finite element models of 1 YO child's head.

A finite element model of 6-month-old child has been developed by DeSantis Klinich at al. [6] was used to investigate the skull injuries in reconstructing accidents that the infant sitting in rear-facing child restraint system (CRS) suffered from airbag deployment during motor vehicle crashes. Roth et al. [7,8] developed a 6-month-old child head numerical model a. The same research group also developed a 3-year-old [9,10] and a17-day-old child numerical head models [11], in which the 3-year-old child head model was mainly used to compare the intracranial injury metrics differences between this 3 year-old model and a scaled adult head model [9], and the 17-day-old model was used to simulate the pediatric skull fracture in reconstructing the real world head trauma for neurological lesions [11]. Coats et al. [12] developed a 1.5MO head FE model and conducted a parametric study to investigate the relative importance of brain material properties and the anatomical variations in suture and scalp on head responses under drop conditions. This model was also used to reproduce Weber's cadaver drop tests [13,14] that focus on bone fracture Liet al. [15,16] developed a parametric pediatric head FE model and morphed a baseline model to a newborn, a 1.5MO, and a 3MO head model, in which only the newborn head FE model was validated against cadaver experiment. Weber [13,14] dropped 50 children aged from 0 to 9 month old onto 5 different impact surfaces under the drop height of 82 cm, which provided important information for studying the skull fracture mechanism and injury criteria.

The latest research about development and validation of the infant head finite element model was conducted by Zigang Li et al. in 2013. From the research done by Zigang et. Al, a statistical model of cranium geometry for 0- to 3-month-old children was developed by analyzing 11 CT scans using a combination of principal component analysis and multivariate regression analysis [18]. Radial basis function was used to morph the geometry of a baseline child head finite element (FE) model into models with geometries representing a newborn, a 1.5-month-old, and a 3-month-old infant head. The results showed that the statistical model of cranium geometry produced realistic cranium size and shape, suture size, and skull/suture thickness, for 0- to 3-month-old children. The pediatric head models generated by morphing had mesh quality comparable to the baseline model. It is observed that, the elastic modulus of skull had a greater effect on most head impact response measurements than other parameters. The same research group developed a 6-month-old child head FE model and the simulated results were compared with the child cadaver experimental under compression and drop conditions [17]. Comparison of results indicated that the FE model showed a good biofidelic behaviour in most dynamic responses. The validated FE model was further used to investigate effects of different drop heights and impact surface stiffness on the head dynamic responses [18].

The European Enhanced Vehicle-safety Committee wants to promote the use of more biofidelic child dummies and biomechanical based tolerance limits in regulatory and consumer testing [19]. Very few findings on newborn ATD found in the literature was validated by cadaver test data from similar age group. Even drop is one of the most frequent causes for infant head injury; the effects of drop height and impact surface stiffness on child head injury were not investigated in the literature in detail. Due to the limitation of child cadavers available for testing, such a model will be extremely useful for investigating the morphology and age effects on pediatric head injuries, and thus providing insights on how to prevent head injuries. The objectives of this study were (1) to develop FEM head for one-year-old ATD dummy to use in occupant safety analysis. (2) to simulate a validation process under drop conditions based on the experimental cadaver drop tests data from published literature.

II. Model Development

A. Baseline Model Development

The baseline model used in this study was a modified version of the 6-year-old Anthropomorphic Testing Device (ATD) model developed by Livermore Software Technology Corporation (LSTC) and National Crash Analysis Center (NCAC). The Model is based on the Hybrid III Six-Year-Old Child Crash Test Dummy (H–III6C, Beta Version). It has been validated to the certification tests illustrated in the Code of Federal Regulations, Title 49, Part 572, Subpart N. Validation results can be found in the accompanying documentation. The mesh of the finite element model of the Hybrid III six-year-old was developed by LSTC by use of the TrueGrid software [20]. TrueGrid is a Hexahedral Mesh Generator. The mesh is based on scanned data of an actual dummy and the drawing package of the dummy [21]. Fig. 1 shows the 6-year-old LSTC Dummy used as baseline model in this study.

