8th Australasian Congress on Applied Mechanics, ACAM 8
23-26 November 2014, Melbourne, Australia

Review of anthropomorphic test dummies for the evaluation of thoracic trauma due to blunt ballistic impacts

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Abstract: Biomechanical responses of the thoraces of finite element models of 4 Anthropomorphic Test Dummies (namely, LSTC Hybrid III deformable, LSTC Hybrid III rigid, LSTC/NCAC Hybrid III and ES-2re) were reviewed by impacting them with the 140 gram wooden projectile with impact speeds of 20 and 40 m/s, and 30 g wooden projectile with 60 m/s. In order to elucidate the usefulness of the ATDs for evaluating blunt thoracic trauma caused by blunt ballistic impacts (projectile mass 20 – 200 gram, velocity 20 – 250 m/s), responses obtained were compared with the human response corridors developed by Wayne State University's researchers. It was evident that none of the thoraces exhibited bio-fidelity for the impact cases considered for the analysis. Thoraces of former three dummies found to be very stiff and the latter yielded realistic responses but Viscous Criterion (VC_{max}) values based on the deflection response were way higher when compared to those obtained from the cadaveric experiments for the similar impact conditions. Values of viscous criterion (VC_{max}), probability for AIS3+ and AIS4+ injuries based on the maximum rib deflections (only for the ES-2re dummy for particular impact locations), were found to be, for some cases, to a certain extent, in agreement with those obtained from the cadaveric experiments. The present study highlights the unsuitability of the numerous thorax models (both physical and finite element), while necessitating the development of the thorax surrogate with an acceptable bio-fidelity. Such biomechanical surrogate of the thorax, for the evaluation of trauma, is essential for the validation of non-lethal ammunition, development of bullet proof vests and chest protectors for the athletes of collision & contact sports.

Keywords: blunt thoracic trauma, anthropomorphic test dummy, the human response corridor, thoracic surrogate, AIS, bio-fidelity, viscous criterion.

1 Introduction

Anthropomorphic Test Dummies (ATDs), both physical and finite element models, have been developed by various organizations involved in the vehicle occupant safety-related research and development. Only two years after the development of human thorax responses and tolerance limits by Kroell *et al* [1], Hybrid III dummy appeared for the first time in simulated tests. Now Hybrid III evolved into a family of dummies that were developed to be used as human surrogates in the simulated front crash tests of the vehicles. Similarly different dummies such as, ES-2Re, SID, Bio-SID, World-SID, etc. have been developed for the simulated vehicle side impact tests. Both Hybrid III and Side Impact Dummies facilitate the quantification of blunt thoracic trauma in terms of the sternal deflection, chest compression and viscous criterion (VC) and head trauma in terms of head injury criterion (HIC). Because of the same reason, Viano *et al* [2] have studied facial injuries of the forehead, zygoma and mandible, due to blunt ballistic impacts by impacting the frangible face of the Hybrid III dummy with the instrumented 35 g, 37 mm blunt projectile. Similar experiments were conducted with cadavers and after it was concluded that Hybrid III dummy's frangible face emulated the human head, as far as the injuries concerned. Using the Hybrid III dummy, Walilko *et al* [3] have studied the head injuries caused by the Olympic boxer's punch. Using Hybrid III dummies, Viano *et al* [4] have studied concussion due to football impacts and compared the outcome with that obtained from Walilko *et al* [3].

Janda *et al* [5] have used Hybrid III child crash test dummy for the evaluation of the blunt thoracic trauma caused by the baseball impacts. Using the thorax of the Hybrid III 50th percentile adult male dummy, Thota *et al* [6] have studied the effect of the energy absorbing mechanisms on the blunt thoracic trauma caused by latest non-lethal projectiles with foam nose.Though blunt head trauma point of view, ATDs performance is comparable with that of biological human head models. So far, no researcher has evaluated the ATD's for their usefulness in predicting the blunt thoracic trauma due to ballistic impacts.

