



Development of Three-Year-Old Child Free Motion Head Form Finite Element Model for Impact Assessment

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ABSTRACT

Free motion head form is a surrogate used in injury assessment of motor vehicle crash and height fall accidents. Heads being the first priority in child injury protection need a biofidelic model that is validated in different impact locations against cadaveric response. In this work, a three-year-old (3YO) child head form finite element (FE) model was developed by scaling down anthropometry of a six-year-old Hybrid III (6YO HIII) dummy head model. The FE model was then validated against the scaled biomechanical response of published nine-year-old cadaver head experimental data. Head skin viscoelastic material properties were tuned to give a good correlation with the scaled cadaver peak head accelerations. Head drop test was conducted on five impact locations: forehead, vertex, occipital and left and right parietal. A good correlation was found between simulation and scaled cadaver results for right parietal, vertex and occipital locations of 3YO child head FE model having less than 7% difference for 153 mm, 152 mm and 148 mm drop heights respectively. Occipital and right parietal locations show fair similarities with scaled cadaver response with a difference of less than 11% for 302 mm drop height. The left parietal of the head FE model, however, is observed to be stiffer than any other impact location with a difference of more than 20% for both 148 mm and 300 mm drop heights. The validated 3YO head form is therefore useful in the evaluation of automotive safety systems and child height fall investigations.

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INTRODUCTION

Head injuries are responsible for high morbidity and mortality rates of people around the world. In United States it accounts for 30% of all injury deaths [1]. It is a calamity that causes death of vehicle occupants of all age groups. The trauma is more destructive to children, whose centre of gravity is higher relative to their body height making them susceptible to head-first fall. Motor vehicle crash, pedestrian collision, falling on playgrounds and shaking-impact syndrome are some of the causes of traumatic brain injury to children. Falls have been the most common cause of closed head injuries for children 2 to 4 years [2]. Thus investigating the injuries severity of child's head on impact using a biofidelic head model capable of predicting biomechanical response is necessary. Lack of

paediatric cadaver data because of ethical reasons makes it very hard to validate the head models for various impact locations.

Anthropometric test device remains the most reliable tool in injury investigations. They are used to measure forces, accelerations and moments which are useful in determining the degree of injury sustained in human body. Child anthropometric test devices (ATDs) for automotive safety systems evaluation are available in series including Hybrid III, CRABI and P and Q series representing children from 0 to 10 year olds [3]. Computer ATD and human models reduces costly physical crash test and it is useful in studying how change in variables affect injury and thus substitute physical dummies. Though development of adult and child ATDs is advancing, validation of paediatric ATD against

the cadaver data is rare because of scarcity of experimental data. Biofidelic child ATD head FE model is necessary in crashworthiness assessment and fall investigations.

Child human head models were developed in recent year for injury investigations [4][5][6]. Loyd[7], compared adult and paediatric cadaver head response with age matched ATD in head drop test with the aim of assessing their bio fidelity. It was found that the ATD heads responses were different from age matched cadaver response. The ATD heads used today are however, validated only for frontal and side impacts. Three-year-old Q3 dummy head was designed for only parietal and forehead impacts and it was validated using scaled adult head response data [8]. 6 year old child Hybrid III dummies were validated based on the Federal Code Regulations specifications for frontal impact only[9][10]. It is important to develop and validate head FE model capable of estimating injuries for different impact locations because the head injury mechanism of children could be due to the contact of head with vehicle interior during impacts. The head impact location is important as, differences in the skull thickness and impact kinematics affect the impact properties [1].

This study is focused on validating three year old child ATD head FE model by comparing its biomechanical response in five impact locations with the scaled response of the nine year old child cadaver head data reported recently by Loyd [7]. This is expected to yield better bio fidelity than scaling adult cadaver data because of large developmental

difference between 3YO child and the adult. Until recently, by Loyd [7], in the hybrid III family, only 50th percentile adult was compared with cadaveric data in frontal impact, but none of child ATDs was validated against human data [1]. The aims of the study are therefore: (1) to morph 6YO HIII dummy head to 3YO head model anthropometry (2) to scale biomechanical response of nine year old child cadaver head to three year old; (3) to validate a three year old child ATD head FE model using the scaled 9YO cadaver data in five impact locations for two drop heights.

