Development and Validation of Newborn Child Head Numerical Model Dummy for Impact Simulations

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Abstract—Computer simulation using Finite Element Model (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. Numerous adult FEM of the head have been developed, but there are relatively few paediatric FEM due to scarcity of material property data for children. Consequently, there are not enough models representing newborn child. Child head injury is a costly problem, both in terms of morbidity and direct medical costs. Indeed, it is the leading cause of death and disability for children under the age 18-years-old. Despite its importance and effect on the population, the study of paediatric head injury is obstructed by the lack of available paediatric Post-Mortem Human Specimen (PMHS) data. As a substitute for PMHS testing, Anthropometric Test Devices (ATDs) and FEM 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 newborn (NB) FEM for head dummy and simulated results compared with the child cadaver experimental data under drop test conditions. This intended for automotive crashworthiness assessment. The model was developed by using both deformable and rigid body materials. The newborn head anthropometric data were obtained from published journal articles. Using recent published material property data, the infant skull, skin and scalp FEM of the newborn ATD head was developed to study the response in head drop tests. The head assembly was validated by using three different head drop tests setups. The three impact locations are one frontal/forehead, and two lateral (right and left parietal) drop tests. All tests with drop height of 130 mm are the certification procedure. The benchmark model used in this study was a modified version of the 6-year-old numerical model developed by Livermore Software Technology Corporation and National Crash Analysis Center. A morphing method within LS-Prepost software was used.

Index Terms—crashworthiness assessment, newborn head dummy model, finite element, head injury criteria

I. INTRODUCTION

According to epidemiological studies [1], Traumatic Brain Injury (TBI) is a serious cause of death and disability among the young paediatric population. TBI, also called acquired brain injury or simply head injury, occurs when a sudden trauma causes damage to the brain [2]. Head injury is leading cause of paediatrics fatality and disability in the United States [3]-[5], in which drop/fall is one of the most frequent causes [6], [7]. 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 newborn child’s head is still scarce.

A finite element model of 6 month-old (MO) child has been developed by DeSantis Klinich et al. [8] 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. [9], [10] developed a 6 MO child head numerical model. The same research group also developed a 3 year-old (YO) [11], [12] and a 17 day-old (DO) child numerical head models [13], 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 [11], and the 17DO model was used to simulate the paediatric skull fracture in reconstructing the real world head trauma for neurological lesions [13]. Coats et al. [14] developed a 1.5MO head FEM 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 [15], [16] that focus on bone fracture. Li et al.
[17], [18] 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 [15], [16] dropped 50 children aged from 0 to 9MO onto 5 different impact surfaces under the drop height of 82cm, 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 [15], [16].

The latest research about development and validation of the infant head FEM was conducted by Z. Li et al. [18] in 2013. From the research done by Z. Li et al. [18], a statistical model of cranium geometry for 0 to 3MO children was developed by analyzing 11 CT scans using a combination of principal component analysis and multivariate regression analysis [17]. Radial basis function was used to morph the geometry of a baseline child head FEM into models with geometries representing a newborn, a 1.5MO, and a 3MO infant head. Model validation was conducted against peak head accelerations and contact force were collected from the tests, and only the skull fracture patterns were reported in that study [15], [16]. 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 [17]. Comparison of results indicated that the FEM showed good biofidelic behaviour in most dynamic conditions [17]. 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 drop heights and impact surface stiffness on the head dynamic responses [19].

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 [20]. Very few findings on newborn 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 useful 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 newborn ATD dummy to use in occupant safety analysis, and (2) to simulate a validation process under drop conditions based on the experimental cadaver drop tests data from published literature.

II. MODEL DEVELOPMENT

Baseline model development: The baseline model used in this study was a modified version of the 6YO 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 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, Subpart N. Validation results can be found in the accompanying documentation. The mesh of the FEM of the Hybrid III 6YO was developed by LSTC by use of the TrueGrid software [21]. TrueGrid is a Hexahedral Mesh Generator. The mesh is based on scanned data of an actual dummy and the drawing package of the dummy [22]. Fig. 1 shows the 6YO LSTC Dummy used as baseline model in this study. The simulation of a frontal head drop test was done and compared with the experimental data. From the results, a 4.8% error was obtained, so the simulation results are considered acceptable and can be used as a reference for the newborn simulation analysis.

Table I shows the basic statistics of the current version of the model.

| TABLE I. 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 newborn head was developed by using mesh morphing technique in LS-DYNA Software. This method works by constraining the parts to be morphed (Morph nodes) 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. Hence, in order to make a more precise adjustment, a finer solid mesh was used.

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. [23]. Table II shows the anthropometric data used in the simulation model. The measurement identification and detail measurement of FEM dummy were illustrated in Fig. 2 and Fig. 3. The head model can be considered as a 50th percentile newborn head.

**TABLE II. ANTHROPOMETRIC DATA FOR NUMERICAL INFANT HEAD [23]**

<table>
<thead>
<tr>
<th>Component</th>
<th>Head bread</th>
<th>Head circumference</th>
<th>Head depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>103mm</td>
<td>388mm</td>
<td>134mm</td>
</tr>
</tbody>
</table>

![Figure 2. Comparison of the average human skull contours for 1M, 24M and 120M [23].](image)

![Figure 3. Details measurement of infant dummy head FEM.](image)

**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. [24] and Coats et al. [25], [26] were considered in this model. Coats et al. [25], [26] have investigated material properties of newborn skull and sutures. The constitutive law of sutures and fontanel 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. [24] has compared and summarized most of the previous experimental data available before 2006. Coats et al. [25], [26] 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 III 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 III. MATERIAL PROPERTIES OF NEWBORN HEAD FOR THE COMPUTATIONAL SIMULATION [24], [26]**

