"Relaxed" HBM – an Enabler to Pre-Crash Safety System Evaluation

Chintan Shelat, Pronoy Ghosh, Ravikiran Chitteti, Christian Mayer

Abstract This research addresses relaxation of existing human body finite element (FE) model, i.e. classical THUMS-D in LS_DYNA. The methodology discussed identifies proposed corridors for relaxation; modifications carried out to model pertaining to relaxation and verify the simulations based on 1 g frontal braking pulse. "Relaxed" THUMS-D delivers fairly good response in terms of head excursions. This model is able to deliver a response within the defined corridors after inclusion of Active Muscles. The modifications carried out to the model comprised of elastic moduli, connection in head-neck complex and connections between spine and skin. "Relaxed" THUMS-D model in totality delivered more head excursions compared to the defined corridors without any muscle activity.

Keywords Relaxation, active HBM, muscle, viscoelastic, frontal braking.

I. INTRODUCTION

The increasing shift in automotive safety towards the use of active safety systems has opened up avenues for development of tools to supplement the assessment of such systems. The current developments are oriented towards integrated safety, which requires models suitable for both pre-crash and in-crash phases. Consequently, Human Body Models (HBMs) form one such innovative pre-requisite to assess these systems in a virtual tool chain. HBMs have been traditionally developed for crash simulations and are not sufficient for the requirements of pre-crash in two aspects: (1) muscle activity; and (2) soft tissue response in pre-crash phase. This is concluded based on previous research conducted on THUMS version 3 and its derivatives like THUMS-D (refer figure 1 & 2) where these models were found to yield stiffer response in pre-crash phase [1] [2]. These models originally lacked in active muscles and even on addition of active muscles, head and torso excursions illustrated in figure 1 & 2 did not significantly altered. This indicated that THUMS version 3 & its derivative models were not sensitive and required to be softened to be suitable for pre-crash scenarios.

Hence, there is a need to develop a model which possesses good prediction capabilities in pre-crash environment and the data like position, velocities, stresses etc. can be then transferred to crash phase evaluation. The first step undertaken to achieve this was reducing the stiffness of these models which were developed and validated to suit requirements of crash. This process of reducing the model stiffness is referred to as "Relaxation" in this study. Once the relaxation is achieved, the developed active muscle model [1] could be added to simulate very realistic human behaviour for the pre-crash phase. The term "relaxation" of a human body is not well defined in context of human response under influence of deceleration frontal pulse. "Relaxation" can have different meanings in different contexts. For the purposes of this particular study, however, it is defined as the state of human occupant with only passive muscle activity. This state is expected to be different from the response of a cadaver and is expected to be closer to that of a human being, e.g. sleeping occupant in a driven vehicle. This state of occupant is expected to involve only the effect of passive response of the muscles (primarily mechanical properties of the muscles or with significantly low muscular activation).

Previous researchers [3] [4] have conducted modifications in the existing THUMS model to make it more suitable for the pre-crash phase. These modifications involved changing the connection between vertebra and the soft tissues, reducing stiffness of the soft tissues, etc. However, the issue of relaxation was not addressed methodically.