It is important to note that, validation of all ATDs has been carried out with the human response corridors developed by Kroell *et al* [1] which were pertinent to the automotive impacts. The human response corridors developed by Bir *et al* [7] for the test conditions pertinent to the blunt ballistic impacts to the thorax could be useful for the review of ATDs. Therefore, using these human response corridors, three front impact dummies and a side impact dummies were reviewed to find out their suitability for the measurement of the blunt thoracic trauma of interest. If correlation exists with the cadaver test data, ATDs can be used for the validation of non-lethal munitions, chest protectors for sports personnel and safety solid sports balls.

FE models of the ATDs were selected for the study, because of the inherent advantages of the FEA simulations. Non-linear FEA simulations facilitate the measurement various engineering parameters (deformation, various stresses, energy interactions and kinematics of the projectile), some of which beyond the capability of physical tests. Most importantly, physical tests entail costly equipment.

Systematic method devised for the review and usefulness of the ATDs for the blunt thoracic trauma due to ballistic impacts from the outcome of the non-linear FEA impact simulations were presented in this paper.

2. Methodology

Finite element models of four ATDs used in the study were; 50th percentile male Hybrid III deformable dummy (LSTC), 50th percentile male Hybrid III rigid dummy (LSTC), NCAC Hybrid III deformable dummy (LSTC/NCAC) and ES-2re (LSTC). Material properties for the wood used in the simulations were as collected from the published literature (Green [8], Green *et al* [9], Murray *et al* [10]). MAT_WOOD material model (available in LS-DYNA) was considered for the projectile in all impact simulations. In the present study, no parameters, material models or components of the ATDs were altered. Simulations parameters such as ERODE in *CONTROL_TIME_STEP, DTMIN in CONTROL_TERMINATION, *CONTROL_HOURGLASS and element formulations utilized from previously published work (Thota *et al* [11]) . All impact simulations were carried out by using LS-DYNA, which is a non-linear finite element solver developed by Livermore Software Technology Corporation, USA. LS-DYNA user manuals provide the details pertinent to the material models, control cards and many other input parameters (Hallquist [12]). Procedural steps for evaluation of the usefulness of the ATDs for blunt thoracic trauma caused by high speed projectile impacts were as shown in the Figure 1. Impact points selected for four dummies were as shown in the Figure 2.

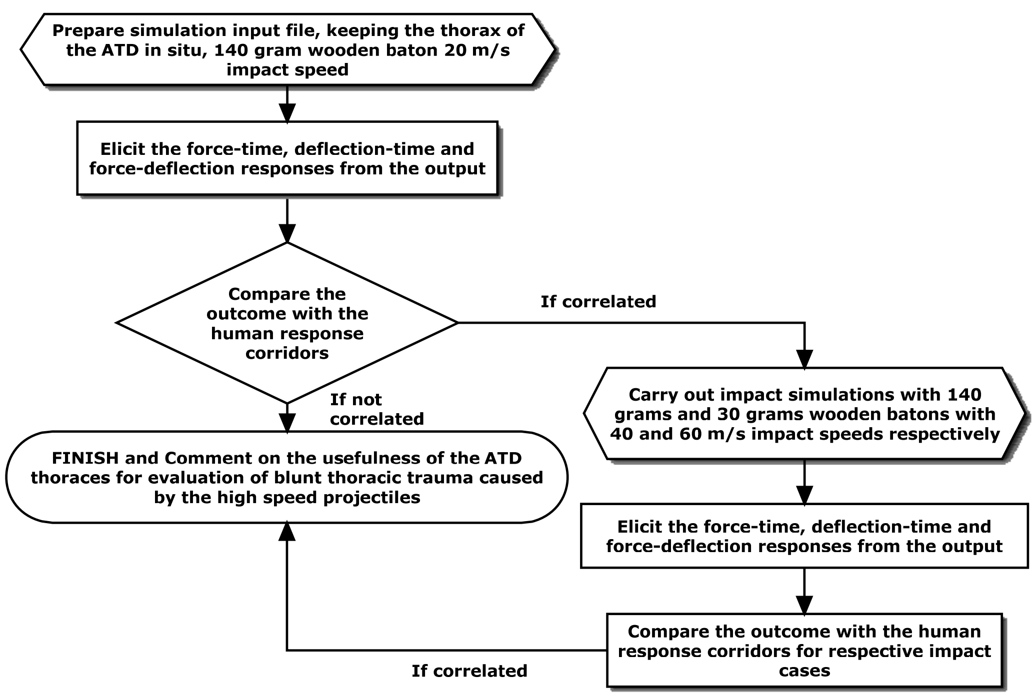

Figure 1: Procedural steps to evaluate the suitability of the ATDs for ballistic impacts