MATERIAL AND METHODS

Base Line Model Description

The 3YO dummy head modelling was done taking reference to Hybrid III 6 year old head finite element model Version: LST0.104.BETA, which is the latest child head FE model in Livermore Software Technology Corporation (LSTC). This model was developed by LSTC in conjunction with National Crash Analysis Centre (NCAC) and was validated based on the certification test of Code of Federal regulations, Title 49, Part 572, Subpart N. Detailed description of Hybrid III six year old dummy model are given in [10]. The head structure includes skull, skin, transducers and instrument mount and head pivot pin. It was selected as baseline model to model three year old head because it is currently the latest child crash dummy FE model in Hybrid III family. The head model consisting the skull and skin was isolated from the dummy as shown in Figure 1.

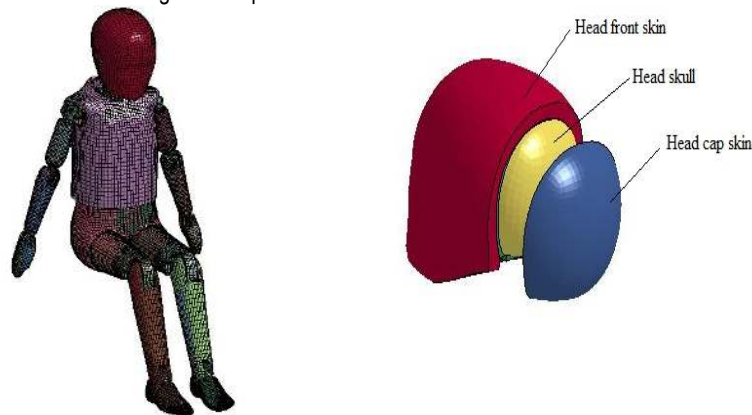


Figure 1: Hybrid III 6YO child dummy FE model [11]

Head Modelling

In developing the three year old child dummy head (designated as D_{3YO} in this paper), it was ensured that the mass and dimensions of the head matched closely to the mean of each parameter of three year old child head. The scaling was carried out using morphing technique in Ls-Dyna software. Morphing was done in LS PREPOST by constraining the parts to be morphed (*Morph*

nodes) within a solid hex mesh (*Constraining Element*). After *Constrain* has been activated, the hex mesh was transformed in any direction, and the *Morph nodes* will follow. The nodal coordinates are transformed appropriately according to their relative position within their constraining solid element [12]. The head model constrained in morphing box is shown in **Figure 2**.

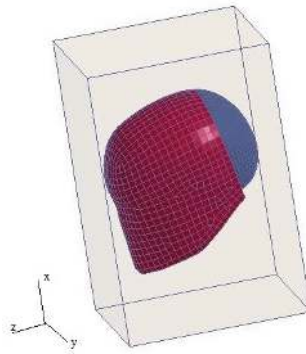


Figure 2: 6YO HIII head FE model constrained in morphing box

Scaling factors were applied in λ_x , λ_y and λ_z for the head breadth, head depth and head height respectively. The differences

between the D_{3YO} and three year old child dimensions were within 1% as shown in Table 1.

Table 1: Scaling 6YO HIII dummy head model to 3YO dimensions

Description	6YO HIII (Measured)	3YO child dimension [13]	Scaling Factors	FE Model (D_{3YO}) 3YO	Percentage Difference (%)
Head Breadth (cm)	14.6	13.4	0.92	13.6	-0.7
Head Height (cm)	14.8	13.7	0.93	18.4	0.5
Head Depth (cm)	17.2	17.4	1.01	17.6	-0.6
Head Circumference (cm)	52.1	49.5	0.95	48.7	0.8
Head Weight (kg)	3.5	2.40	0.69	2.33	3

The target mass of D_{3YO} segment was achieved by scaling the density of each part contained in it using the same scaling factor. This is necessary in order to keep the CoG in its initial position after mass reduction.

