THREE YEARS OLD CHILD NECK FINITE ELEMENT MODELISATION

Raphaël Dupuis
Frank Meyer
Rémy Willinger
Université Louis Pasteur
France
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ABSTRACT

Despite of recent progresses in occupant safety, the protection of children are not still optimal. To offer a better understanding of child injury mechanisms, the present study proposes a human-like finite element model of a three years old child's neck. The subject was scanned with a medical scanner. The images were first semi-automatically segmented in order to extract the soft tissues and the bones. In the second step, we separate the different bones slice by slice on the geometry previously reconstructed. The anatomic structures are identified and each vertebra is reconstructed independently with special attention for the articular process. In a second step, we have generated a original meshing on the previous geometry to obtain a finite element model of the child's neck. The anatomical structures incorporated are the head, the seven cervical vertebrae (C1–C7), the first thoracic vertebra (T1), the intervertebral discs and the principle ligaments which are modelled using non-linear shock-absorbing spring elements. The stiffness values used are taken from literature, and scaled down using scale factors from Irwin. This model incorporates 7340 shell elements to model the eight vertebrae, the head and 1068 solid 8-node elements to model the intervertebral discs. Contact between the articular surfaces is represented by interfaces permitting frictionless movement. Since this study does not aim to reproduce bone fractures, we have modelled the cervical vertebrae as rigid bodies.

A scaling factor for the intervertebral discs modulus of 0,705 is supposed by Yoganandan for the 3 year old child, this values conduce to disc modulus of the order of 100 MPa.

Given that validation data were not available, the model validation was conduced against Q3 dummy component sled tests. The accelerometric responses of the head model were similar with those recorded experimentally with a Q3 dummy neck in rearward, frontal and lateral impact direction.

INTRODUCTION

Each year, more than 700 children are killed on European roads and 80.000 are injured. The EC project CHILD (Child Injury Led Design) aims to improve the protection offered to children in cars by increasing the understanding about the injuries sustained and providing innovative tools and methods for improvement of Child Restraint Systems (CRS) in cars.

One of the tools developed is a three year old child head and neck finite element model. If some models are existing in the literature like Van Ratingen's [1] or Yoganandan's [2] model, they differ largely in term of purpose and methodology.

Multi-body Child Neck Model

Child multi-body neck finite element models are mainly models developed under MADYMO. Thus, TNO developed 3, 4, 5, 6, 8, 10 and 12 year old child models usable in automotive crash test reconstruction. The models are carried out by the assembly of cylinders, ellipsoids, parallelepipeds connected to each other by joints with one or more degrees of freedom and different stiffness according to mobility.

The models were validated by reproducing the tests carried out on Q serie dummies. A scaling was conduced on corridors resulting from the tests on volunteers and PMHS carried out by Mertz and Patrick [3] and Patrick and Chou [4]. Corridors of validation [1, 5] were then considered as the reference for the child (see figure 1).

The three year old child MADYMO model is most recent child model. It was developed by TNO in parallel of the Q3 dummy. Its validation was conduced within the framework of the EC CREST project. The Q3 model is directly issued from the dummy CAD. The head/neck elements were similar to those of the dummy.