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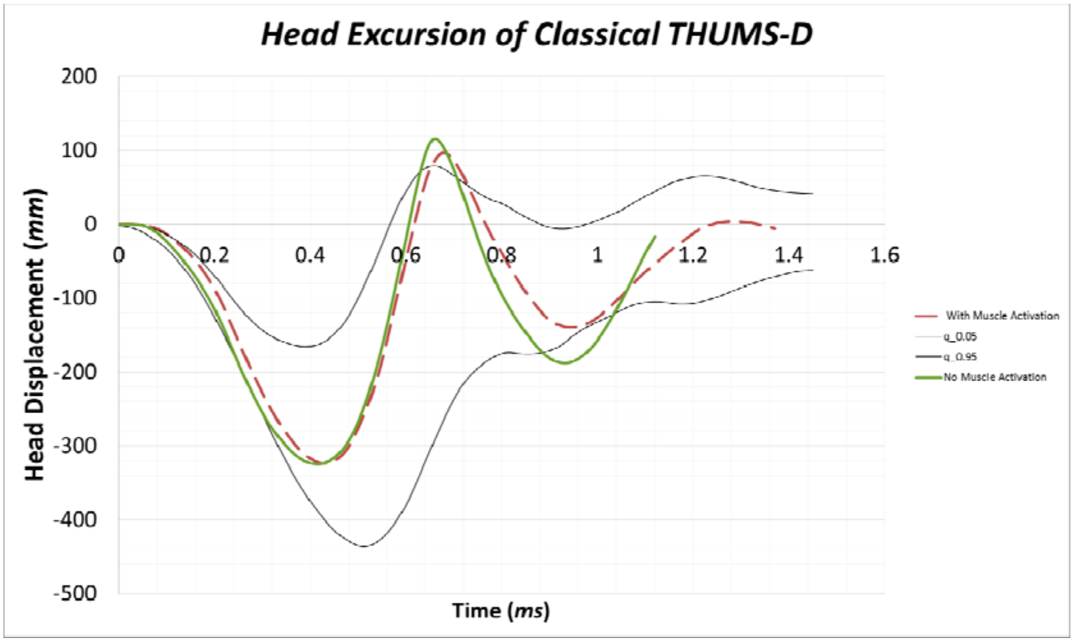


Fig. 1. Head Excursion of Classical THUMS-D in 1*g* braking pulse.

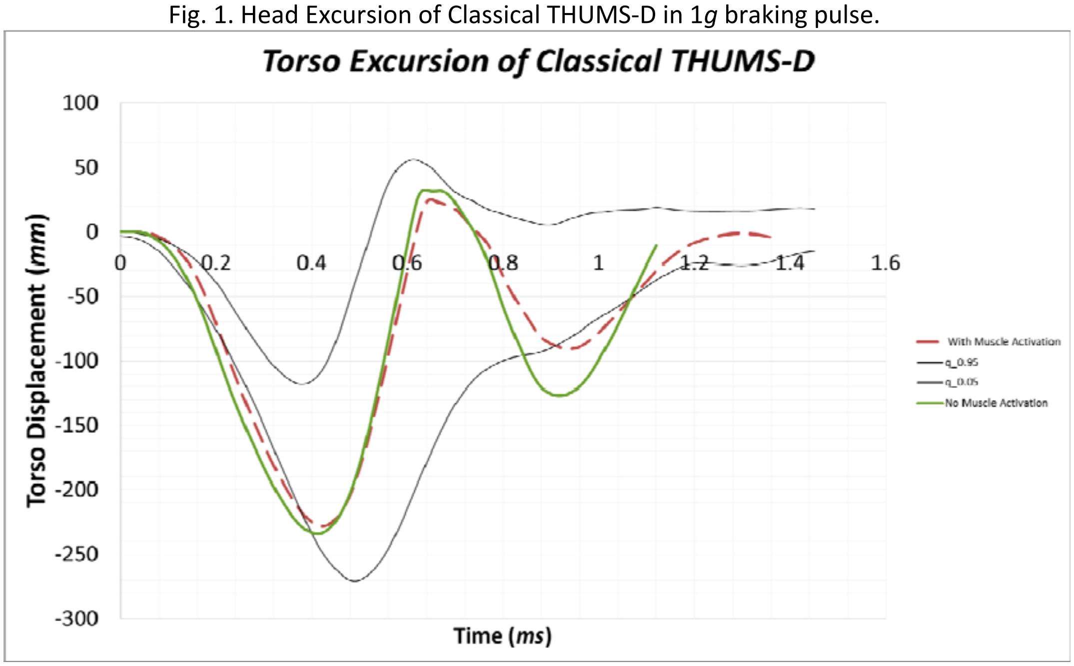


Fig. 2. Torso Excursion of Classical THUMS-D in 1*g* braking pulse.

The focus of this study is to modify the existing HBM and ensure that it is sensitive to the addition of active musculature in pre-crash phase simulations. In the pre-crash phase, there are no injuries that are anticipated to the vehicle occupant therefore, soft tissue response should primarily be modified to achieve valid kinematics of the vehicle occupant.

II. METHODS

The approach undertaken in this study can be segregated into four sections, described in turn below.

