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Finite Element Modelling of 1 Year-Old Pediatric Head with Fontanel Impact: Validation Against Experimental Data

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ABSTRACT

Background: In this study, a biofidelic finite element models (FEM) of 1-year-old head with fontanel was used to investigate child head dynamic response under drop impact conditions. Computer simulation using FEM are often used as a substitute for human experimental head injury studies, especially in predicting car accident injuries, enhance understanding of injury mechanism and develop prevention strategies. The use of FEM in crash test dummies is advantageous over physical dummies because of the lower cost and repeatability. A morphing method within LSPrepost software was used to morph the geometry of a baseline child head FEM into models with geometries representing a 1-year-old infant head with fontanel. Although the finite element method has been widely used for investigating adult head injury from impact, only a few 3D pediatric head FEM that complete with AF morphology have been reported. The surface area of the AF at age 1-year old used in this study is 184.2 mm2 that obtained from published journal. The model was developed by using both deformable and rigid body materials. The 1-year-old head anthropometric data were obtained from published journal articles. Using recent published material property data, the infant skull, skin and scalp FEM of the 1-year-old ATD head was developed to study the response in head drop tests. The head assembly was validated by using two different head drop tests set-ups. The two impact locations are frontal/forehead, and lateral (left parietal) drop tests. All tests with two different drop heights of 150 mm and 300 mm are the certification procedure. **Objective:** to develop FEM head for 1-year-old ATD dummy to use in occupant safety analysis, and to simulate a validation process under drop conditions based on the experimental cadaver drop tests data from published literature **Results:** For the forehead impact, a good correlation in terms of accelerations (G) between experiment and simulation were observed. It is intended for automotive crashworthiness assessment. **Conclusion:** **A** FEM of the 1-year-old head was developed in this study, and was validated against experimental data in terms of acceleration.

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INTRODUCTION

The fontanels are fibrous , membrane-covered gaps where more than two cranial bones are juxtaposed (Kiesler and Ricer, 2003). Lying between the bilateral frontal and parietal bones, the anterior fontanel (AF) reflects an expansion of the metopic, sagittal, and coronal suture lines. The AF remains patent prior to midline approximation of the coronal and sagittal sutures, shrinking with progressive ossification of surrounding bones (Woods and Johnson, 2010). Jonathan Pindrik *et al* investigate radio –graphically acquired normative range s of anterior fontanel closure (AFC) and surface area (SA) in healthy full –term infants by using high -resolution head computed tomography (CT) scans. This study provides reference charts detailing AFC frequency and AF SA as a function of age. Wide variabil ity of AFC timing and AF size among healthy infants suggest that early or delayed AFC may represent normal variants (Jonathan *et al*., 2014, Davies *et al*., 1975, Pedroso *et al*., 2008).

According to epidemiological studies (D.Viano *et al*., 1997), traumatic brain injury (TBI) is a serious cause of death and disability among the young paediatric population. TBI, also called acquired brain

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injury or simply head injury, occurs when a sudden trauma causes damage to the brain (Marcia Vita National, 2002).Head injury is leading cause of paediatrics fatality and disability in the United States (J.F. Kraus *et al*., 1990, M.F. Ballesteros *et al*., 2003, S.M. Atabaki, 2007), in which drop/fall is one of the most frequent causes (J.A. Langlois *et al*., 2006, CDC, 1990).Finite element model (FEM) is a widely used tool to investigate the dynamic response of the adult head under impact. Nevertheless, compared to adult models, three dimensional finite element models of 1-year-old child's head is still scarce.