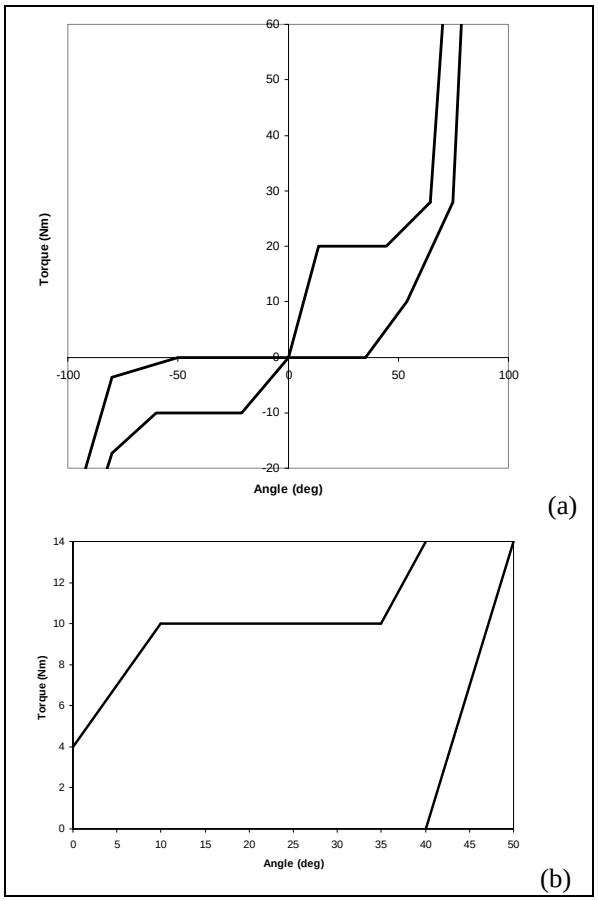

Figure 1. Corridor of behaviour of the Q3 neck dummy in term of moment/angle of flexion in flexion/extension (a) and lateral inflection (b) [1].

The validation was carried out by reproducing tests on the model similarly as previously realised on Q3 in frontal, rearward, lateral direction and of pendulum test. The stiffness and the damping coefficients of the various articulations were then tuned to adjust the dummy response.

Detailed Finite Element Models

Only two child human like cervical spine models were founded in the literature.

The first was that developed by Kumaresan and Yonganandan [2]. They developed three finite element models for three different ages: 1, 3 and 6 years. These models were limited to the cervical C4-C6 segment and resulted directly from the adult model [6-8]. It has to be noticed that this adult model was developed in order to realize static simulations. Three types of model construction were adopted: first a pure geometrical scaling, then the introduction of anatomical specificities without any scaling, and finally a method where the two preceding approaches were combined.

This first approach consisted in a pure geometrical scaling of the adult finite element model. No geometrical modification and no anatomical specificity according to the age were introduced in the model. Comprehensive laws of the ligaments and the discs were not scaled, but maintained similar to those of adult.

For calculation and meshing reasons (divergence of the model), it was impossible to conduce a "scaling down" of the model, i.e. a scaling factor lower than 1. In order to solve this problem, they decided to realize a "scaling up" at 120%, 140%, 160% and 180%. The results were then extrapolated by supposing that the answer is linear according to the coefficient of scale and thus of the age.

With this methodology, they decided not to apply any scale factor to the geometry of the adult. Its dimensions were thus identical to those of the adult. In the other hand, some modifications of the mechanical characteristics of different the component was applied according to the age (see table 1).

Table 1.
Description of the geometrical specifications incorporated by Kumaresan [2] in the Yoganandan's adult model according to the age.

	1 year old	**3 year old**	**6 year old**
Spinous process	Growth cartilage present	Fused	Fused
Transvers process	Costal growth cartilage present	Costal growth cartilage present	Costal growth cartilage fused
Neuro-central cartilage	Present	Present	Missing
Growth cartilages of superior and inferior plate	Presents	Presents	Presents
Articular facets angle	60°	53°	48°
Unciform apophysis	Missing	Missing	Missing
Discal fiber percentage reported to the adult	80%	85%	90%
Nucleus volume compared to disc volume	90%	85%	80% (idem as adult)
Ligamentar stifness compared to the adult's	80%	85%	90%

It should be noted that all anatomical specificities integrated in the finite element model result directly from medical observations. The ligament stiffness or the volume of nucleus were selected to study the influence of these parameters.

In this last approach, Kumaresan [2] coupled the two preceding approaches, i.e. to carry out a geometrical scaling, to modify the mechanical characteristics of the ligaments and discs, and to integrate anatomical specificities according to the age.

The comparison of the three types of models was done in static by applying either a compressive force (100N and 400N), or a couple (0,25Nm and 1Nm) at the top of C4, and by measuring the variation of principal mobility compared to that of the adult.

It appeared that there was a rigidification of the rachidian segment studied according to the age, the 1 year old child being much more flexible than the 6 year old child. Moreover, it has been noticed that the independent parameters which lead to the strongest increase in mobility were anatomical specificities and new comprehensive laws (approach 2), rather than simple dimensional scaling (approach 1), the combination of the two approaches (approach 3) being that which increased more mobility.