1. ***Classical THUMS-D Human Body Model***: The HBM used and modified to achieve a relaxed response in this study is the THUMS-D 50th percentile occupant model. The THUMS-D model represents a mid-size adult male occupant FE model, whose height and weight are 175 cm and 73.5 kg, respectively. The model is derived from THUMS version 2. This model was previously modified for in-house Daimler AG usage. The modifications conducted on this model involved mesh refinement in several body regions, connections in lower extremities and implementation of a new shoulder model. The

modification and validation of the model is discussed in detail in our previous studies [5-6]. This model is henceforth, in the study is referred as classical THUMS-D as it was developed for the crash phase. Figure 3 below illustrates the classical THUMS-D model used for creating “Relaxed” THUMS-D.

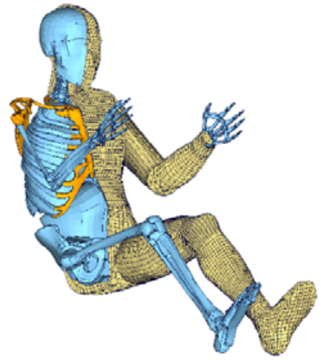


Fig. 3. Classical THUMS-D model.

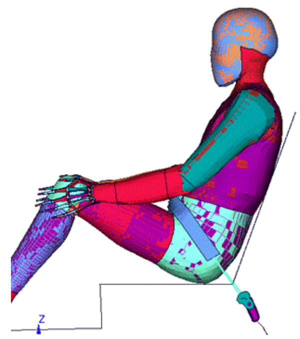


Fig. 4: Load case for relaxation.

2. ***Modifications in Classical THUMS-D to create “Relaxed” THUMS-D***: Next step was to adopt an approach that could lead to such modifications as would give the “Relaxed” THUMS-D. For this, two factors were deemed of high importance:
   a. minimum changes in terms of connections and removal of organs;
   b. Material modifications within physiological limits.

   The changes carried out to the model are described below.

   Model-specific Modifications

   - Head-to-Neck flesh mesh was improved as the internal nodal connections were poor. This modification may not always be applied to other models, but in the case of classical THUMS-D the internal nodal connections were not properly attached. Hence, a new mesh was created ensuring smooth flow of mesh from Head to Neck to Torso. Figures 5 and 6 illustrate the head-neck connectivity of Classical THUMS-D and “Relaxed” THUMS-D. The overall mass of the head-neck was maintained at 5.56 kg and centre of gravity and inertia were ensured to be within 5% of the base values.

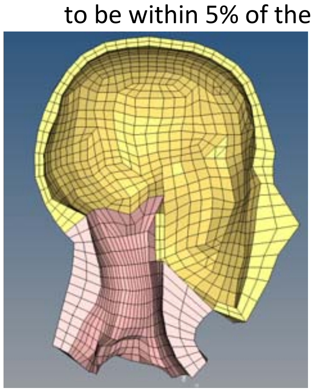


Fig. 5. Classical THUMS-D head-neck connection.

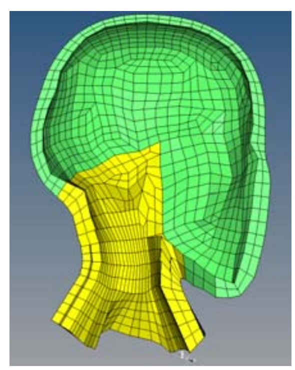


Fig. 6. “Relaxed” THUMS-D head-neck connection.

Generic Modifications

- Skin to Vertebrae connections was removed.
- All the muscles were deactivated (Passive) but kept in the model.
- Material properties were modified for certain body regions.