Material Properties Modelling

A linear viscoelastic model was assigned to the head skin (Material type 6, in Ls-dyna software). The suitable stiffness and

viscosities of the skin values were used to ensure similar response with scaled cadaver experimental data in the five impact locations. Long term shear modulus, G_1 , short term shear modulus, G_0 , and bulk modulus, K were found to affect the stiffness and hence, suitable values were used to get appropriate peak resultant acceleration in all impact locations. An increase in these parameters stiffens the material and amplifies the peak resultant

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acceleration. The decay constant parameter, β , was found to affect the contact time between rigid plate and dummy head. The skull was modelled using rigid material model

(Material type 20, in Ls-dyna software). Other head components were also modelled as rigid materials. Table 2 shows the material properties of the head.

Table 2: Material properties of the head model

Head Component	Material Model	Parameters						
		E (MPa)	ρ (Kg/m^3) 10^3	K (MPa)	G_0 (MPa)	G_1 (MPa)	ϑ	β (1/Sec)
Head front skin (6YO HIII)	Linear viscoelastic	NA	1.2	23.6	8	5	NA	250
Head front skin (D_{3YO})	Linear viscoelastic	NA	1.2	3	0.5	0.1	NA	250
Head cap skin (6YO HIII)	Linear viscoelastic	NA	1.2	23.6	8	5	NA	
Head cap skin (D_{3YO})	Linear viscoelastic	NA	1.2	2	0.25	0.08	NA	250
Skull (Front/Cap) (6YO HIII)	Rigid	70000	2.45	NA	0.3	NA	NA	NA
Skull (Front/Cap) (D_{3YO})	rigid	4700	1.8	NA	0.2	NA	0.2	NA

ρ : mass density, E : Elastic Modulus, K : Bulk Modulus, ϑ : Poison's Ratio, G_0 : Short Term Shear Modulus, G_1 : Long Term Shear Modulus, β : decay constant

From Table 2, it can be seen that the D_{3YO} viscoelastic material parameters were generally lower than 6YO HIII. The bulk modulus, K , G_0 , and G_1 , values were lowered to achieve the skin stiffness that will yield peak resultant acceleration that correlates with cadaver response. The density was adjusted to match the weight of D_{3YO} head.

Viscoelastic material model applied in D_{3YO} skin modelling on the other hand is the material model 6 in Ls Dyna Software. It allows the modelling of viscoelastic behaviour of beams, shells and solids [14]. Linear viscoelasticity is computed based on deviatoric stress tensor:

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

Where the shear relaxation behaviour is given by:

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

Cadaver Head Drop Test Experimental Work by Loyd 2011

Head peak resultant acceleration which is related to head injury criteria (HIC) is the parameter used to measure the head injury severity associated with impacts. HIC is the standard metric used estimate injury risk and determine when brain concussion and skull fracture will transpire. Among other head biomechanical response parameters, Head peak resultant acceleration is the only one that is currently applied in ATD heads validation. The head model was validated using scaled 9YO cadaver head data obtained from Loyd,2011 [7].

Loyd conducted head drop experiment on fresh frozen unembalmed paediatric cadaver head obtained from donor institution of Duke University. The nine year old child cadaver head data used in the current study was a male black American who died

from end stage renal disease. The head mass was measured and photo target was marked on the head in order to ease the monitoring of head rotation and translation in the experiment. The cadaver heads were dropped from 150cm and 300 cm for frontal, right parietal, left parietal, vertex and occipital location on to platen mounted on load cell. High speed camera was used to capture the response and force-time data was recorded using Lab view which was used for the calculation of

acceleration-time history. Heads were placed in net that was attached to a pulley. It was then adjusted to the desired height and released by burning the fishing line giving free fall of the head. The schematic diagram of the head drop test was as shown in Figure 4. The acceleration-time pulse was evaluated by dividing the force-time pulse by the head drop mass and the peak resultant acceleration was considered as the peak of the acceleration-time curve.