Nevertheless, even if the tendencies observed seemed to be in conformity with the experiment results on animals [9, 10], no experimentation on child is available to validate these results quantitatively, limitation which the authors concede readily. Even if these models were finally not validated, it should be retained that the inclusion of geometrical specificities of the child can offer comprehension of the injury mechanisms.

The other three year old child finite element model founded was that developed by Mizuno [11] by scaling from a Total Human Model for Safety (THUMS) AM50human finite element model to investigate the potential injury risks from restraints. The geometrical scaling factors were chosen so that λ_x, λ_y, λ_z have values as similar as possible, and the material properties scaling factors were determined in the literature [12, 13]. The model has been validated for thorax impact according to Hybrid III 3YO dummy requirements. No information are available on neck validation.

MATERIAL AND METHODS

Geometrical reference

A three year old male child was scanned with a ELSCINT Helix 3.0 (Elscint Ltd., Ma'alot, Israel) scanner, in order to realize a medical exam. The slice thickness was 1.1 mm with a table feed of 1 mm (pitch 0.9). After insuring that no abnormality was detected, and after depersonalising the exam, the images were first semi-automatically segmented in order to extract skin and bones. This stage was conducted at IRCAD from software developed in partnership with the Epidaure project of INRIA for the automatic 3D patient reconstruction [14-16], and provided us a rapid and precise result [17] but no differentiation between the vertebrae was obtained (see figure 2).

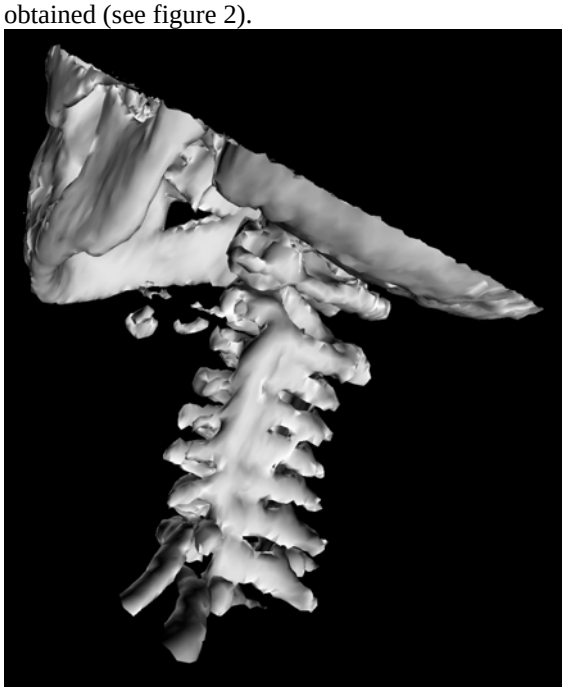

Figure 2. Fully automatic reconstruction of the spine. All vertebrae are virtually stuck together, due to little thickness of the intra articular space..

In a second step, we separated the different bones slice by slice on the previously reconstructed model. Anatomical structures were identified (specifically the articular process) and each bone (i.e. the seven cervical vertebrae, the inferior part of the skull and the mandible) was reconstructed individually (see figure 3). The whole model was exported into a VRML format to be readable on any computer with freeware. The physical bone model was obtained using the FDM (fused deposition modelling) technology on a Prodigy Plus machine (Stratasys Inc., Eden Prairie, MN). The physical model realized in ABS polymer (see figure 4) was strong and durable, and the model accuracy compared with CT scan slices was inferior to 0.8 mm on the main dimensions.

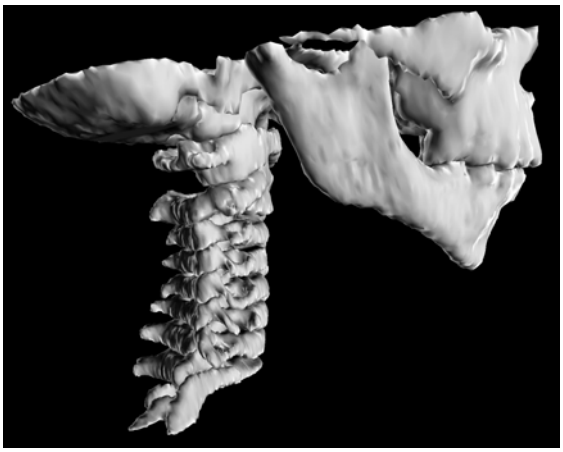

Figure 3. Complete reconstruction of the cervical spine of a three year old child: front and right view. All bones are separated and can be visualized independently.