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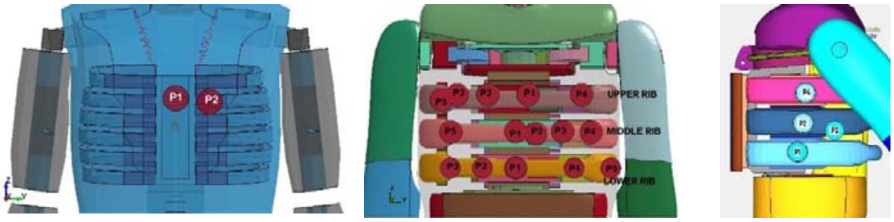

Figure 2: Impact points – Three hybrid III LSTC dummies (left), ES-2re dummy frontal impact (middle), side impact (right).

Non-linear FEA simulations were carried out with three impact conditions (Table 1) similar to those used by Bir *et al* [7].

Table 1: Details of the projectile

Impact condition	Projectile details	Impact speed
LP_20	Wooden baton, 140 g, 100 mm length, 37 mm diameter	20 m/s
LP_40	Wooden baton, 140 g, 100 mm length, 37 mm diameter	40 m/s
SP_60	Wooden baton, 30 g, 28.5 mm length, 37 mm diameter	60 m/s

Biomechanical responses of thoraces of the ATDs for the LP_20 case, if comparable with those presented by Bir *et al* [7] for the similar case, simulations for remaining two impact conditions were carried out. It is important to note that for all cases, acceleration pulses were processed using SAE Class 600 filter and for processing deflection responses no filter was used. Later portions of this paper, for the sake of convenience, three impact conditions used will be referred as LP_20, LP40 and SP_60 respectively.

Thoracic injury was quantified using the equation (1) for viscous criterion, which is a product of maximum chest compression and maximum velocity of chest compression (VC_{max}). Values of VC_{max} provide the real means of validation of FE models, as it is an efficient predictor of thoracic trauma caused by blunt impacts. Viscous criterion or soft tissue criterion values can be calculated using the formula given below.

$$VC = S.\ (Y/D).\ dY/dt \tag{1}$$

Where,

VC= viscous criterion

S = scale factor (based on the ATD used in the simulation or physical tests)

Y= chest deformation or chest deflection

D= deformation constant (based on the ATD used in the simulation or physical tests), and

dY/dt = rate of chest deformation

The guidelines laid down by SAE International [13] provide the scaling factors and deformation constants for all ATDs.

VC_{max} of 1 m/s indicates 25% risk of AIS3+ thoracic injury with Y/D equivalent to 33% (Viano *et al* [14]). $VC_{max} \leq 1$ has been included as the compliance requirement in various automotive safety standards such as FMVSS 214, ECE R94, and ECE R95, EuroNCAP (both frontal and side impacts)

For all relevant impact cases of ES-2re dummy, VC values were calculated using equation (1) above with the maximum rib deflections in lieu of thorax deformation. Probabilities for AIS3+ and AIS4+ injuries were calculated by using logistic regression model available in the literature Kent *et al* [15].

$$p(AIS3+) = 1/(1+e^{(2.0975-0.0482\times max.rib\ deflection)}) \tag{2}$$

$$p(AIS4+) = 1/(1+e^{(3.4335-0.0482\times max.rib\ deflection)}) \tag{3}$$

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Where,

p(AIS3+) = probability for injury greater or equal to score 3 on the abbreviated injury scale

p(AIS4+) = probability for injury greater or equal to score 4 on the abbreviated injury scale

max.rib.deflection = maximum rib deflection

It is important to note that the equations (2) and (3) are applicable to only ES-2re dummy. By comparing the biomechanical responses and VC_{max} values obtained for all impact cases of pertaining to ATDs with the cadaveric test results, suitability of ATDs for evaluation of the blunt trauma was elicited and presented.