A finite element model of 6month -old (MO) child has been developed by De Santis Klinich *et al.* (2002) 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.* (S. Roth *et al*., 2007, S. Roth *et al*., 2008) developed a 6 MO child head numerical model. The same research group also developed a 3year -old (YO) (S. Roth *et al*., 2010, B. Coats *et al* ., 2007) and a17day-old (DO) child numerical head models (S. Roth *et al*., 2010), in which the 3YO child head model was mainly used to compare the intracranial injury metrics differences between this 3YO model and a scaled adult head model (B. Coats *et al*., 2007), and the 17 DO model was used to simulate the paediatric skull fracture in reconstructing the real world head trauma for neurological lesions (S. Roth *et al*., 2010). Coats *et al.* (B. Coats *et al*., 2007) developed a 1.5MO head FEM and conducted a par ametric 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 (W. Weber, 1984, W . Weber, 1985) that focus on bone fracture. Li*et al.* (Z. Li *et al*., 2011, Z. Li *et al*., 2013) developed a parametric paediatric head FEM and morphed a baseline model to a newborn size, a 1.5MO, and a 3MO head model, in which only the newborn head FEM was validated against cadaver experiment. Weber (W. Weber, 1984, W. Weber, 1985) dropped 50 children aged from 0 to 9 MO 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. However, no quantitative data, such as head acceleration and contact force were collected from the tests, and only the skull fracture patterns were reported in that study (W. Weber, 1984, W. Weber, 1985).

The latest research about development and validation of the infant head FEM was conducted by Zhigang Li *et al.* (Z. Li *et al*., 2013) in 2013. From the research done by Zhigang Li et. al (Z. Li *et al*., 2013), a statistical model of cranium geometry for 0 to 3MO children was develope d by analyzing 11 CT scans using a combination of principal component analysis and multivariate regression analysis (Z. Li *et al*., 2011). Radial basis function was used to morph the geometry of a baseline child head FEM into models with geometries represen ting a newborn, a 1.5MO, and a 3MO infant head. Model validation was conducted against peak head accelerations in cadaver tests under different impact conditions, and optimization techniques were used to determine the mechanical properties. The results sho wed that the statistical model of cranium geometry produced realistic cranium size and shape, suture size, and skull/suture thickness, for 0 to 3MO children. The paediatric head models generated by morphing had a mesh quality comparable to the baseline mod el. 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 6MO child head FEM and the simulated results were compared with the child cadaver experimental under compression and drop conditions (Z. Li *et al*., 2011). Comparison of results indicated that the FEM showed good biofidelic behaviour in most dynamic responses. The validated FEM was further used to investigate the effects of different d rop heights and impact surface stiffness on the head dynamic responses (Kate de Jager and Michiel van Ratingen, 2005).

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 (Kate de Jager and Michiel van Ratingen, 2005). Very few findings on 1-year-old ATD found in the literature was validated by cadaver test data from similar age group. Even though 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 use ful for investigating the morphology and age effects on paediatric head injuries, and thus providing insights on how to prevent head injuries. The objectives of this study are (1) to develop FEM head for 1 -year-old ATD dummy to use in occupant safety analy sis, and (2) to simulate a validation process under drop conditions based on the experimental cadaver drop tests data from published literature.

Model Development:

Baseline Model Development:

The baseline model used in this study was a modified version of the 6YOAnthropomorphic 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 6YO Child Crash Test Dummy (H–III6C, Beta Version). It has been validated to the certification tests described in the Code of Federal Regulations, Title 49, Part 572, Sub part N. Validation results can be found in the accompanying documentation. The mesh of the FEM of the Hybrid III 6YO was developed by LSTC. True Grid is a Hexahedral Mesh Generator. The mesh is based on scanned data of an actual dummy and the drawing package of the dummy (Umashankar *et al*, 2013). Fig. 1 shows the 6YO LSTC Dummy used as baseline model in this study.

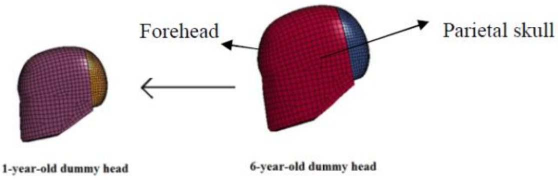


Fig. 1: 6YO LSTC Dummy used as baseline model.

Table 1 shows the basic statistics of the current version of the model:

Table 1: 6YO 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

Head Geometry and Morphing Activity:

The FEM of ATD 1-year-old head was developed by using mesh morphing technique in LS-DYNA Software. This method works by constraining the parts to be morphed within a solid hex mesh. Once “ Constrain” has been activated, the hex mesh can be changed accordingly, and the morph nodes will follow. The nodal coordinates are transformed based on their relative position within their containing solid element. In order to make a more precise adjustment, a finer solid mesh was used. 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*.