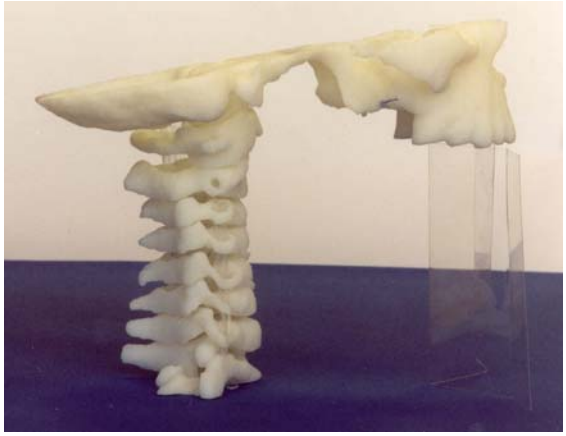

Figure 4. Physical model of the cervical spine of a three year old child. Global lateral view including skull base (C0).

Finite element modeling

In order to stick to our geometrical reference, we deformed and remeshed the geometrical meshing of an existing adult model [18]. The anatomical structures incorporated and illustrated in figures 5 to 8 are the head, the seven cervical vertebrae (C1–C7), the first thoracic vertebra (T1), the intervertebral discs and the principle ligaments, including the anterior longitudinal ligament (ALL), anterior-atlanto occipital membrane (AA-OM), posterior-atlanto occipital membrane (PA-OM), techtorial membrane (TM), posterior longitudinal ligament (PLL), flavum ligament (LF), supraspinous ligament, interspinous ligament (ISL), transverse ligament (TL), alar ligament (AL), capsular ligaments (CL) and the apical ligament (APL).

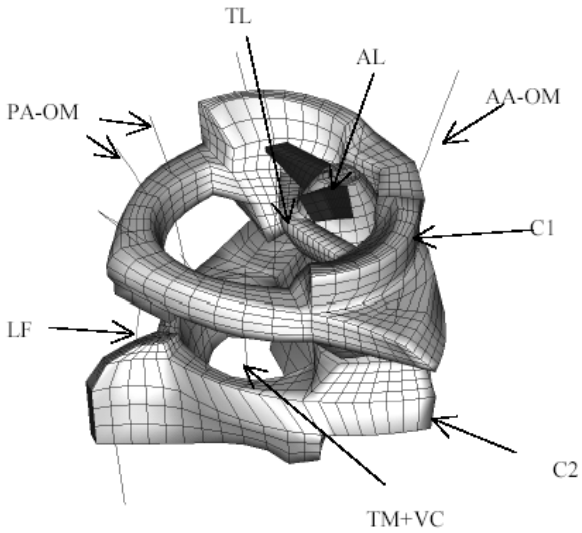

Figure 5. Ligamentary system of the upper cervical spine (C1-C2).

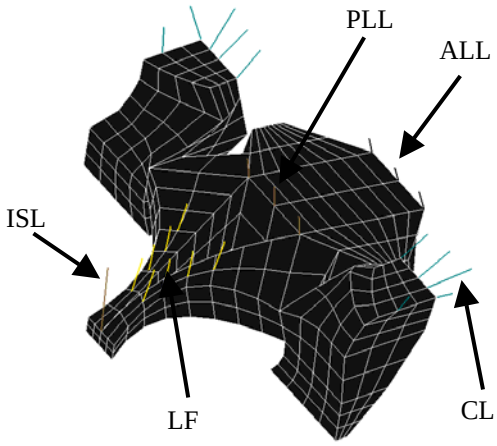

Figure 6. Ligamentary system of the lower cervical spine (C3).

These are modelled using non-linear shock-absorbing spring elements. The behaviour laws of each ligament in both the lower and upper cervical spines, are defined by referencing to three complementary studies: Myklebust [19], Chazal et al. [20] and Yoganandan et al. [21]. The Chazal et al. study [20] highlights the non-linear viscoelastic behavior of ligaments whereas Yoganandan et al. [21] gives information on their failure properties. The overall behavior of the ligaments can then be characterized by three pairs of coefficients α_1, α_2, α_3 determining the zone of low rigidity or neutral zone, the linear part, and finally the plastic behavior. The coefficients used for our model are described in Table 2 and a representation of the typical behavior of the five ligaments of the lower cervical spine is illustrated in figure 9.