<table>
<thead>
<tr>
<th>Component</th>
<th>Elastic Modulus (MPa)</th>
<th>Poisson’s ratio</th>
<th>Mass density (kg/m³)</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skull</td>
<td>29</td>
<td>0.22</td>
<td>2150</td>
<td>Coats et al. (2006) &amp; Franklyn (2007)</td>
</tr>
<tr>
<td>Suture</td>
<td>4</td>
<td>0.49</td>
<td>1130</td>
<td>Coats et al. (2006) &amp; Franklyn (2007)</td>
</tr>
<tr>
<td>Scalp</td>
<td>16.7</td>
<td>0.42</td>
<td>1200</td>
<td>Coats et al. (2006) &amp; Franklyn (2007)</td>
</tr>
</tbody>
</table>

**Elastic (MAT_01):** Elastic is an isotropic material and is available for beam, shell and solid elements in LS-Dyna [27]. The axial and bending damping factors are used to damp down numerical noise. The expression for force resultant, \( F_i \), and moment resultant, \( M_i \), 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 (MAT_06):** Stress and strain analysis of a visco-elastic material presents many technical hitches for real problems of complex geometry and in which inhomogeneity 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 [28]. The shear relaxation behaviour is described from a time \( t \) dependent shear modulus as [29]:

\[
G(t) = G_e + ( G_s - G_e ) e^{-\beta t}
\]

where \( G_e, G_s, \) and \( \beta \) 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 [30]. Here, the Jaumann stress rate is used:

\[
\sigma' = \frac{1}{2} \int_G ( t - \tau ) D_{ij}(\tau) d\tau
\]

where the prime denotes the deviatoric part of the stress rate, \( \sigma' \) and the strain rate \( D'_{ij} \).

III. RESULTS AND MODEL VALIDATION

**Cadaver test from literature and FEM validation under drop conditions:** The newborn ATD dummy head FEM
was dropped from 130mm height onto the fixed rigid surface at forehead and parietal locations. Three drop conditions were included in these simulations. The impact velocity exerted on the FEM was equal to 1.597m/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 those 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. 4 illustrates the simulation of the drop test of the newborn ATD dummy head model at 130mm height.

The frontal drop test events are shown in Fig. 5. The contact time from head skin to rigid shell is 3 milliseconds. From Fig. 5, it appears that the maximum value calculated for Von Mises stress was about 53.2Pa 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. 6. Also shown in Fig. 6 are lines indicating the peak values of accelerations from references [31], [32] for comparison of peak values. The peak resultant accelerations from the simulation are approximately 10% to 28% higher than the experimental test results. The comparison of peak resultant acceleration and average time duration for all the 3 drop conditions are shown in Fig. 6. In Table IV, the percentage errors were calculated according to different impact locations of the head. A fairly good agreement of peak resultant accelerations between test and simulation were found for all the conditions.

![Figure 4. Frontal drop test set up.](image)

![Figure 5. Distribution of von Mises stress for frontal drop test simulation.](image)

![Figure 6. Resultant acceleration vs time graph of frontal, left and right parietal for 6YO and newborn head responses (Note: The peak values from references [31], [32] are indicated as lines since acceleration time curve is not available).](image)
The head assembly was validated by using three different set-ups of head drop tests as shown in Table IV. Both tests with drop height of 130 mm are the certification procedure. The biomechanical target of the newborn ATD head is based on the rigid surface cadaver drop tests conducted by Hodgson and Thomas [31] and Cristian Gehre [32]. The head bio-fidelity test results for the newborn ATD FE dummy head model is also shown in Table IV.

### IV. SUMMARY

In this study, a biofidelic FEM of a newborn head was developed and compared with the newborn child cadaver test. The drop tests were conducted in three different location: forehead, right parietal and left parietal. The peak resultant acceleration value gives indication on the stiffness of the part. The comparison of results showed that the newborn 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 newborn FEM is a little stiffer than the counterpart of newborn cadaver. The above inconsistency can probably attribute to the following reasons: (1) material properties of some components (skin/scalp, skull) in the present head FEM are from the test 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 exactly the same and this could also cause some errors.

As a conclusion, a FEM of the newborn head was developed in this study, and was validated against experimental data in terms of head acceleration. Child biomechanics suffers strongly from great limitations in terms of experimental cadaver data. Ethical issues limit the type of experiments which can be conducted, yet these experiments are required for mathematical model validation.

### ACKNOWLEDGMENT

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### REFERENCES


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**TABLE IV. THE HEAD BIO-FIDELITY TESTS RESULT FOR THE NEWBORN ATD DUMMY HEAD MODEL**

<table>
<thead>
<tr>
<th>FE dummy head model</th>
<th>Impact direction</th>
<th>Drop height (mm)</th>
<th>Target</th>
<th>Experimental result [31], [32]</th>
<th>Simulation result</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newborn</td>
<td>Frontal (Forehead)</td>
<td>130</td>
<td>124±3</td>
<td>120±3</td>
<td>143.8</td>
<td>19.8</td>
</tr>
<tr>
<td></td>
<td>Lateral (Right parietal)</td>
<td>130</td>
<td>112±3</td>
<td>116.7±1</td>
<td>148.6</td>
<td>26.8</td>
</tr>
<tr>
<td></td>
<td>Lateral (Left Parietal)</td>
<td>130</td>
<td>112±3</td>
<td>116.7±1</td>
<td>149.6</td>
<td>28.0</td>
</tr>
<tr>
<td>6 YO-as a reference</td>
<td>Frontal (Forehead)</td>
<td>130</td>
<td>124±3</td>
<td>122±3</td>
<td>133.9</td>
<td>9.7</td>
</tr>
</tbody>
</table>
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