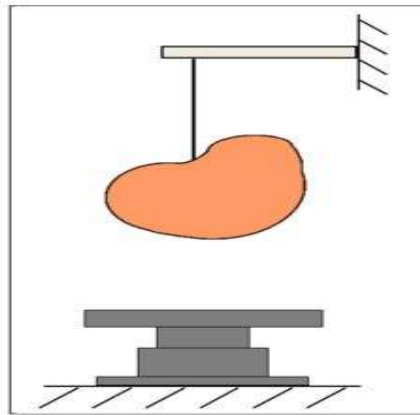


Figure 4: Schematic diagram of cadaver head drop test by Loyd,2011 [7]

To simulate cadaver drop test of Loyd it is important to set the head model in the same way with experimental set up. In this work, for frontal impact, the head was tilted so that z-axis form an angle of 28.5 deg with horizontal while the mid sagittal plane is vertical and for lateral impact the mid sagittal

plane was tilted to make 35 deg with impact surface from the top of the head [15]. For vertex and occipital impacts, the head was oriented such that the mid sagittal plane is 90 deg to the impacting surface. Figure 5 shows the positioning angles, impact locations and simulation set up.





Figure 5: Head drop test orientation for five impact locations

Scaling Biomechanical Response

Response based scaling method has been applied by many researchers in biomechanical response scaling [16][17][18][19][20]. Scaling 9YO child biomechanical response to 3YO seems to be better because of closeness in terms of size, geometry and material properties. Due to the lack of three year old cadaver head response data to validate the present model, a nine year old child head biomechanical response data from Loyd [7] was scaled using the method proposed by Mertz et al [21]. The head drop test condition was considered as a spring-mass system, where head mass m , impact a rigid plate with impact velocity v , so that, the

head stiffness k can be described by the following equation:

$$k = \frac{EA}{L} \quad (5)$$

Where, E is the bone elastic modulus A is the impact area and L is the head length, and thus stiffness scaling factor is:

$$\lambda_k = \frac{\lambda_E \lambda_x \lambda_y}{\lambda_z} \quad (6)$$

Where, $\lambda_x, \lambda_y, \text{ and } \lambda_z$ are the scaling factors of the head height, head breadth, and head length respectively as shown in Figure 6. λ_E is the elastic modulus scaling factor.

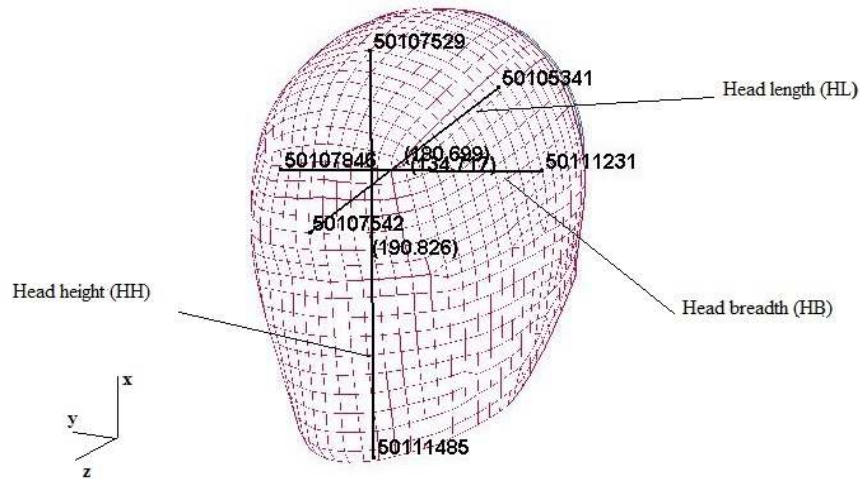


Figure 6 Axis orientations for scaling factors

The length scaling factors are therefore equal to:

$$\lambda_x = \frac{HH_{3YO}}{HH_{9YO}} \quad (7)$$

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$$\lambda_y = \frac{HB_{3YO}}{HB_{9YO}} \quad (8)$$

$$\lambda_z = \frac{HL_{3YO}}{HL_{9YO}} \quad (9)$$

Mertz and Irwin (1997) [22], established a curve fitting relating skull modulus as a function of age, based on the studies of McPherson and Kriewall (1980)[23] who presented elastic

modulus for bending of parietal bone of six year old and new born as 6.6 GPa and 2.5 GPa respectively, while adult parietal bone elastic modulus was presented by Hubbard (1971)[24]. Figure 7 shows Irwin's curve. It is used in finding the skull elastic modulus of 3YO and 9YO children for the determination of head peak acceleration scaling factors:

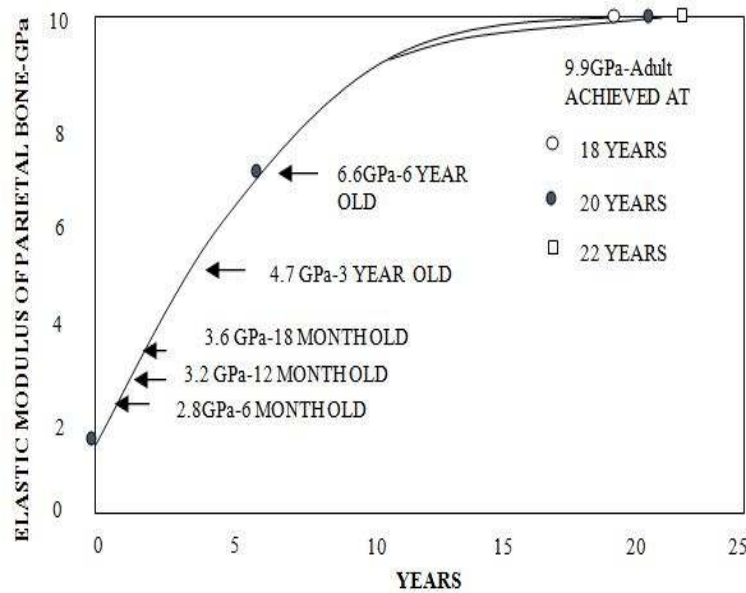


Figure 7 Skull Young's modulus as a function of age as established by Mertz & Irwin (1997) [22]

Elastic modulus ratio:

$$\lambda_E = \frac{E_{3YO}}{E_{9YO}} \quad (10)$$

The skull elastic modulus was found by interpolation from Irwin's curve: $E_{3YO} = 4.7 \text{ GPa}$ and $E_{9YO} = 7.4 \text{ GPa}$

Head acceleration scaling factor as derived by van Ratingen et al. (1997) is:

$$\lambda_a = \sqrt{\frac{\lambda_k}{\lambda_m}} \quad (11)$$

Where λ_m is the mass scaling factor and λ_k is the stiffness scaling factor (eqn. 5). To determine λ_m , we first determine the characteristic length scaling factor (λ_{CL}) which involves summing the circumference, breadth and length of the head using eqn. (13) for each size and taking their ratios [25]. Using this approach, the characteristic length scaling factor is:

$$\lambda_{CL} = \frac{CL_{3YO}}{CL_{9YO}} \quad (12)$$

Where the characteristic length is given as:



$$CL = HC + HB + HL \quad (13)$$

Assuming constant density:

$$\lambda_m = (\lambda_{CL})^3 \quad (14)$$

No specific dimensions of the cadaver head were given in the Loyd's study; hence, anthropometric data of Snyder et al. (1977) was applied to the nine year old child cadaver. Table 3 shows the scaling factors obtained using equations 5 to 14.