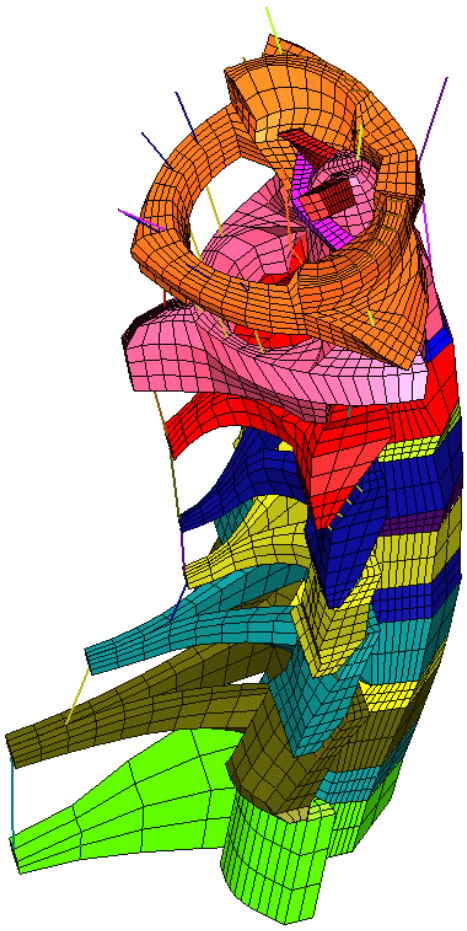

Figure 7. Surface meshing of the cervical spine (C1-T1), including its ligamentary system.

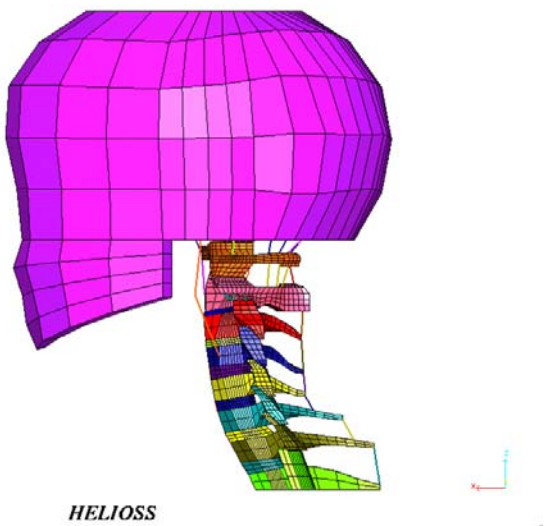

Figure 8. Complete finite element model of the head and neck complex of a three year old child.

Table 2.
Coefficients used to define the ligaments constitutive laws [20]. The rupture strengths are taken from Myklebust [19].

	A (α_1)		B (α_2)		C(α_3)
	$\varepsilon/\varepsilon_{max}$	F/F_{max}	$\varepsilon/\varepsilon_{max}$	F/F_{max}	ε_{max}
ALL	0,21	0.11	0,78	0.87	0,58
PLL	0,25	0.12	0,77	0.89	0,45
FL	0,28	0.21	0,76	0.88	0,21
ISL	0,3	0,17	0,75	0,87	0,4
CL	0,26	0.15	0,76	0.88	0,41

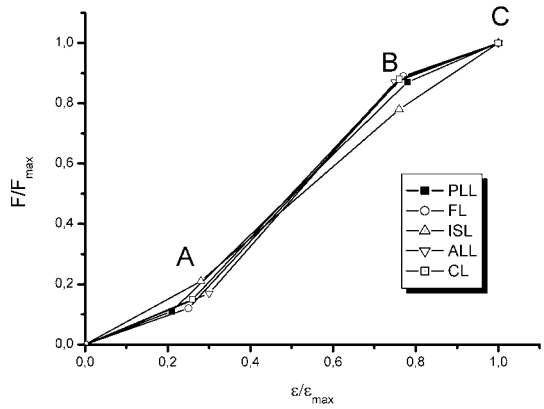

Figure 9. Behaviour laws of the anterior longitudinal ligament (ALL C2-C5), posterior longitudinal ligament (PLL C2-C5), flaval ligament (FL C2-C5), interspinous ligament (ISL C2-C5), capsular ligament (CL C2-C5) [20, 21].

