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Development and Validation of One-year-old Child Neck Numerical Model Dummy for Impact Simulations

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ABSTRACT

Background: Although a number of finite element model (FEM) adult neck models have been developed to understand the injury mechanisms of the neck in automotive related crash scenarios, there have been fewer efforts to develop a child neck model. In this study, a one-year-old neck FEM was developed for application in the improvement of pediatric safety related to automotive crash. Therefore, there are not enough models representing one-year-old child. Child neck injury is a costly problem, both in terms of morbidity and direct medical costs. Despite its importance and effect on the population, the study of one-year-old neck injury is obstructed by the lack of available paediatric post mortem human specimen (PMHS) data. This paper presents the development and validation of a one-year-old FEM for neck dummy and simulated results compared with the child Anthropomorphic Test Device (ATD) experimental data under neck pendulum test procedure. It is intended for automotive crashworthiness assessment. The model was developed by using both deformable and rigid body materials. The one-year-old neck anthropometric data was obtained from published journal articles. Using recent published material property data, the paediatric skull, skin and scalp FEM of the one-year-old ATD head and neck were developed to study the response in neck pendulum tests. The neck test procedure was validated by using two different pendulum tests set-ups. The two pendulum test set-ups are neck extension test and neck flexion test. A pendulum was developed using LS-DYNA that follow the specifications from National Highway Traffic Safety Administration (NHTSA) part 572, subpart R (12-month-old) dummy performance calibration test certification procedure. The pendulum was release and fall freely from a height to achieve an impact speed of 2.5 m/s in neck extension test and 5.2 m/s in neck extension test as measure at the center of the pendulum accelerometer at the instant contact with the honeycomb. The benchmark model used in this study was a modified version of the six-year-old numerical model developed by Livermore Software Technology Corporation and National Crash Analysis Center. A morphing method within LS-Prepost software was used. Objective: to develop and validate a one-year-old neck FEM for application in the improvement of pediatric safety related to automotive crash. Results: For neck flexion test, the pendulum ΔV with respect to impact velocity are 1.67 m/s when t=10ms, 4.04 m/s when t=20ms and 4.87 m/s when t=25ms. For neck extension test, the pendulum ΔV with respect to impact velocity are 1.13 m/s when 6 ms, 1.99 m/s when 10 ms and 2.516 m/s when t=14ms. Conclusion: A FEM of the one-year-old neck was developed in this study, and was validated against experimental data in terms of velocity.

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INTRODUCTION

More than 1.2 million people die each year in road accidents worldwide and as many as 50 million others are injured and handicapped (World Health Organization 2009). To reduce traffic road accidents, the government and consumer organizations proposed and implemented safety regulations determined from data recorded during laboratory crash tests with new vehicle models. Anthropometric test devices(ATD)/dummies are frequently occupied in these vehicle crash tests to evaluate injury risk for vehicle occupants (Barbat *et al*. 2013; Forman *et al*. 2006; Hu *et al*. 2012; Sherwood *et al*. 2013) and pedestrians (Fredriksson *et al*. 2011; Kerrigan *et al*. 2012; Untaroiu *et al*. 2008). The Q-dummies (test device for child occupant restraint), a dummy showing advanced biofidelity, has been developed

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and continuously improved by the National Highway Traffic Safety Administration (NHTSA) to provide an advanced crash test dummy for crash safety analysis (Kate de Jager and Michiel van Ratingen, 2005). Rapid advances in both computational power and crash simulation technology enables the use of a computational component complementary to experimental testing, especially in the optimization of vehicle components or restraint systems during the manufacturer's design process (Adam and Untaroiu 2011; Bose *et al*. 2010; Untaroiu *et al*. 2007). However,to provide maximum utility of the dummy computational model, the biofidelity of its components should be assessed against the test data recorded from the physical dummy and the data corridors available from child ATD experimental data and tests.