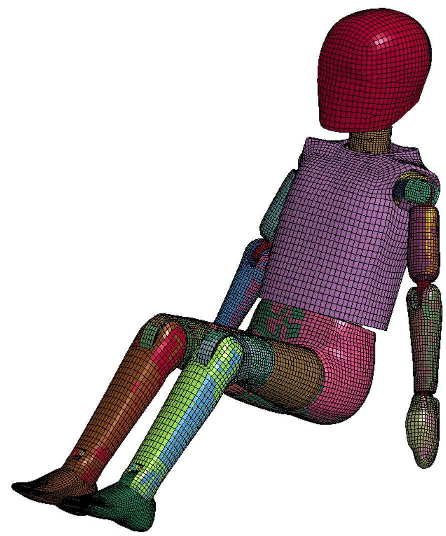

Fig. 1. 6-year-old LSTC Dummy

The following table is a brief overview over the basic statistics of the current version of the model:

TABLE I
6 YEAR-OLD LSTC MODEL SUMMARY

Number of nodes	199,121
Number of solid elements	127,154
Number of shell elements	45,032
Number of beam elements	142

B. Head Geometry

The FE model of ATD 1 YO head was developed by using mesh morphing technique in LS-DYNA Software. The first step for the fitting process is to define the constraints of the model shaping. The finite element model of the skin, head skull, and head skull cap should be kept intact even if these parts are moved or modified. In this case special entities, the Morphing Boxes, are created around the head area. The Morphing Boxes are used to modify the head model shape, in this case they are used to scale down the selection during the fitting process (Fig. 2). The parts inside the boxes can be controlled only in directions *x*, *y* and *z*.

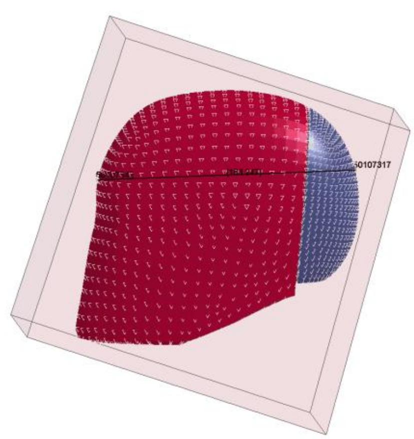

Fig. 2 Morphing activity

The head assembly is made of skull including visco-elastic skin layer, and accelerometers load cell. A non-linear visco-elastic material model (MAT_06) was used for the skin and an elastic material (MAT_01) was used for the skull and beam of the load cell. The beam connects the skull to the load cell housing. Load cell housing and accelerometer mounting are made of rigid material MAT_20.

C. Anthropometry

Global measurements of the head model were checked based on anthropometric studies concerning the evolution of the head during growth. The main dimensions (length, width, and circumference) of the model were compared to anatomical studies reported by K.Weber[22]. Table II shows the anthropometric data that used in the simulation model. The measurement identification and detail measurement of FE dummy model was illustrated in Fig. 3.

TABLE II
ANTHROPOMETRIC DATA FOR 12MO HEAD [24]

Head breadth	127 mm
Head circumference	462.3 mm
Head depth	165.1 mm

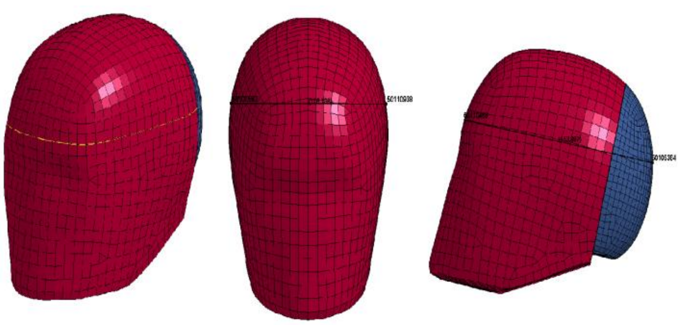

Fig. 3 Details measurement of 1 YO dummy head FE model.

D. Material Properties

As explained in the introduction, only a small number of studies report mechanical properties of child head components. Thus mechanical properties reported by Franklin et al and Coats et al were considered in this model [23]. Coats and Margulies [24,25] have investigated material properties of newborn skull and sutures. The constitutive law of sutures and fontanels were considered as linear elastic based on tension tests. The constitutive law of the skull was elastic–plastic with rupture, based on three-point bending tests.

An extensive literature review on child head material properties by Franklyn et al. has compared and summarized most of the previous experimental data available before 2006. Coats et al. conducted bending and tension tests on skull and suture using 23 pediatric cadavers from 21 weeks gestational age to 13-month old. The results showed that age and location did not have significant effects on elastic modulus of skulls from 0 to 13-month-old children. Material properties of the facial bones were considered the same as the skull. Table 3 shows the material properties that used in the simulation.