Table 3: Summary of scaling factors

Quantity		9YO	3YO	Scaling factors
Mass	λ_m	NA	NA	0.8208
Head height (cm)	λ_x	19.0 ^a	19.0	1.0000
Head breadth (cm)	λ_y	14.2 ^a	13.5	0.9507
Head length (cm)	λ_z	18.6 ^a	18.0	0.9677
Head circumference (cm)	NA	52.3 ^a	48.3	NA
Elastic Modulus (GPa)	λ_E	7.4	4.7	0.6351
Stiffness (GN/m)	λ_k	NA	NA	0.6239
Acceleration (g)	λ_a	NA	NA	0.8718

^a (Snyder, 1977)

To establish biofidelity requirement, the peak resultant acceleration of 9YO child cadaver head was scaled to D_{3YO} response using acceleration scaling factor λ_a shown in Table 3. The scaled values for the five impact

location for the two drop heights are shown in Table 4. The drop height was kept constant based on equal stress/equal velocity scaling method.

Table 4: Scaled cadaver experimental data

Impact Location	Drop Height (mm)	9YO child cadaver head Peak Resultant Acceleration (g) (Loyd, 2011)	Acceleration scaling factor λ_a	D_{3YO} head Scaled Peak Resultant Acceleration (g)
Forehead	151	102.6	0.8718	89.4
Left parietal	148	83.3	0.8718	72.6
Right Parietal	153	100.2	0.8718	87.4
Vertex	152	105.4	0.8718	91.9
Occipital	148	95.8	0.8718	83.5
Forehead	302	146.3	0.8718	127.5
Left parietal	300	123.3	0.8718	107.5
Right Parietal	302	142.5	0.8718	124.2
Vertex	299	130.8	0.8718	114.0
Occipital	302	150.8	0.8718	131.5

From Table 4, it can be seen that peak acceleration values are higher on dropping from larger heights due to high impact velocities and D_{3YO} peak acceleration values

are lower than the 9YO which explains the flexibility of younger child head skull.

Head Drop Test Simulations Set Up

The morphed dummy head model has an element size that is computationally stable and economical for which calculation takes only 9 minutes to complete. Impact velocities were calculated based on the drop height between head and impact plate according to the relation:

$$v = \sqrt{2gh} \quad 15$$

Where h is the height of fall and g is gravitational acceleration.

Surface to surface contact with a friction coefficient of 0.2 as suggested by Li et al (2013) [26] is defined between head and rigid plate. Hourglass energy was set to be

10% of the total energy. The drop test was carried out for two drop heights for each impact location. Sign conventions used are in accordance to Society of Automotive Engineers (SAE) recommendations [27]. A SAE 1000 Hz filter was used to process the output data. The peak value of head resultant acceleration history measured by the accelerometer located at the D_{3YO} head CoG is then compared with scaled 9YO cadaver head peak acceleration from loyd experiment for validation.

Simulations were conducted using finite element solver Ls-Dyna version 971. Dynamic simulation time was allowed to terminate at 10 milliseconds. Figure 8 shows a section view of the model at different stages of the simulation for frontal impact.

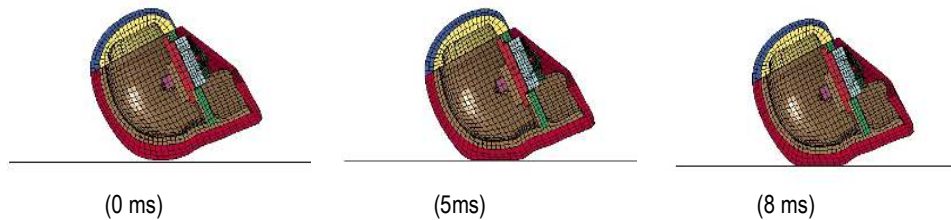


Figure 8: Head response at some stages of simulation

RESULTS AND DISCUSSIONS

For frontal impact, the results is more closer to cadaver data for the 302 mm drop height, than 151 mm in which case the head model appear to be 24.3% less stiff than

scaled cadaver results as seen in Table 5. Therefore, the head model is considered more biofidelic for 302 mm drop height in which the difference was about 10%.