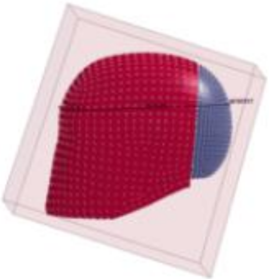


Fig. 2: Morphing activity.

The head assembly is made of skull including visco -elastic skin layer, and accelerometer 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.

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 Loyd A.M. (Loyd A .M, 2011). Table 2 shows the anthropometric data used in the simulation model. The measurement identification and detail measurement of FEM dummy were illustrated in Fig. 3 a nd 4. The head model can be considered as a 50th percentile 1-year-old head.

Fontanel:

For measurement of transverse and longitudinal dimensions, 3D images were oriented to place the AF coplanar with the radiology viewer, allowing visualization of the foramen magnum inferiorly through the patent fontanel. The transverse dimension (W) represented the distance between lateral apices of the AF along the coronal suture (Fig. 5). The longitudinal dimen sion (AP) represented the net distance between anterior and posterior apices of the AF along the sagittal suture (Fig. 5). Fig. 5 shows that this high - resolution, 3-dimensional reconstructed head computed tomography demonstrates measurement of the transverse and longitudinal dimensions of a patent AF, allowing calculation of the AF surface area.

Measurements were tailored to estimate the long and short internal axes of a quadrilateral with sides tangential to the AF borders, as described previously (Davies *et al*., 1975, Pedroso *et al*., 2008). Based on prior studies, the AF SA was estimated as,

$$SA = W*AP*1/2 \quad (1)$$

Table 2: Anthropometric data for numerical 1-year-old head (Loyd A.M, 2011).

Head breadth	122 mm
Head circumference	455 mm
Head depth	148 mm

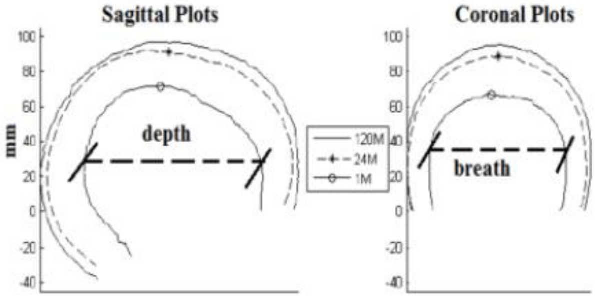


Fig. 3: Comparison of the human skull contours for 1M, 24M and 120M (Loyd A.M, 2011).

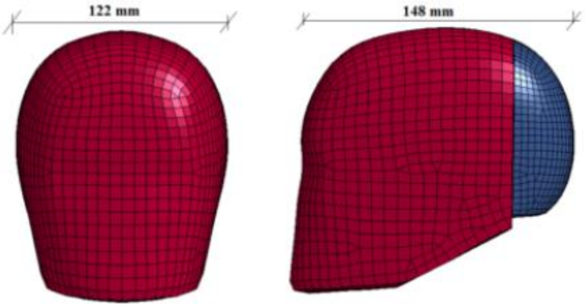


Fig. 4: Details measurement of 1-year-old dummy head FEM.

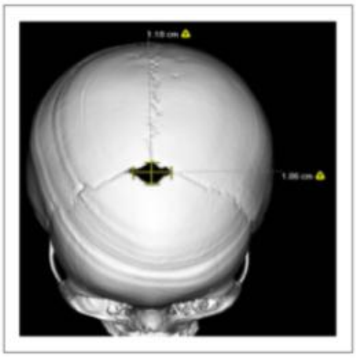


Fig. 5: Measurement of AF, transverse and longitudinal dimensions (Davies *et al*., 1975).

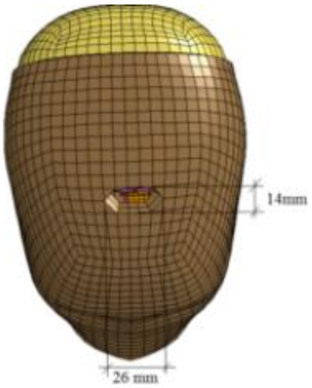


Fig. 6: Actual measurement of AF surface area.

Table 3: Anterior Fontanel (AF) Median Surface Area (SA) as a Function of Age -Group (Jonathan *et al*., 2014).