Therefore, in this study, the skull was assumed homogeneous and the same elastic modulus was used in 0- to 3-month-old head models. The material property of skull was considered as linear elastic and visco-elastic material model was used for the skin.

TABLE III
MATERIAL PROPERTIES OF 1 YO HEAD FOR THE COMPUTATIONAL SIMULATION [23,25]

Components	Elastic (MPa)	Poisson ratio	Density (kg/m3)	Sources
Skull	29	0.22	2150	Coats et al (2006) & Franklyn (2007)
Suture	4	0.49	1130	Coats et al (2006) & Franklyn (2007)
Scalp	16.7	0.42	1200	Coats et al (2006) & Franklyn (2007)

*Elastic material (MAT_01)***.** Elastic is an isotropic material and is available for beam, shell and solid elements in LS-Dyna [28]. The axial and bending damping factors are used to damp down numerical noise. The formula for force resultants, F_i, and moment resultants, M_i , includes the damping factors as follows:

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

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

Viscoelastic material (MAT_06). Stress and strain analysis of a visco-elastic material presents many technical hitches for real problems of complex geometry and in which in-homogeneity arises due to temperature or age differences of the material. The standard transformation approaches permit solution when a closed form solution of equivalent elastic problems is available [29].

The shear relaxation behaviour is described from a time dependent shear modulus as [28]:

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

Where G∞, Go, and β were the material constants, that found by the load-time curve.

A formulation that has found wide acceptance for large strain inelastic analysis is the updated Lagrangian Jaumann (U.L.J.) formulation [29]. Here, the Jaumann stress rate is used:

$$\sigma'_{ij} = 2\int_0^t G(t-\tau) D'_{ij}(\tau) d\tau$$

Where the prime denotes the deviatoric part of the stress rate, σ'_{ij} and the strain rate D'_{ij}

III. RESULTS AND MODEL VALIDATION

*Cadaver Test from literature &FE model validation under drop conditions***.** The 12MO ATD dummy head FE model was dropped from 130 mm height onto the fixed rigid surface at forehead/ frontal location. The initial velocity exerted on the FE model was equal to 1.597 m/s, which were computed based on the drop heights. The coefficient of friction between head and impact surface, and the hourglass energy in LS-DYNA were defined the same as those described in the section of FE model validation under drop conditions. The sign conventions of the SAE J211 standard were used in the simulations for all measured values. Figure 4 demonstrates the simulation of the drop test of the 12MO ATD dummy head model at 130 mm height. The head drop test has been performed according to the TNO Q3 dummy user documentation [31].

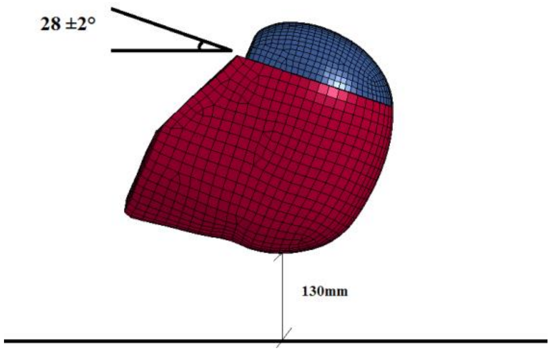

Fig. 4 Frontal head drop test configuration

The frontal drop test events are shown in Figure 5. The contact time from head skin to rigid shell is 3 milliseconds. The results of simulations tests are shown in Figure 6. The peak resultant acceleration from the simulation is approximately less than 2% lower than the experimental test results. The comparison of peak resultant acceleration and average time duration for the frontal drop condition is shown in Figure 6. In Table IV, the percentage errors were calculated and compared with the experimental results. A fairly good agreement of peak resultant accelerations between cadaver experiment and simulation results were found for the frontal drop test conditions.