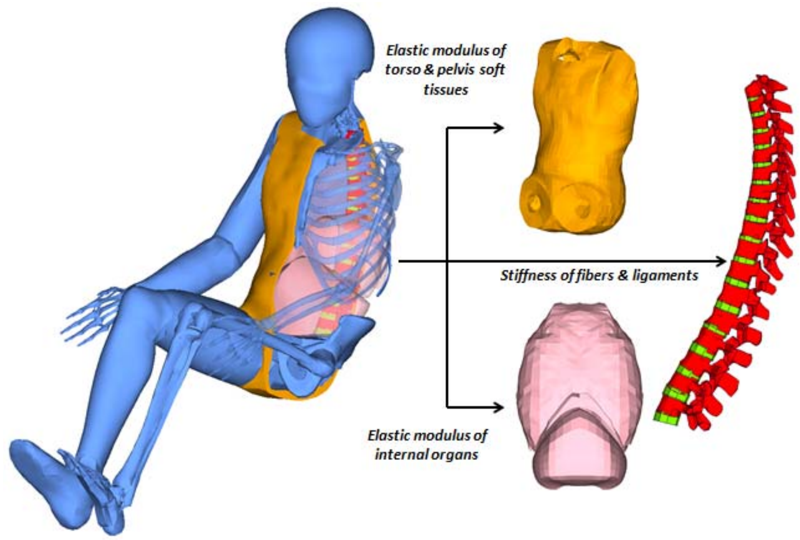


Fig. 7. Modifications in material properties conducted in torso region for model relaxation.

The material modifications were restricted only to changing the elastic moduli in material properties to ensure that minimum modifications were conducted in classical THUMS-D. The information pertaining to these values was obtained from past research works. Figure 7 illustrates the regions of the body where the modifications were conducted whereas Table illustrates the lowest levels of elastic modulus's available for different body regions. An objective of the current study was to get higher head and torso excursions for the classical THUMS-D, therefore lower values of elastic modulus's than those existing in the classical THUMS-D were considered. However, a detailed Design of Experiments (DOE) was conducted to understand the influence of various parameters.

			All Values in GPa	
Part	**Parameter**	**Existing Value**	**Lowest**	**Source**
Thorax Skin	Bulk Modulus	0.01	0.0029	[4]
Thorax Fiber	Scale Factor	1	0.006	[11]
Thorax Ligaments	Scale Factor	1	0.013	[12]
Thorax Annulus Inner	Elastic Modulus	0.0001	--	--
Thorax Annulus Outer	Elastic Modulus	0.013	3.40E-03	[13]
Thorax Nucleus	Elastic Modulus	0.000013	--	--
Lumbar Fiber	Scale Factor	1	0.006	[11]
Lumbar Ligaments	Scale Factor	1	0.013	[12]
Lumbar Annulus IN	Elastic Modulus	0.0001	--	--
Lumbar Annulus OUT	Elastic Modulus	0.013	3.40E-03	[13]
Lumbar Nucleus	Elastic Modulus	0.000013	--	--
Pelvis Inner Solids	Elastic Modulus	0.002296	1.36E-04	[14]
Pelvis Inner Shell	Elastic Modulus	0.02	1.36E-04	[14]
Upper Abdomen Solids	Elastic Modulus	0.0016	2.50E-05	[14]
Lower Abdomen Solids	Elastic Modulus	0.0384	4.50E-05	[14]
Upper Abdomen Shell	Elastic Modulus	0.00168	2.50E-05	[14]
Lower Abdomen Shell	Elastic Modulus	0.022	4.50E-05	[14]
Buttock Skin	Bulk Modulus	0.005	2.90E-03	[4]

Table 1. Literature survey of material parameters for various body organs.

The body parts which were studied in the DOE involved skin stiffness, fibre stiffness & internal organs for the effect on the response. Skin stiffness had maximum influence following internal organs, disc and fibres. All parameters had a positive correlation with the excursions, however, only skin stiffness and internal organs were found to have maximum impact. The reason could be the contribution of the fibres of spine was not as significant, possibly due to either differences in stiffness values of skin and spine or modelling of the spine. The spine in case of classical THUMS-D comprises of rigid vertebras and deformable discs.

3. ***Load Case for Validation of "Relaxed" THUMS-D***: The model was relaxed based on load case derived from the OM4IS project data [7]. The load case is illustrated in Fig. 4 above. The original experiments were conducted using different configurations, such as frontal braking, lateral manoeuvre and combined manoeuvre. In the volunteer tests conducted in OM4IS, no marker trajectories were available in the lumbar spine. Therefore, occupant kinematics was not captured in pelvis region. However, from video recordings no major sliding motions were identified [7]. As no significant movement was observed in the pelvis region, the seat base angle in the simulation model was therefore considered as 0^o. However, in volunteer tests the base was inclined at 10^o with respect to the horizontal. All the other dimensions for the simplified sled were maintained as per the requirements of the tests. The configuration considered for this study involves only a lap-belt on a rigid seat, with the vehicle deceleration of 1 g at low speed of 12 km/h.