3. Results and Discussion

3.1 LP_20 impact condition

Thoraces of the 4 ATDs were subjected to LP_20 impact condition and from the simulation output, biomechanical responses (force-time and deflection-time) were elicited. Impact force was measured with an accelerometer mounted on the back face of the projectile and chest deflections were measured based on the impact location and also at the point where maximum deflection occurred. None of the impacts for all ATDs yielded any significant spinal acceleration and whole body movement. Therefore, the relative displacement of the chest wall with respect to the spine was evaluated by measuring the nodal displacements on the jacket.

Frontal impacts of the former three dummies did not yield any realistic force-time response due to the high stiffness of those thoraces. Even after processing the force response with SAE class 600 filter, the magnitudes of the forces were very unrealistic (peak impact force was in the order of 25 kN which clearly indicates that the thoraces of all ATDs are stiff). Therefore, only deflection-time responses of the thoraces were presented (Figure 3).

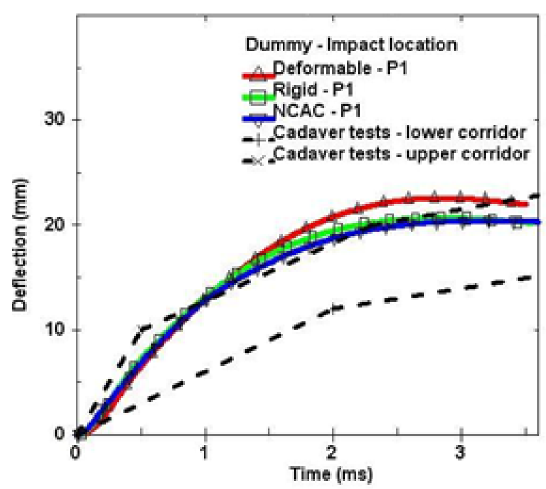

Figure 3: Dynamic chest deflection of the Hybrid III thoraces (LP_20 impact condition)

Euro SID dummy's finite element model and physical model widely used in tests for crashworthiness of the vehicles. As shown in the Figure 2, fifteen impact points were considered for the frontal impact. Only impact points P1, P2 on the lower rib, P1, P2 & P3 on the middle rib, P1& P2 on the top rib provided adequate loading surface to the projectile and yielded realistic force and deflection responses. Other frontal impact points, due to the skidding of the projectile, mechanical responses were very less and, therefore, ignored for the study. Four impact points were considered for side impact. Impact on the side surfaces did not yield any chest deflection as the stiffness offered by the thorax was very high. Dynamic force and deflection response of the ES-2re to the LP_20 impact were shown in the Figure 4 and Figure 5, respectively.

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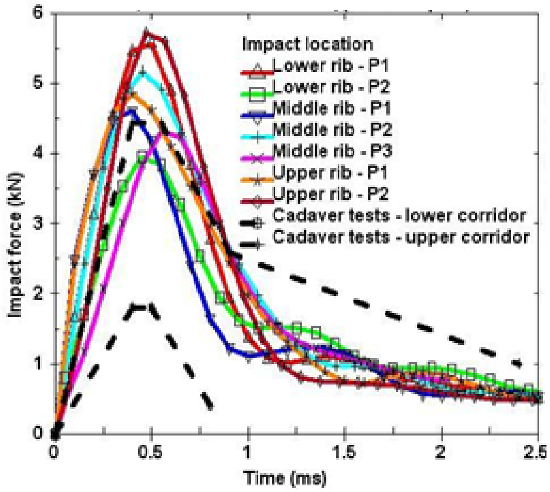

Figure 4: Dynamic force response (ES-2re, LP_20)

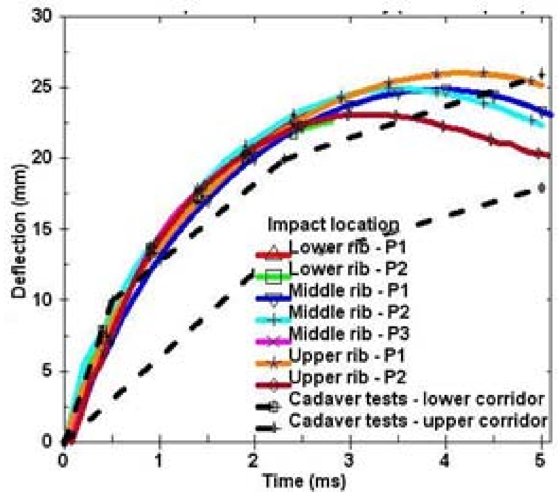

Figure 5: Dynamic deflection response (ES-2re, LP_20)