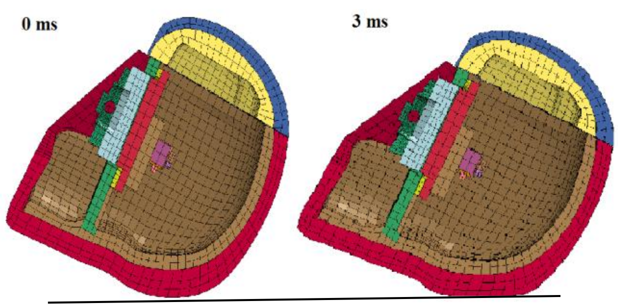

Fig. 5 Frontal drop test event at time 0 & 3

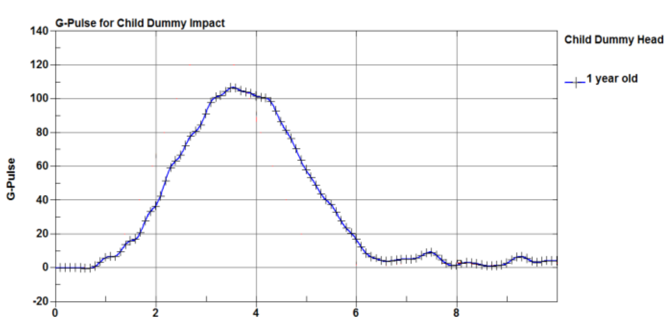

Fig. 6 Resultant acceleration vs time graph of 12MO Frontal Drop test

The head assembly was validated by using one set-up of head drop tests (Table IV). The test with drop height of 130 mm is the certification procedure. The biomechanical target of the 12MO ATD head is based on the rigid surface cadaver drop tests conducted by Hodgson and Thomas [30]. Table IV shows the head bio-fidelity test results for the 12MO ATD FE dummy head model.

TABLE IV
THE HEAD BIO-FIDELITY TESTS RESULT FOR THE 12MO ATD DUMMY HEAD MODEL

Impact direction	Drop height (mm)	Target (G)	Test result (G) [30]	Simulation result (G)	Error (%)
Frontal	130	108 ±29	112±1	109	1.8

IV. SUMMARY

In this study, a biofidelic FE Model of a 12MO head was developed and compared with the 12MO child cadaver test. The drop test was conducted in one impact direction; frontal/ forehead location. The comparison of results showed that the stiffness of the 12MO head dummy model is less stiff than the corresponding experimental child cadaver test. The peak resultant acceleration is slightly lower than from the experimental test. This is probably because the 12MO FE model is a less stiff than the counterpart of 12MO cadaver. The above inconsistency can probably attribute to the following reasons: (1) the accurate impact location between the head and impact surface in the simulation and the experimental test are not exactly the same and this could cause some errors, (2) material properties of some components (skin/scalp, skull) in the present head FE model are from the test data of adult head due to scarcity of twelve-month-old cadaver test data which most likely overestimate the global stiffness of head.

As a conclusion, a finite element model of the 12MO head was developed in this study, and was validated against experimental data in terms of head acceleration.

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REFERENCES

[1] J.F. Kraus, A.Rock, P.Hemyari, Brain injuries among infants, children, adolescent, and young adults, American Journal of Diseases of Children 144 (1990) 684-691

[2] M.F. Ballesteros, R.A. Schieber, J. Gilchrist, P. Holmgreen, J.L. Annest, Differential ranking of causes of fatal versus non-fatal injuries among US children, Injury Prevention 9(2003) 173. http://dx.doi.org/10.1136/ip.9.2.173

[3] S.M. Atabaki, Pediatric head injury, Pediatrics in Review 28(2007) 215–224.

[4] J.A. Langlois, W. Rutland-Brown, K.E. Thomas, Traumatic Brain Injury in the United States: Emergency Department Visits, Hospitalizations, and Deaths, Centers for Disease Control and Prevention, National Center for Injury Prevention and Control, Atlanta, GA, 2006.

[5] CDC, Childhood injuries in the United States, American Journal of Diseases of Children 144 (1990) 627–646.

[6] K.D. Klinich, G.M. Hulbert, L.W. Schneider, Estimating infant head injury criteria and impact response using crash reconstruction and finite element modeling, Stapp Car Crash Journal 46 (2002) 165–194.

[7] S. Roth, J.S. Raul, B. Ludes, R. Willinger, Finite element analysis of impact and shaking inflicted to a child, International Journal of Legal Medicine 121 (3) (2007)223–228. http://dx.doi.org/10.1007/s00414-006-0129-3

[8] S. Roth, J.S. Raul, R. Willinger, Biofidelic child head FE model to simulate real world trauma, Computer Methods and Programs in Biomedicine 90 (2008) 262–274. http://dx.doi.org/10.1016/j.cmpb.2008.01.007

[9] S. Roth, J.S. Raul, J. Ruan, R. Willinger, Limitation of scaling methods in child head finite element modeling, International Journal of Vehicle Safety 2 (4) (2007)404–421. http://dx.doi.org/10.1504/IJVS.2007.016750

[10] S. Roth, J. Vappou, J.S. Raul, R. Willinger, Child head injury criteria investigation through numerical simulation of real world trauma, Computer Methods and Programs in Biomedicine 93 (1) (2009) 32–45. http://dx.doi.org/10.1016/j.cmpb.2008.08.001

[11] S. Roth, J.S. Raul, R. Willinger, Finite element modeling of paediatric head impact: global validation against experimental data, Computer Methods and Programs in Biomedicine 99 (2010) 25–33. http://dx.doi.org/10.1016/j.cmpb.2009.10.004

[12] B. Coats, S.S. Margulies, S. Ji, Parametric study of head impact in the Infant, Proceedings of Stapp Car Crash Journal51 (2007) 1–15.