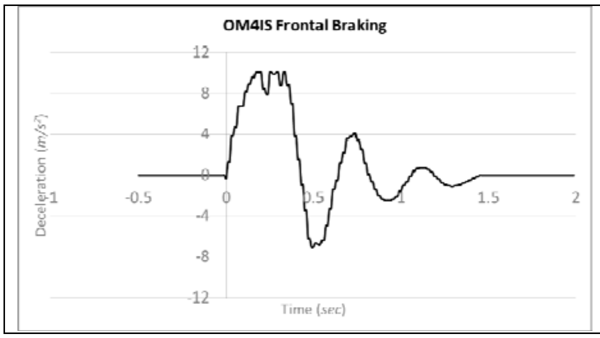


Fig. 8. Frontal 1 g braking pulse.

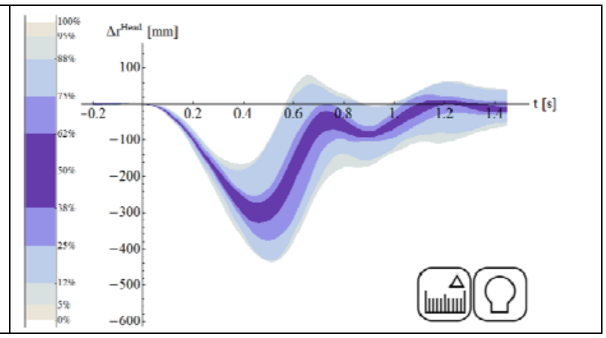


Fig. 9. OM4IS Corridors for 1 g frontal braking.

This configuration of experiment was designed to validate future Active HBMs in a simplified environment. The load case for the simulation environment was reduced to a simplified rigid sled model with the classical THUMS-D positioned, with only a belt, on a rigid sled and subjected to a 1 g braking pulse (low speed, 12 km/h). The frontal braking 1 g pulse assigned to the simplified sled model is shown in Fig. 8. Figure 9 above illustrates the corridors of head forward excursion of the volunteer over time. Similar corridor was also created for the torso region.

4. ***Corridor Development for "Relaxed" THUMS-D***: The OM4IS project provided head excursion quartiles for all the volunteer data for low g. The data was divided into three groups by the awareness of the volunteer, i.e. aware, anticipated and unaware. These corridors define the movement of a volunteer under the influence of a 1 g frontal braking pulse. This is a global response corridor encompassing anthropometric differences and various levels of muscle activity in the volunteers. However, these corridors might not completely suffice to the requirements of relaxation due to this existing muscular activity in all the volunteers. Therefore, before relaxing the classical THUMS-D, an attempt was made to define a relaxation corridor (a region that could define the bounds of a volunteer where there is minimal muscle activity) built on the developed head excursion quartiles. Three approaches were considered for the creating such corridor
    a. Standard Deviation – creating a 1- standard deviation corridor based on existing data;
    b. Characteristic Curve [8] – technique described by [9] was used to develop corridors. A one-standard deviation range was used in both displacement and time;
    c. Quartile Approach – outer bounds, i.e. extreme 5% band can be considered.

Figures 10 illustrates the respective nature of curves derived using these techniques. The drawback of deriving curves based on standard deviation approach was that in the rebound phase, contraction of the corridors was observed. This means that during rebound phase, head excursion would be limited, and this was contradictory when we compared it with the response of the most relaxed volunteer. The second approach by [9] led to a very different characteristic curve and was also discarded. Finally, in the current study, quartile corridors developed by OM4IS data proved the best corridors with the minimal outliers, therefore the response that goes outside of these quartile corridors was considered to be the most relaxed response for the unaware case.