The latest research about development and validation of the infant head FEM was conducted by Jacob B. Putnam *et al*. on 2014 (Jacob B. Putnam *et al*., 2014). The objectives of their study were to update the THOR head–neck finite element (FE) model to the specifications of the latest dummy modifications and to develop and apply a new optimization-based methodology to calibrate the FE head–neck model based on experimental test data. In conclusion, the optimization-based calibration methodology was effective as it markedly improved model performance and the calibrated head–neck model demonstrated application in a crash safety analysis, showing slight head–neck injury sensitivity to pretest positioning in a frontal crash impact scenario. The main goal of this study was to develop the components of the head and neck finite element model (FEM) and validate with the child Anthropomorphic Test Device (ATD) experimental data under neck pendulum test procedure. This research was performed corresponding to the lack of three dimensional finite element models of 1-year-old child's head and neck. The neck test procedure was validated by using two different pendulum tests set-ups. The two pendulum test set-ups are neck extension test and neck flexion test. A pendulum was developed using LS-DYNA that follow the specifications from National Highway Traffic Safety Administration (NHTSA) part 572, subpart R (12-month-old) dummy performance calibration test certification procedure (NHTSA, 2001).

Methodology:

Development of the Head–Neck Dummy FEM:

The ATD head–neck Finite Element Model (FEM) was developed using LS-Dyna (LSTC, Livermore) software version LS-Prepost 4.0 and LS-Dyna manager version 971. 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 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 True Grid software (TrueGrid). 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 Mahadevaiah *et al*, 2013). Figure 1 shows the cross section of one-year-old head and neck FEM used in this study. The simulation of a pendulum neck extension test and pendulum neck flexion test were done and compared with the experimental data.

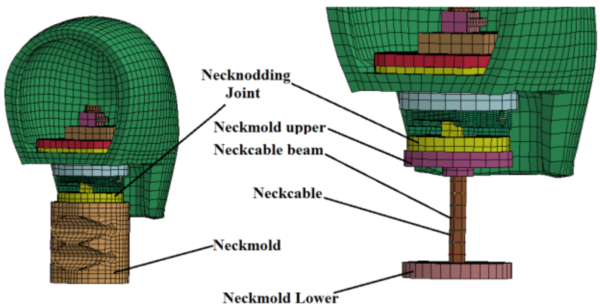


Fig. 1: Cross section of head and neck FEM

The FEM of ATD one-year-old 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 accurate adjustment, a finer solid mesh was used.

The head and neck 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. The material type 7 (Blatz-ko_rubber) is used to model some of the rubber components and material type 62 (viscous foam) is used to model the foam components. The standard dummy instrumentation (accelerometers, load cells, potentiometer) is represented in the FE model and the polarities are set according to the SAE J211 recommendation (LSTC, 2007).

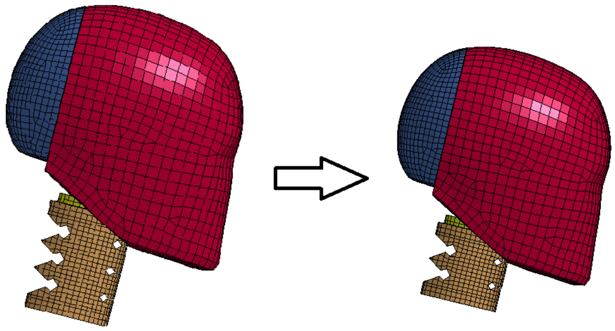


Fig. 2: Head geometry and morphing activity.

Anthropometry. The main dimensions (breath and circumference) of the model were compared to anatomical studies reported by Richard G. Snyder (Richard G. Snyder, 2009). Table 1 shows the anthropometric data used in the simulation model. The head geometry and morphing activity of one-year-old neck FEM were illustrated in Figure 2. The head model can be considered as a 50th percentile one-year-old neck.

Table 1: Anthropometric data for numerical one-year-old neck (Richard G. Snyder, 2009)

Neck breadth	67.1 mm
Neck circumference	219 mm

Material Model And Material Properties:

As explained in the introduction, only a few studies report mechanical properties of child neck components. Thus mechanical properties reported by Franklyn *et al*. (Franklyn *et al*., 2007) and Coats *et al*. (Coats *et al*., 2006) were considered in this model. Coats et. al (Coats *et al*., 2006) have investigated material properties of one-year-old skull. For the initial version of the one-year-old neck FEM, there are no material tests were available. Thus the FE-materials were determined by adjusting the material parameters until certification criteria were matched. Table 2 shows the material property values used in the simulation.