From the Figures 5 and 6, force response obtained for the impact point "Lower rib – P2" was within the human response corridors. Peak forces for all impact other points were 10-40% more than the upper limit of the force corridor. Peak deflections and rate of chest deformations for all impact points were more than the upper limit of the human deflection response corridor. Only ES-2re was considered for the further analysis. Owing to the high stiffness, all Hybrid III dummies were discarded for further study.

3.2 LP_40 impact condition

Thorax of the ES-2re was subjected to LP_40 impact condition and force-time and deflection-time responses were elicited (Figure 6 and Figure 7).

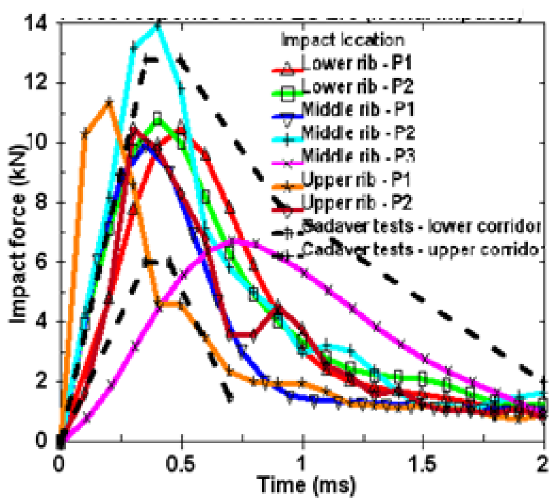

Figure 6: Dynamic force response (ES-2re, LP_40)

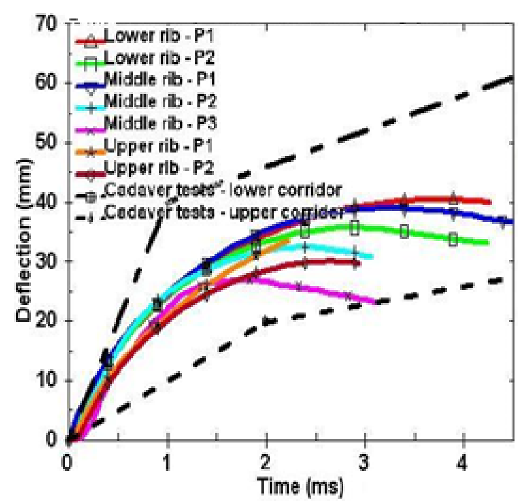

Figure 7: Dynamic force response (ES-2re, LP_40)

From the Figure 6, it was evident that dynamic force responses (Force-time responses) obtained for midpoints (P1) of all 3 ribs were within the human response corridors developed from the cadaver tests. For the point P2, peak forces were more than the upper corridor and for the point P3 the forces were low because of the inadequate loading surface. From the dynamic deflection plot (Figure 7) it was evident that the deflection-time responses obtained for all the points were within the human response corridors but the rate of chest deflection is very different from that obtained from the cadaver tests.

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3.3 SP_60 impact condition

Force-time and deflection-time responses elicited from the simulations' output of SP_60 impact case were as shown in the Figure 8 and Figure 9 respectively.

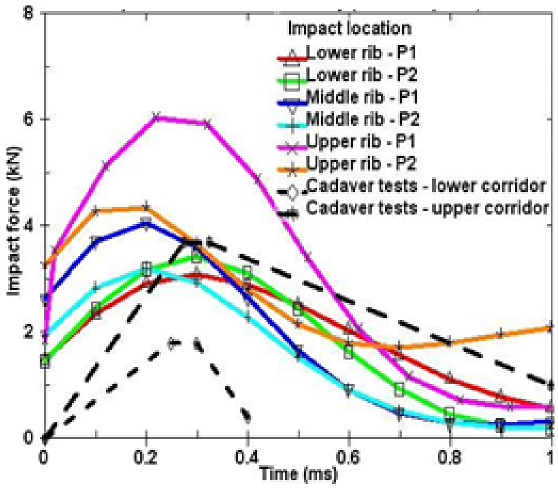

Figure 8: Dynamic force response (ES-2re, SP_60)