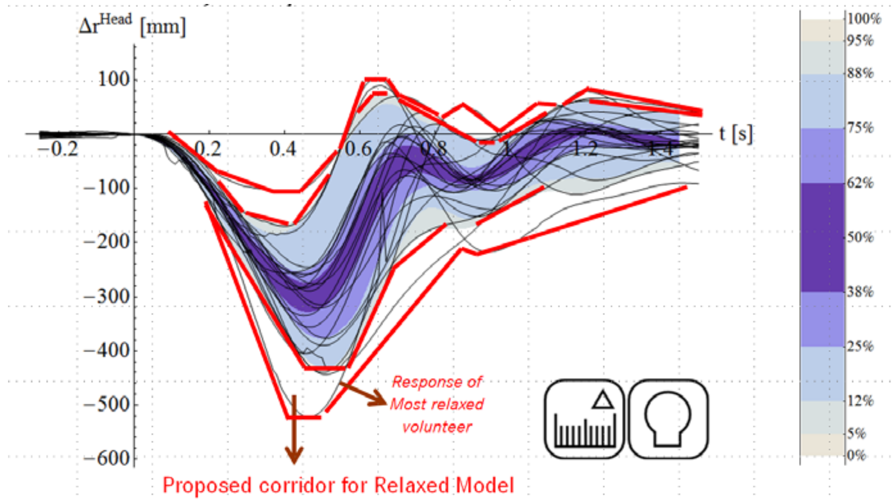
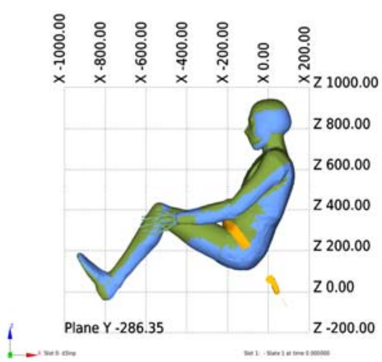


Fig. 10. Quartile Approach.

III. RESULTS

The feasibility of any parameter was verified by testing the classical THUMS-D for the 1 g loading pulse from OM4IS and measuring the excursions of the head and torso region. Figure 11 and 12 illustrates head and torso excursions for the final model with all the modifications.



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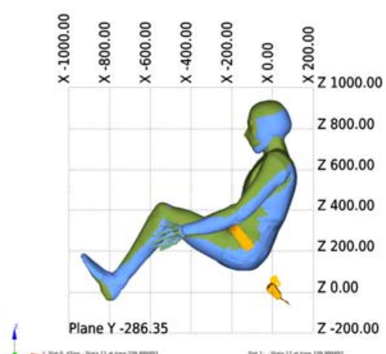

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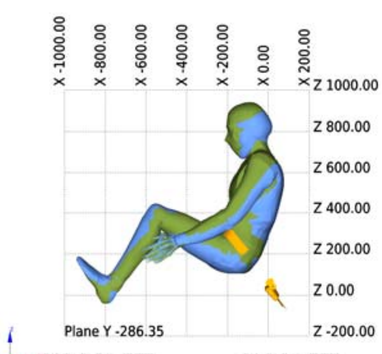

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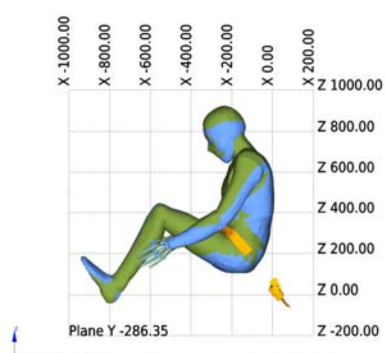

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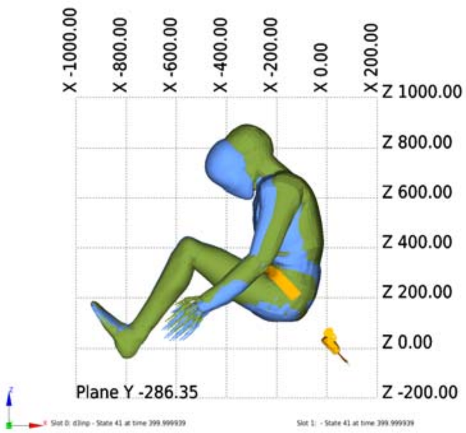