Table 2: Material properties of one-year-old head for the computational simulation

Components	Elastic (MPa)	Poisson ratio	Density (kg/m3)	Sources
Skull	29	0.22	2150	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 (LSTC, 2009). The axial and bending damping factors are used to damp down numerical noise. The expression for force resultants, Fi, and moment resultants, Mi, includes the damping factors are as follows:

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

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

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 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, 1968):

$$G(t) = G_\infty + (G_0 - G_\infty)e^{-\beta t} \quad (3)$$

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

Anequation that has found wide acceptance for large strain inelastic analysis is the updated Lagrangian Jaumann (U.L.J.) formulation (K. J. Bathe, 1982). Here, the Jaumann stress rate is used:

$$\sigma'_{ij} = 2\int_0^t G(t-\tau)D'_{ij}(\tau)d\tau \quad (4)$$

Where the prime denotes the deviatoric part of the stress rate, and the strain rate.

3. Model Validation, Results and Discussions

ATD Experimental Test from literature and FEM validation under pendulum test conditions.

Pendulum Neck Test:

The neck validation procedure was performed by using the pendulum neck test. In this test, the neck along with head and occipital condyles joint was mounted on a rigid pendulum and hit the aluminum honeycomb. Figure 3 shows the setup for this pendulum neck test. The length of pendulum was 2 m and it was swung to an elastic stopper that made from aluminum honeycomb. The neck test procedure was validated by using two different pendulum tests set-ups. The two pendulum test set-ups are neck extension test and neck flexion test. A pendulum was developed using LS-DYNA that follow the specifications from National Highway Traffic Safety Administration (NHTSA) part 572, subpart R (12-month-old) dummy performance calibration test certification procedure. The pendulum was release and fall freely from a height to achieve an impact speed of 2.5 m/s in neck extension test and 5.2 m/s in neck extension test as measure at the center of the pendulum accelerometer at the instant contact with the honeycomb. The pendulum neck test is used to observe the velocity versus time curve and compare with the experimental acceptable range values.

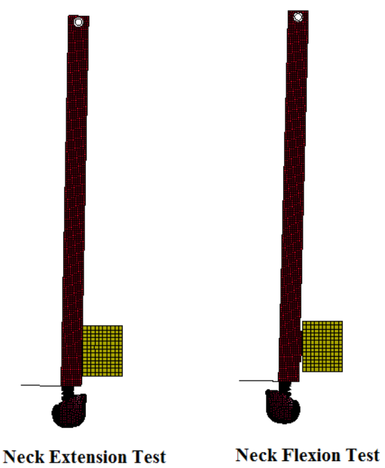


Fig. 3: Pendulum test set up

Figure 4 and Figure 5 shows the flexion test and extension test of the neck. Both head moment and pendulum velocity correspond well and still in the range of bio-fidelity corridor.