In order to take into account the initial lengths of the ligaments in the model as well as those measured anatomically by Yoganandan et al. on the lower cervical spine [21] we calculated the laws as follows :

$$\begin{cases} d_i = L_o * \alpha_{\max} * \alpha_i \\ F_i = F_{\max} * \alpha_i \end{cases} \qquad i = 1,2,3.$$

Where L_0 is the initial length of the ligament and d_i its deformation.

According to Irwin [12] and Yoganandan [25] scaling factors, all ligament behaviour laws were scaled in term of force.

The total height of the model is 17,3 cm and its weight is 4,57 kg. This model incorporates 7340 shell elements to model the eight vertebrae, the head and 1068 solid 8-node elements to model the intervertebral discs. Contact between the articular surfaces is represented by interfaces permitting frictionless movement. Since this study does not aim to reproduce bone fractures, we have modelled the cervical vertebrae as rigid bodies, taking their

inertial moments and masses from Deng [22] and scaled down using scale factors from Irwin [12] (see table 3).

Table 3.
Cervical vertebrae inertial properties applied to the center of gravity.

Name	Mass [g]	Ixx [g.mm²* 10^4]	Iyy [g.m²* 10^4]	Izz [g.m²* 10^4]
T1	78.5	0.846	0.626	0.129
C7	58	0.763	0.328	0.965
C6	58	0.763	0.328	0.965
C5	50	0.636	0.210	0.753
C4	56	0.773	0.221	0.897
C3	70	0.816	0.325	1.01
C2	86	0.902	0.662	1.24
C1	57	1.28	0.36	1.58

Most models use an elastic law for the intervertebral discs and a wide range of Young's modulus values has been observed, varying from 3,4 MPa in Yoganandan's [21] model to 4,3 MPa for that of Golinski [23] and 200 MPa for that of Dauvilliers [24]. A scalling factor of 0,705 given by Yoganandan [25] for the 3 year old child intervertebral disc is supposed, this values conduced to adopt a disc modulus of the order of 100 MPa.

Model validation

Given that validation data in term of acceleration were not available and that sled tests were only realized on full complete dummy, we were obliged to realize some Q3 dummy component sled tests (see figure 10). Therefore, the base of the Q3 dummy neck was fixed on the sled. A set of three accelerometers was attached to the dummy head to measure linear acceleration. The sled is accelerated in rearward, frontal and lateral direction.

In order to reproduce the experimentation with the numerical model, the model was controlled in terms of first thoracic vertebra speed (see figure 11 and 12).

Figure 10. Q3 dummy component sled test on head and neck.

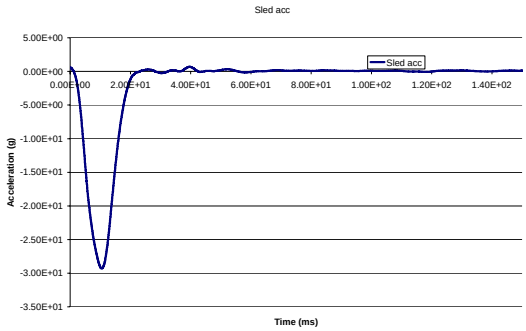

Figure 11. Sled acceleration in frontal impact.

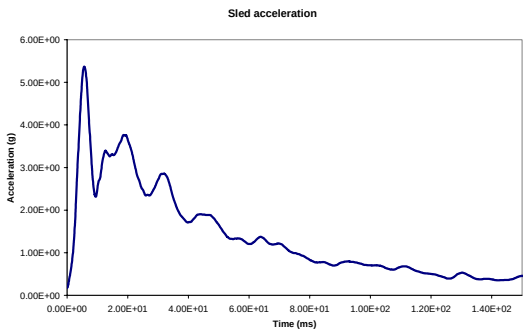

Figure 12. Sled acceleration in rearward impact..