Age Group (months)	Sample size (n)	AF Median SA (mm^2)	AF Minimum SA (mm^2)	AF Maximum SA (mm^2)
0	19	769.3	216.0	1651.9
1	19	879.9	404.8	1869.3
2	18	1022.2	143.8	1324.4
3-4	37	794.8	137.7	1468.9
5-6	38	685.7	2.0	1709.5
7-9	58	472.0	3.4	1417.1
10-12	63	184.2	0.1	2191.4
13-15	52	86.7	0.0	1294.7
16-18	50	2.2	0.0	853.8
19-21	50	0.3	0.0	480.4
22-24	55	0.2	0.0	147.3

Acquisition of AF longitudinal and transverse dimensions allowed estimation of AF SA for all study subjects. The AF median SA increased from 769.3 mm2 during the first weeks of life to 1022.2 mm 2 at age 2 months. After hit the highest point at age 2 months, AF median SA gradually declined to 184.2 mm2 at ages 10 to 12 months and 0.2 to 2.2 mm 2 at ages 16 to 24 months (Table 3, Fig 5) (Davies *et al*., 1975). Fig. 6 shows the actual measurements of W and AP, 26mm and 14mm. From equation (1), the fontanel surface area that was used in this analysis is 182 mm2.

Material Properties:

As explained in the introduction, only a few studies report mechanical properties of child head components. Thus mechanical properties reported by Franklin *et al* (B. Coats and S.S. Margulies, 2003) and Coats *et al* (Zhigang Li *et al*., 2013, Kate de Jager and Michiel van Ratingen , 2005) were considered in this model. Coats et. al (Coats *et al*, 2003, Coats *et al*., 2006), 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* (Franklyn *et al*., 2007) has compared and summarized most of the previous experimental data available before 2006. Coats *et al*. (Coats *et al*, 2003, Coats *et al*., 2006) conducted bending and tension tests on skull and suture using 23 paediatric cadavers from 21 weeks gestational age to 13MO. The results showed that age and location did not have significant effects on elastic modulus of skulls from 0 to 13MO children. Material properties of the facial bones were considered the same as the skull. Table 4 shows the material property values used in the simulation. Also, in this study, the skull was assumed to be homogeneous and has the same elastic modulus as that of 0 to 3MO head. The material property of skull was considered as linear elastic and for the skin a visco-elastic material model was used.

Table 4: Material properties of 1-year-old head for the computational simulation (Coats *et al*., 2006, Franklyn, 2007).

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 (MAT_01):

Elastic is an isotropic material and is available for beam, shell and solid elements in LS-Dyna (Livermore, 2007). The axial and bending damping factors are used to damp down numerical noise. The expression for force resultants, F_i, and moment resultants, M_i, includes the damping factors are as follows:

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

$$M_i^{n+1} = M_i^{n} + \left(1+\frac{DB}{\Delta t}\right)\Delta M_i^{n+\frac{1}{2}} \tag{3}$$

Viscoelastic (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 (E.H. Lee, 1962).The shear relaxation behaviour is described from a time (*t*) dependent shear modulus as (Herrman L.R. and Peterson F.E, 1968):

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

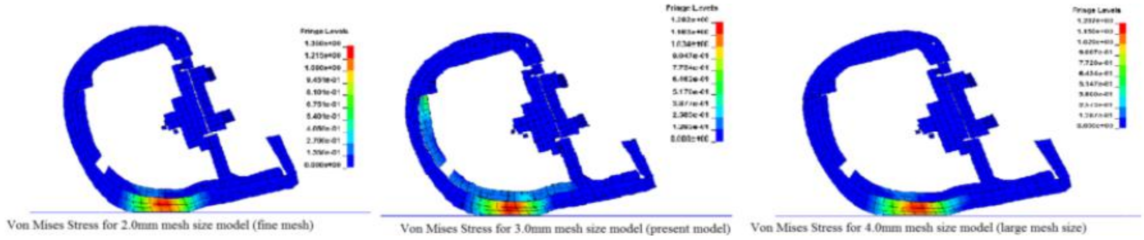
Where G_∞, G_o, and β were the material constants, that found by the load -time curve. An equation that has found wide acceptance for large strain inelastic analysis is the updated Lagrangian Jaumann (U.L.J.) formulation [35]. Here, the Jaumann stress rate is used:

$$\sigma'_{ij} = 2\int_0^t G(t-\tau)D'_{ij}(\tau)d\tau \tag{5}$$

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

Mesh convergence:

Three different mesh size were tested. 4 mm, 3 mm (the present model), and a fine mesh (2 mm). The model meshed with 4 mm elements had a quite high time pitch (1e -3 ms), but element size may not respect the original geometry of complex head structure s. Mesh size was too large. Fine mesh respected to the geometry of the skull head with a low time pitch (7e-5 ms). The present model with the element of 3.0 mm size, combined both of the geometry and acceptable time pitch (0.5e -3 ms) for an acceptable comp utational time. Differences in terms of mechanical outputs did not bring significant difference between 2 mm and 3 mm size elements. Results in terms of von mises stresses were similar and only 5% different were notice in terms of maximum von mises stress (Figure). Simulations performed with the FEM using 3 mm size elements showed that the mesh was sufficiently refined to perform a run in a stable manner over the range of loading conditions, without large element distortion, and gave an acceptable computational time. Fig. 7 shows the von mises stresses comparison for the mesh convergence analysis.



Von Mises Stress for 2.0mm mesh size model (fine mesh)
Von Mises Stress for 3.0mm mesh size model (present model)
Von Mises Stress for 4.0mm mesh size model (large mesh size)

Fig. 7: Von mises stresses comparison for mesh convergence analysis (frontal impact).

Results and Model Validation:

Cadaver Test from literature and FEM validation under drop conditions:

The 1-year-old ATD dummy head FEM was dropped from 150mm and 300mm height onto the fixed rigid surface at forehead and parietal locations. Two drop conditions were included in these simulations. T he impact velocity exerted on the FEM were equal to 1.716 m/s and 2.426 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 to be the same as thos e described in the section of FEM validation under drop conditions. The sign conventions of the SAE J211 standard was used in the simulations for all measured values. Fig.8 illustrates the simulation of the drop test of the 1-year-old ATD dummy head model at 150 mm height.

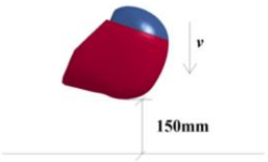


Fig. 8: Frontal drop test set up.

The frontal drop test events are shown in Fig . 8. The contact time from head skin to rigid shell is 3 milliseconds. From Fig.9, it appears that the maximum value calculated for Von Mises stress was about 1.352 Pa and occurred in the scalp area. The distribution of the Von Mises stress may be related to the topology of the scalp and skull, particularly the base which is a very irregular surface. The results of simulations tests for acceleration are shown in Fig . 10. Also shown in Fig . 9 are lines indicating the peak values of accelerations from references (Loyd A .M, 2011) for comparison of peak values. The peak resultant accelerations from the simulation are approxim ately 5% to 33% higher than the experimental test results. The comparison of peak resultant acceleration and average time duration for all the two drop conditions are shown in Fig . 9. In Table 5, the percentage errors were calculated according to different impact locations of the head. For the forehead impact, a good correlation in terms of accelerations (G) between experiment and simulation were observed. For the left-parietal 150 mm drop test, the error was 32.64%, showing the less accurate response.

The head assembly was validated by using two different set-ups and two different height of head drop tests as shown in Table 5. Both tests with drop height of 150 mm and 300 mm are the certification procedure. The biomechanical target of the 1 -year-old ATD head is based on the rigid surface cadaver drop tests conducted by Andre Matthew Loyd (Loyd A.M, 2011). The head bio -fidelity test results for the

1-year-old ATD FE dummy head model is also shown in Table 5.

Summary:

In this study, a biofidelic FEM of a 1-year-old head was developed and compared with the 1-year-old child cadaver experiment. The drop tests were conducted in two different location; forehead and left parietal. The peak resultant acceleration value gives indication on the stiffness of the part. The comparison of results showed that the 1 -year-old head dummy model is slightly stiffer than the corresponding experimental child cadaver test. The peak resultant acceleration is slightly higher than those from the experimental tests. This is probably because the material property used for the 1 -year-old FEM is a little stiffer than the counterpart of 1 -year-old cadaver. The above inconsistency can probably attribute to the following reasons: (1) material properties of some componen ts (skin/scalp, skull) in the present head FEM are from the experiment data of adult head due to lack of paediatric test data which most likely overestimate the global stiffness of head, (2) the exact impact location between the head and impact surface in the simulation and the experimental test are not precisely the same and this could also cause some errors.