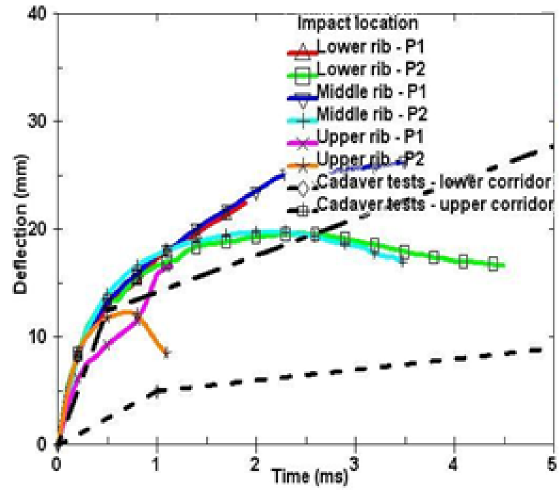

Figure 9: Dynamic force response (ES-2re, SP_60)

The impact duration was very less for this case. In every impact case, the projectile lost the contact with the thorax within 1 ms. Peak forces (unfiltered deceleration pulse) were at 0.2 – 0.3 ms of the impact. Filtered dynamic impact force responses were as shown in the Figure 2.15. Mechanical responses (both force-time and deflection-time) obtained were not in agreement with those obtained from cadaveric tests

Though the mechanical responses, for some impact points appeared to be very close to the human response corridors, rate of chest deflection influences the usefulness of the ATDs for quantifying the thoracic trauma due to blunt ballistic impacts. Therefore, for all impact cases VC_{max} were evaluated.

3.4 Evaluation of the VC_{max} values for all impact cases

VC_{max} values for all of the impact cases were calculated using the equation (1), and deflection responses (Figures 3, 5, 7 and 9) obtained from the simulations.

Scale factor (S) and Deformation constant (D) for all dummies and cadavers utilized for the evaluation of the VC_{max} (Bir *et al* [7], Chang [16]) were as presented in the Table 2. VC_{max} values were as shown in the Figure 10, Figure 11 and Figure 12.

Table 2: Scale factor and deformation constant for all ATDs

ATD name	Scale factor (S)	Deformation constant (D)
Hybrid III, male 95%	1.3	254
Hybrid III, male 50%	1.3	229
Hybrid III, female 5%	1.3	187
BioSID	1.0	175
EuroSID-1	1.0	140
ES-2re	1.0	140
SID-IIs	1.0	138
Cadavers as suggested by Viano et al. 1989	1.3	180

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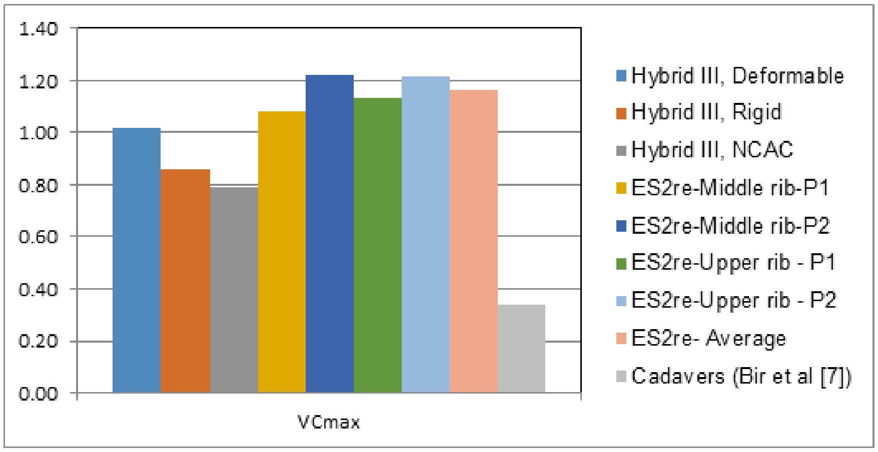