Head linear acceleration values were computed and compared with those recorded experimentally.

RESULTS

The parameters of the model has been tuned in order to fit to the experimental results as shown in figure 13 and 14 for rearward impact, and in figure 15 and 16 for frontal impact. The results in lateral impact hasn't been presented as it will be discussed later.

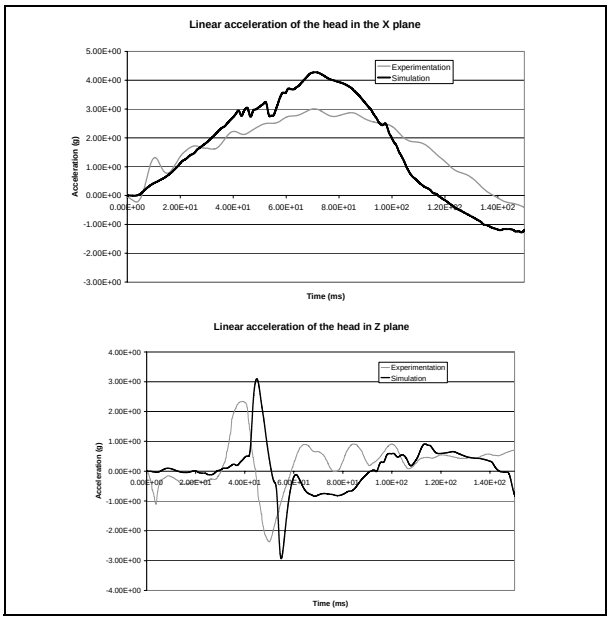

Figure 13. Linear acceleration of accelerometers in rearward impact: experimental data vs. numerical results.