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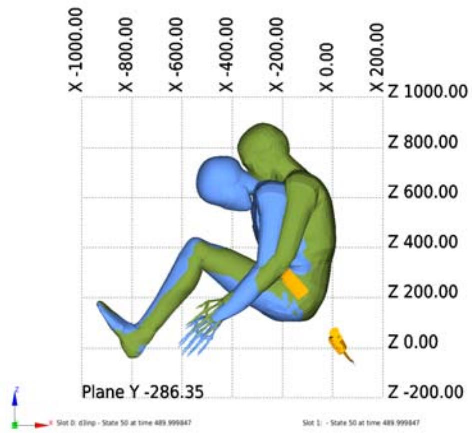
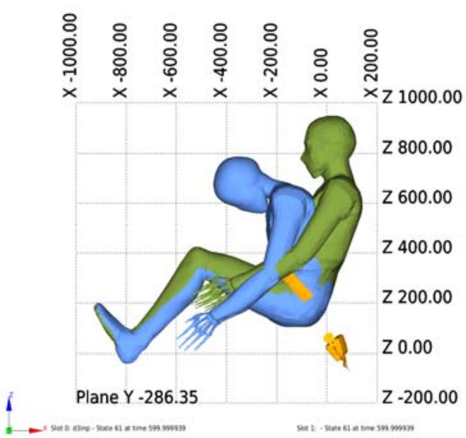


490 ms



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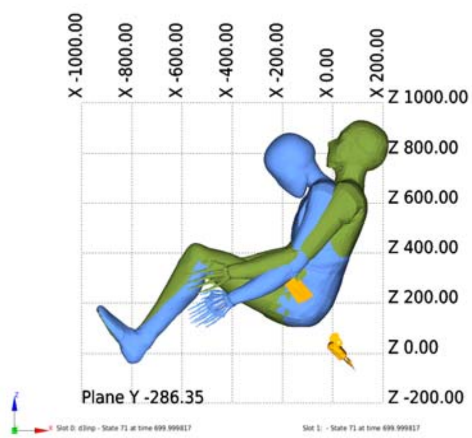

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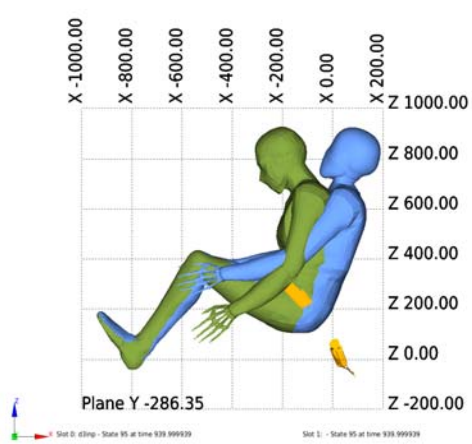

940 *ms*

Fig. 11. Kinematics of classical THUMS-D (GREEN) & "Relaxed" THUMS-D (BLUE) for 1*g* frontal braking pulse

The modifications conducted to the classical THUMS-D to incorporate the aspects of relaxation yielded greater head and torso movement for a 1 g frontal braking pulse, as illustrated in Fig. 12. This was without the inception of any muscle activity.

The modifications discussed above formed development base for "Relaxed" THUMS-D. The active muscles were then incorporated into the "Relaxed" THUMS-D and are henceforth called Active THUMS-D v1.0. Figure 12 illustrates the head excursions experienced with and without the inception of active muscles in the "Relaxed"

THUMS-D. The muscles are completely activated for this particular simulation load case. The muscle model used in this study was the modified Hill-type FE muscle (MAT_156 in LS-DYNA), where the lambda controllers were absent [1].