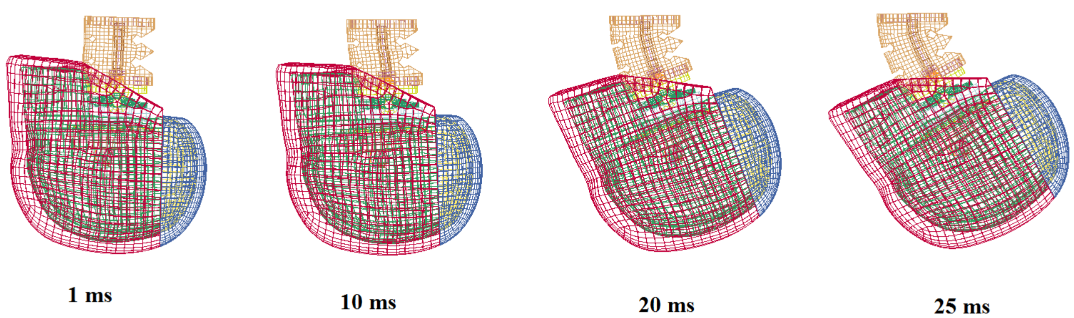


Fig. 4: Pendulum neck flexion test impact event

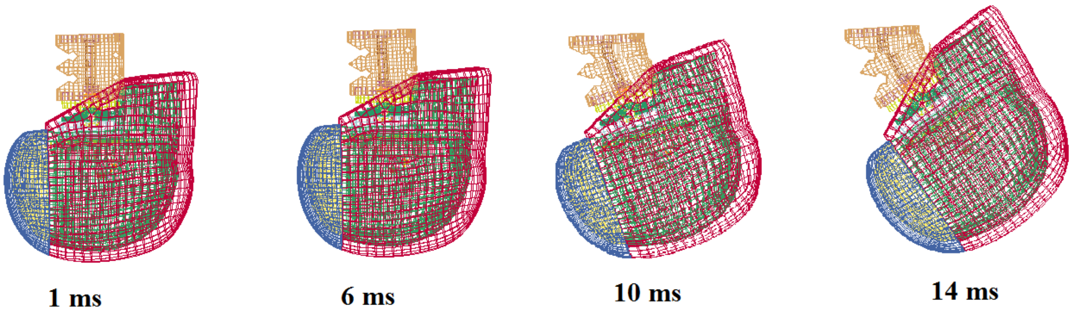


Fig. 5: Pendulum neck extension test impact event

The maximum moment of neck in flexion test is 39.38 Nm as shown in Figure 8(a). The pendulum ΔV with respect to impact velocity are 1.67 m/s when t=10ms, 4.04 m/s when t=20ms and 4.87 m/s when t=25ms. Pendulum impact velocity versus time graph of the pendulum neck flexion test was shown in Figure 6. For extension, the maximum moment of neck is -12.9 Nm. Figure 8 (b) shows pendulum impact moment (Nm) vs time (s) graph of the pendulum neck extension test of one-year-old neck. This value was acceptable since the value is still in the range of the limit. The pendulum ΔV for neck extension test with respect to impact velocity are 1.13 m/s when 6 ms, 1.99 m/s when 10 ms and 2.516 m/s when t=14ms. Pendulum impact velocity versus time graph of the pendulum neck extension test was was shown in Figure 7. The entire response and head-neck rebound were within the bio-fidelity corridor. The results obtained reveals that both flexion and extension tests are in the range of the threshold corridor.

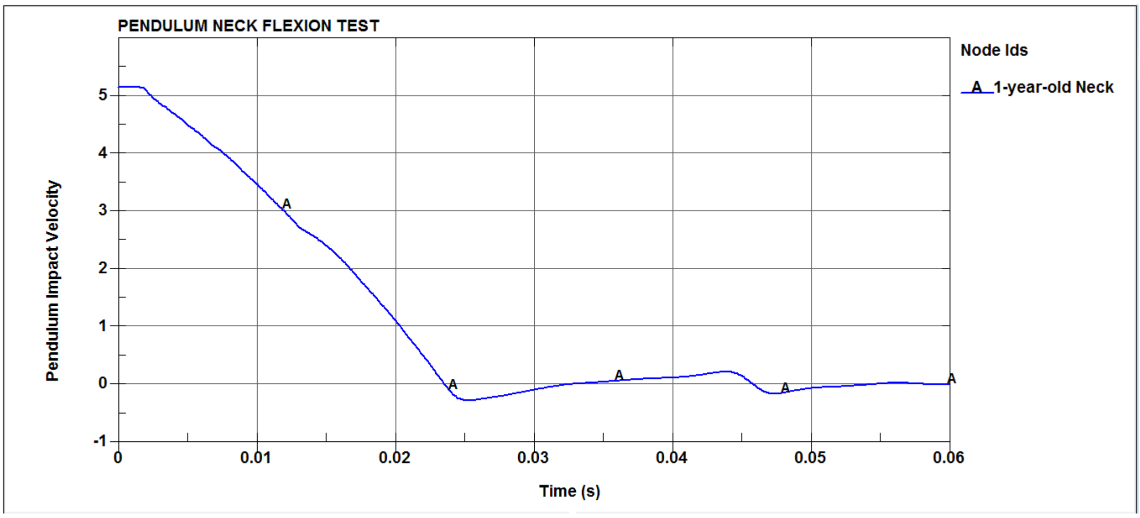


Fig. 6: Pendulum Impact Velocity (m/s) vs Time (s) graph of pendulum neck flexion test of one-year-old neck.