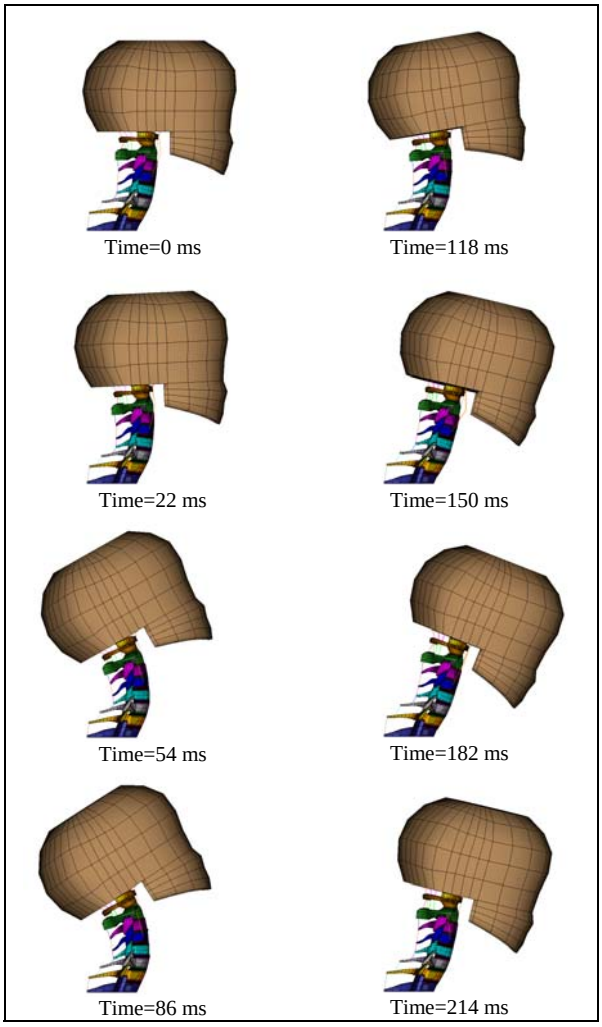

Figure 14. Model configurations in rearward impact

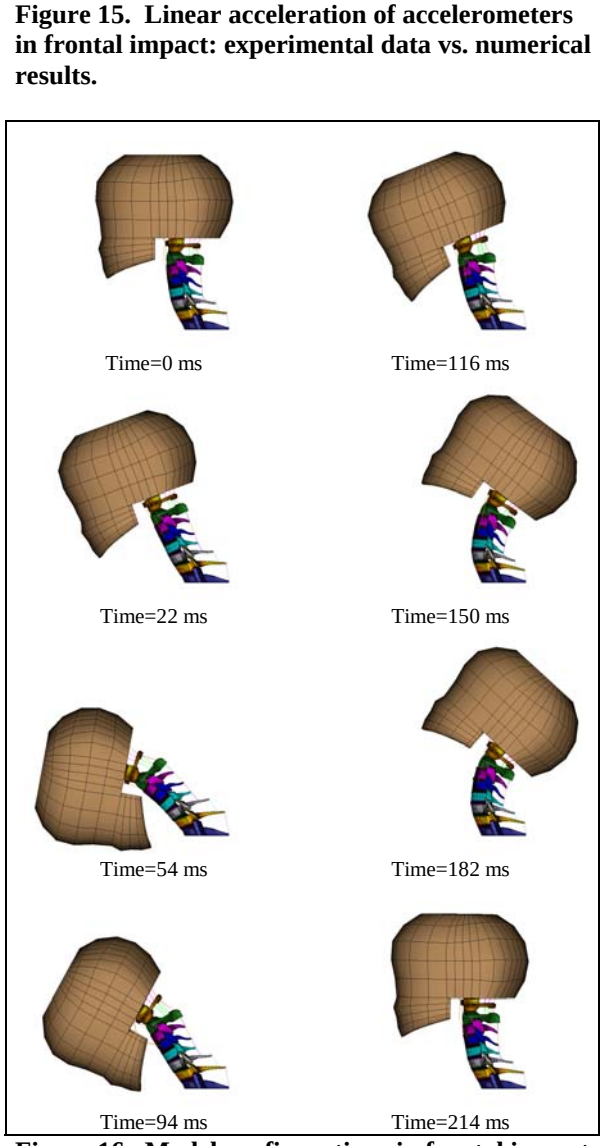

Figure 15. Linear acceleration of accelerometers in frontal impact: experimental data vs. numerical results.

Figure 16. Model configurations in frontal impact

It can be observed that in rearward impact, the model correctly reproduce the acceleration of the head dummy center of gravity. The first peak amplitude present a good correlation in both the X axis and in the Z axis. The temporal position of this peak is also very near to the experimental's, with a little late on the Z axis.

In frontal impact, we can notice that in the first milliseconds after impact, the experimental and numerical curves are completely superposed, and that the peak amplitude is similar for the X axis.

However, the parameter set is not suitable to reproduce the behaviour in lateral impact. Indeed, if the results in term of acceleration are correct among X and Y axis during the first fifty milliseconds, the acceleration in Z direction is incorrect. No parameter set has been founded to reproduce at the same time the Q3 neck dummy comportment in frontal and rearward impact, and in lateral impact

DISCUSSION

The main discussion concerning the method is the validation of the model with regards to a dummy. In fact, no in-vitro or in-vivo experimentation on children neck has never been conduced. The data usable for infant finite element model validation are never "first hand" data, but only obtained by scaling adult results. The scaling coefficient of mechanical properties are based on three in-vitro tests (2 newborns and a 6 year old child) on parietal bone. With the inter-individual variation on human mechanical properties, we can wonder about the credibility of these scaling factors. That's why we decided to use the Q3 dummy as reference, because it proved its reliability in accident reconstructions that offers good correlation with injuries (EC CREST and CHILD program). We can notice that the methodology used by Mizuno [11] to validate its three year old child model is the same, even if it was on the torso. All this comfort us about our method.

The choice of the geometrical reference to realize our finite element model meshing can also be discussed. The medical scanner was realized on a three year old child, and because of anonymisation procedure, we didn't have information about its corpulence (weight, height…). However, it appeared us that it was a better solution to remesh a geometrical reference, than to apply a pure scaling on an adult model, moreover with similar scaling factor in the three direction as made Mizuno [11].

CONCLUSION

A three year old child human like neck finite element model was developed, based on a three year old child medical scanner. The model include intervertebral discs and almost all intervertebral ligaments. It was compared with Q3 dummy neck that was validated with regards to scaled NDBL corridors. The three year old child neck finite element model validation was performed in frontal and in rearward impact. The model will be used for accident reconstruction in order to evaluate local injuries and to provide basis for injury criteria.

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