Table 5: Comparison of acceleration values for scaled cadaver and D_{3YO}simulation results

Impact Location	Drop Height(cm)	Impact Velocity mm/sec	Scaled Cadaver Results (g)	Simulation Results (D _{3YO})(g)	Difference (%)
Forehead	151	1721	89.0	67.7	-24.3
Left parietal	148	1704	72.3	89.7	23.6
Right Parietal	153	1733	88.8	82.3	-5.8
Vertex	152	1727	91.5	85.7	-6.7
Occipital	148	1704	83.1	86.1	3.1
Forehead	302	2434	127.5	112.9	-11.5
Left parietal	300	2426	107.5	129.4	20.3
Right Parietal	302	2434	124.2	132.4	6.6
Vertex	299	2422	114.0	139.4	22.3
Occipital	302	2434	131.5	145.2	10.4

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For left parietal however, the head model peak resultant acceleration was 23.6% and 20.3% above the scaled cadaver values for 148 mm and 300 mm drop heights respectively as shown in Table 5. This indicates a stiffer skin in this location. But the discrepancy could be attributed to the lack of knowledge of exact impact point on the cadaver head, coupled with the fact that experimental cadaver accelerations was not measured from centre of gravity of the head in Loyd's study .

Peak resultant acceleration of right parietal impact shows good agreement with the scaled cadaver results for the two drop heights with a difference within 7%. The head model experienced biofidelic response in vertex location where it is only 6.7% less stiff for a drop height of 152 mm which indicated a good correlation with scaled cadaver data. For 299 mm drop height, the head model peak resultant acceleration over predicted the scaled cadaveric data by 25.4g.

For occipital impact location, a good correlation between head model and scaled cadaver data is observed. The simulation result was approximately within 10% different from scaled cadaver data for the two drop heights. Model biofidelity is obvious at 148 mm drop height where the head model deviates from experimental data by only 3%. The simulation results can be seen in Figure 13.

It can be observed from that the simulation results from five impact locations for the two drop heights were found to be within 25% difference from scaled cadaver data as indicated in Table 5. Right parietal, vertex and occipital locations appeared to be biofidelic having less than 7% difference from the scaled cadaveric data for lower drop heights, while forehead, occipital and right parietal show fair similarities with scaled cadaver data with a difference of less than 12% for higher drop heights. Left parietal of the head model, however, is observed to be very stiff, than any other impact location with a difference of more than 20% higher for the two drop heights as shown in Table 5. It was also observed from Figure 9 to 13 that the acceleration pulse is higher for higher falling height which explained high injury risk on falling from higher heights.

In general, a good correlation was achieved between the D_{3YO} head FE model

and scaled cadaver values considering the fact that cadaver experiment was carried out only on one sample for nine year old. Better biofidelity could be obtained by validating the head model using more cadaver head samples that could give an allowance to accommodate the errors on the current model and also by modifying the head geometry. It is also important to note that the exact impact location point of the cadaver was not known, and accelerometers were not installed exactly at the head centre of gravity in Loyd experiment. Moreover, experiments on the cadaver are not on living humans. Actual accelerations may differ due to the change of physical properties. All these could lead to some discrepancies between head model and scaled cadaver data.

The child dummy head FE model could now be used to estimate the head injury response of three year old child especially for the right parietal, vertex and occipital locations that cannot be estimated using current 3YO HIII dummy head model. Further work could also be carried out to construct the dummy head model using the geometry and material properties found in this study that can be applied in the physical crash test and forensic investigation of child height fall

CONCLUSION

This study describes the process of scaling crash dummy head FE model to a given anthropometry. This will enable head of children of various ages to be modelled for impact investigations. Method of scaling cadaver data to a given age was also discussed. Thus limited cadaver data could be utilized to validate head models whose data is not available. The impact response of three year old child head form FE model was validated against scaled nine year old child cadaver head response data by comparing their peak resultant accelerations for five impact locations. Forehead, right parietal, vertex and occipital show good agreement with scaled cadaveric data, while left parietal appeared to be stiff with more than 20% difference for the two drop heights. The difference between head model and scaled cadaver data for all impact locations and drop heights was within 25%. This study utilizes recently available child cadaver data in validating three year old child head form FE



model in multiple impact locations. The head model could therefore be useful in car FE model crashworthiness assessment, forensic investigations, and evaluating safety equipment, child seat and play ground.

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