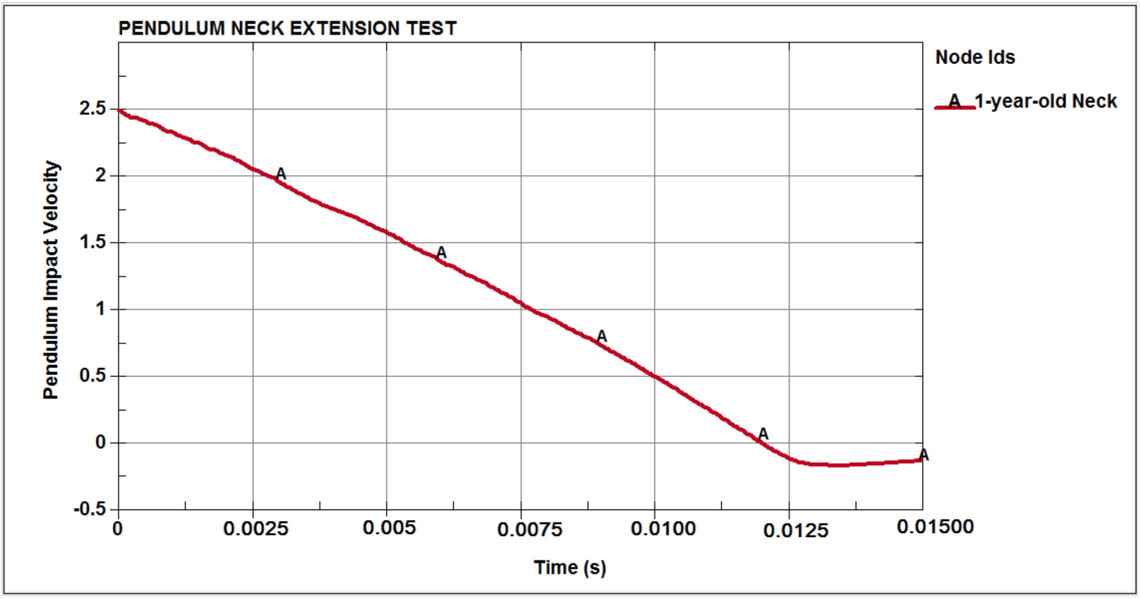
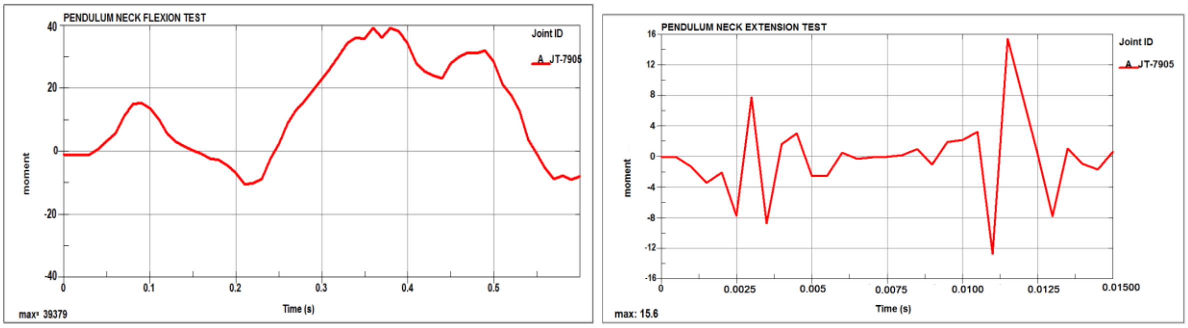


Fig. 7: Pendulum Impact Velocity (m/s) vs Time (s) graph of pendulum neck extension test of one-year-old neck.