[13] W. Weber, Experimental studies of skull fractures in infants. Zeitschrift fur Rechtsmedizin, Journal of Legal Medicine 92(1984) 87–94.

[14] W. Weber, Biomechanical fragility of the infant skull. Zeitschrift fur Rechtsmedizin, Journal of Legal Medicine 94(1985) 93–101.

[15] Z. Li, J. Hu, M.P. Reed, J.D. Rupp, C.N. Hoff, J. Zhang, B. Cheng,Development, validation, and application of a parametric pediatric head finite element model for impact simulations, Annals of Biomedical Engineering 39 (2011) 2984–2997. http://dx.doi.org/10.1007/s10439-010-0205-1

[16] Z. Li, J. Hu, M.P. Reed, J.D. Rupp, C.N. Hoff, J. Zhang, B. Cheng, Erratum to: Development, validation, and application of a parametric pediatric head finite element model for impact simulations, Annals of Biomedical Engineering 41 (1) (2013) 215–220. http://dx.doi.org/10.1007/s10439-012-0682-5

[17] Z. Li, J. Hu, M.P. Reed, J.D. Rupp, C.N. Hoff, J. Zhang, B. Cheng, Development, validation, and application of a parametric pediatric head finite element model for impact simulations, Annals of Biomedical Engineering 39 (2011) 2984–2997. http://dx.doi.org/10.1007/s10439-011-0380-8

[18] Zhigang Li, Xiao Luo, Jinhua Zhang, Development/global validation of a 6-month-old pediatrichead finite element model and application in investigation of drop-induced infant head injury, Computer Methods and Programs in Biomedicine II 2 (2 0 1 3) 309–319.

[19] Kate de Jager, Michiel van Ratingen, ASSESSING NEW CHILD DUMMIES AND CRITERIA FOR CHILD OCCUPANT PROTECTION IN FRONTAL IMPACT , , Proceedings of the 19th International Technical Conference on the Enhanced Safety of Vehicles (ESV) June 2005 Paper no. 05-0157

[20] www.truegrid.com, True*Grid*® is a Registered Trademark of XYZ Scientific Applications, Inc.

[21] Umashankar Mahadevaiah et al, Documentation of LSTC Hybrid III 6-year-old FEM, 2013

[22] K.Weber et al., Child Anthropometry for Restraint System Design, The University of Michigan, 1985, 34 pages

[23] Franklyn, M., S. Peiris, C. Huber, and K. H. Yang. Pediatric material properties: a review of human child and animal surrogates. Crit. Rev. Biomed. Eng. 35(3–4):197–342, 2007.

[24] B. Coats, S.S. Margulies, Characterization of paediatric porcine skull properties during impact, in: Proceedings of the IRCOBI Conference, Lisbon, 2003.

[25] B. Coats, S.S. Margulies, Material properties of human infant skull and suture at high rates, J. Neurotrauma 23 (8) (2006) 1222–1232. http://dx.doi.org/10.1089/neu.2006.23.1222

[26] Livermore software Technology Corporation, 2007, LS-DYNA keyword user's manual.

[27] E. H. LEE, Viscoelasticity. In *Handbook of Engineering Mechanics* (edited by W.FLVGGE), Chapter 53. McGraw-Hill, New York (1962).

[28] Herrman L.R., Peterson F.E.: A numerical procedure for viscoelastic stress analysis. In: Proceedings of the Seventh Meeting of ICRPG Mechanical Behavior Working Group, Orlando (1968)

[29] K. J. Bathe, Finite Element Procedures in Engineering Analysis. Prentice-Hall, Englewood Cliffs, NJ (1982).

[30] Hodgson, V.R., Thomas, L.M. "Head impact response". Vehicle Research Institute Report VRI 7.2 SAE. 1975.

[31] TNO, 2003, "MADYMO Database manual version 6.1", TNO Automotive, Delft, The Netherlands

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