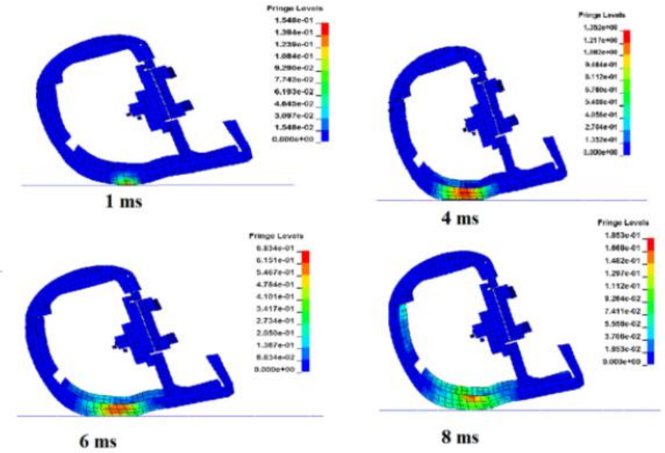


Fig. 9: Distribution of von Mises stress for frontal drop test simulation.

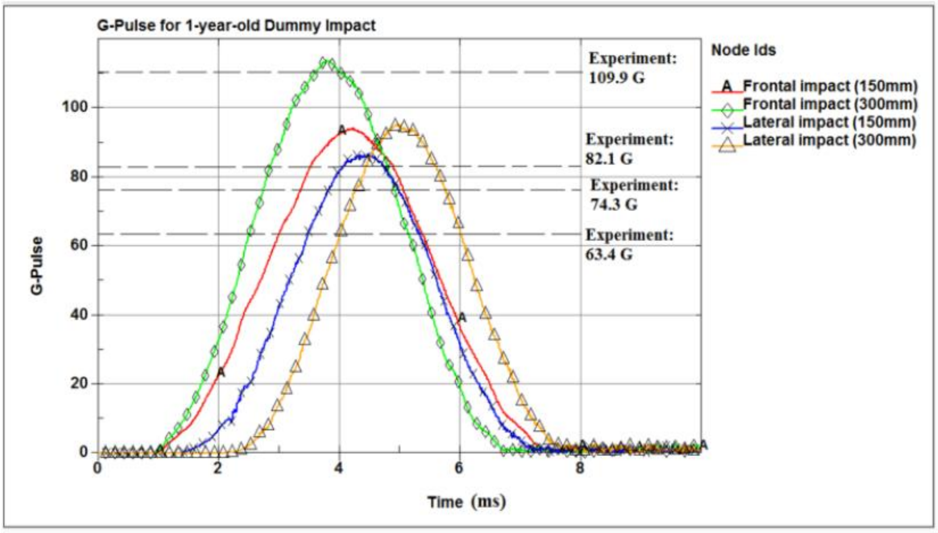


Fig. 10: Resultant acceleration (G-Pulse) vs time graph of Frontal and Left parietal for 1-year-old head responses (Note: the peak values from references [Loyd A.M, 2011] are indicated as lines since acceleration time curve is not available).

Table 5: The head bio-fidelity tests result for the 1-year-old ATD dummy head model.

FE dummy head model	Impact direction	Impact location	Drop height	Peak resultant head acceleration (g)		
				Experimental result	Simulation result	Error (%)
1-year-old	Frontal	Forehead	150mm	82.1 G	91.9 G	11.94
	Frontal	Forehead	300mm	109.9 G	114.0 G	3.73
	Lateral	Left parietal	150mm	63.4 G	84.1 G	32.64
	Lateral	Left parietal	300mm	74.3 G	92.4 G	24.36

As a conclusion, a FEM of the 1 -year-old head was developed in this study, and was validated against experimental data in terms of G -pulse values (ac celeration). Child biomechanics suffers strongly from great limitations in terms of experimental cadaver data.

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