(a) (b)

Fig. 8: Pendulum Impact Moment (Nm) vs Time (s) graph of (a) pendulum neck flexion test of one-year-old neck and (b) pendulum neck extension test of one-year-old neck

The neck-headform assembly was mounted on the pendulum so the midsaggital plane of the headform is vertical and coincides with the plane of motion of the pendulum as shown in Figure 3. The moment and rotation data channel are defined to be zero when the longitudinal centerline of the neck and pendulum are parallel. The test should be conducted without inducing any torsion of the neck. The one-year-old ATD neck-headform assembly was release with the pendulum and allow it to fall freeely to achieve an impact velocity of 5.2 ±0.1 m/s for flexion and 2.5 ±0.1 m/s for extension measured at the center of the pendulum accelerometer at the instant of contact with the honeycomb. Time-zero is defined as the time of initiol contact between the pendulum striker plate and the honeycomb hexcel.

The peak resultant moment from the neck pendulum tests are in the range with ATD experimental test results. The comparison of simulation velocity for both flexion test and extension test are tabulated in Table 3 and Table 4. The pendulum ΔV with respect to impact speed were calculated from pendulum initial impact speed (V1) and final speed at a certain time (V2). A fairly good agreement of peak moments and pendulum velocity between specification test and simulation were found for all the conditions.

Table 3: Neck Flexion Results (572.143(b)(1) & (572.153(c)(4)(ii)

Parameter		Specification	Simulation Result	ΔV
Pendulum impact speed		5.1 m/s ≤ speed ≤ 5.3 m/s	5.15 m/s	N/A
Pendulum ΔV with respect to impact speed	@ 10 ms	1.6 m/s ≤ ΔV ≤ 2.3 m/s	3.48 m/s	1.67 m/s
	@ 20 ms	3.4 m/s ≤ ΔV ≤ 4.2 m/s	1.11 m/s	4.04 m/s
	@ 25 ms	4.3 m/s ≤ ΔV ≤ 5.2 m/s	-0.03 m/s	5.18 m/s
Plane D Rotation		Peak Moment 36 Nm ≤ moment ≤ 45 Nm	39.28 Nm	N/A

Table 4: Neck Extension Results (572.143(b)(1) & (572.153(c)(4)(ii)

Parameter		Specification	Simulation Result	ΔV
Pendulum impact speed		2.4 m/s ≤ speed ≤ 2.6 m/s	2.5 m/s	N/A
Pendulum ΔV with respect to impact speed	@ 6 ms	0.8 m/s ≤ ΔV ≤ 1.2 m/s	1.37 m/s	1.13 m/s
	@ 10 ms	1.5 m/s ≤ ΔV ≤ 2.1 m/s	0.51 m/s	1.99 m/s
	@ 14 ms	2.2 m/s ≤ ΔV ≤ 2.9 m/s	-0.16 m/s	2.66 m/s
Plane D Rotation		Peak Moment -12 Nm ≤ moment ≤ -23 Nm	-12.9 Nm	N/A

Conclusion:

In this study, a biofidelic FEM of a one-year-old neck-headform was developed and compared with the one-year-old ATD experimental test data. The pendulum tests were conducted in two different tests; neck flexion test and neck extension test. For neck flexion test, the pendulum ΔV with respect to impact velocity are 1.67 m/s when t=10ms, 4.04 m/s when t=20ms and 4.87 m/s when t=25ms. For neck extension test, the pendulum ΔV with respect to impact velocity are 1.13 m/s when 6 ms, 1.99 m/s when 10 ms and 2.516 m/s when t=14ms. The maximum moment of neck in flexion test is 39.38 Nm and for extension, the maximum moment of neck is -12.9 Nm. The entire response and head-neck rebound were within the bio-fidelity corridor. The results obtained reveals that both flexion and extension tests are in the range of the threshold corridor.

As a conclusion, a FEM of the one-year-old neck was developed in this study, and was validated against experimental data in terms of velocity and moment.

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