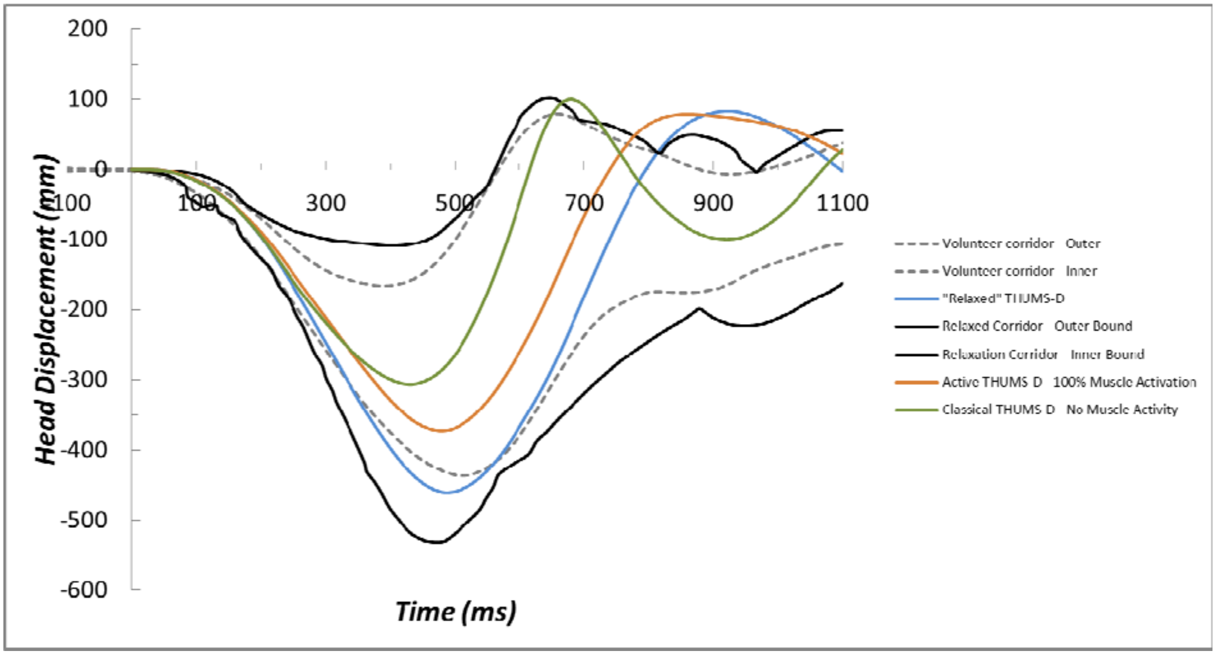

Fig. 12. Head excursion of Active THUMS-D and “Relaxed” THUMS-D.

IV. DISCUSSION

“Relaxed” THUMS-D delivers fairly good response in terms of head excursions. This model is able to deliver a response within the defined corridors after inclusion of Active Muscles. However, there is a need to explore behaviour of neck flexion – extension, angular rotations of head w.r.t. occipital condyle, etc.

One observation was that with every modification, there was a slight shift in the peak and the span of the head excursion response. This could be attributed to the viscoelastic behaviour of the soft tissues. Classical THUMS-D has soft tissues modelled as linear viscoelastic material (*MAT_006 – MAT_VISCOELASTIC), for which some of the parameters were modified. This material model consists of linear rheological models and belongs to the theory of finite linear viscoelasticity [10]. LS-DYNA offers three groups of material laws for modelling viscoelasticity. One of the groups comprises linear rheological models (*MAT_006, *MAT_061 & *MAT_076). The characteristic of this model is that it works on the concept of fading memory and - allows the use of Prony series. MAT76 consists of a generalised Maxwell element for both the deviatoric and volumetric stress contribution. As a consequence, the material functions G(t) and K(t) are Prony series with N and M terms, respectively, and can cover many time decades. The currently used *MAT_006 viscoelastic mode is a special case of MAT76. If the equilibrium contribution (corresponding beta=0) in the Prony series is included, then N = 2 and M = 1:

$$G(t)=G1 \exp(-betaG1 *t) + G2 \exp(-betaG2*t)=Ginf+(G0-Ginf)*\exp(-beta*t)$$

$$K(t)=K1=K$$

This means that the resistance offered by such a system would be comparatively less than similar constitutive laws, like MAT76 (subjected to the condition that Prony terms N>1 and M>1).

V. CONCLUSIONS

The need to relax the Classical THUMS-D was addressed in this study and was achieved with minimal modifications to the model. “Relaxed” THUMS-D developed in this process yielded suitable global response for the 1 g frontal braking load case, but kinematic validity of this model cannot be completely ensured. Accordingly, the model needs to be further improved in the context of other manoeuvres, and kinematic validation is required based on tests conducted on volunteer relaxation tests conducted in OM4IS project.

VI. References

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