Figure 10: VCmax values for LP_20 impact condition

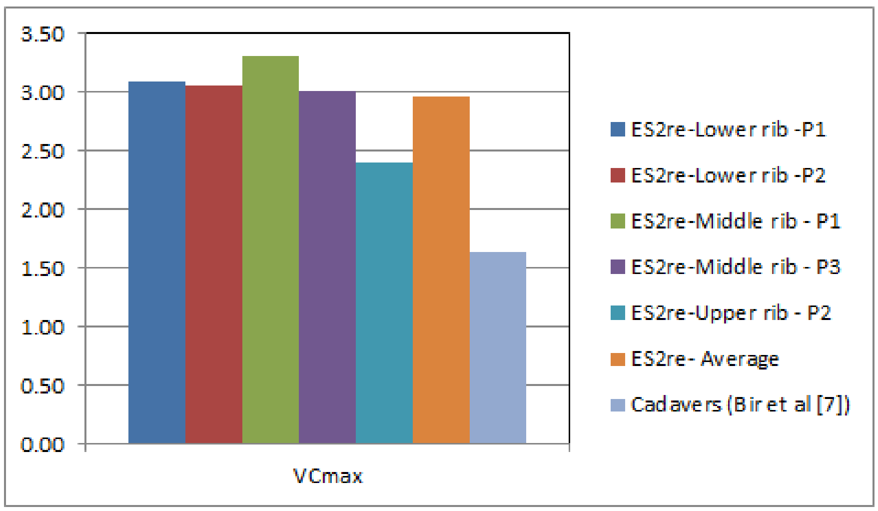

Figure 11: VCmax values for LP_40 impact condition

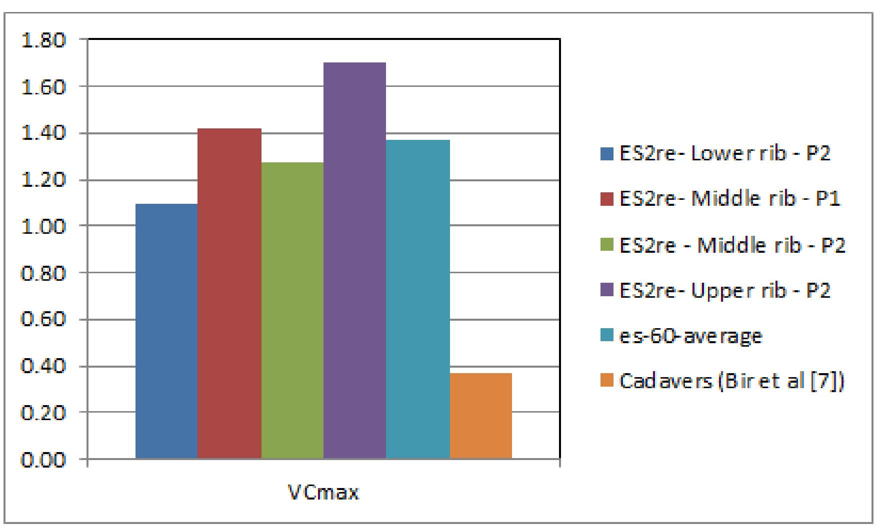

Figure 12: VC_{max} values for SP_60 impact condition

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VC_{max} values for all impact cases were not in correlation with those obtained from the cadaver tests of the respective cases. Therefore, dynamic chest deflection responses as a function of time obtained for ES-2Re were not useful to the evaluation of blunt thoracic trauma caused by ballistic impacts.

3.5 Evaluation of p(AIS3+) and p(AIS4+) using maximum rib deflections of ES-2Re side impact dummy

In order to explore the last possibility whether ES-2re could be useful for the evaluation of the trauma due to high speed blunt ballistic impacts, maximum rib deflections were calculated from nodal displacements of the rib liners. To elucidate the thorax-projectile interaction, rib liners and ribs in initial and final positions during the impact were shown in the Figure 13 (For the sake of clarity, foam jacket was removed). Deflection of the ribs was measured using the nodes on the ribs. Mechanical responses of all three ribs were similar for similar impact points. Therefore, deflections for each impact condition, only two points on one of the three ribs were evaluated and were as shown in the Figure 14. It is important to note that no electronic filter was used for processing of the displacement data obtained for the nodes of rib liners.

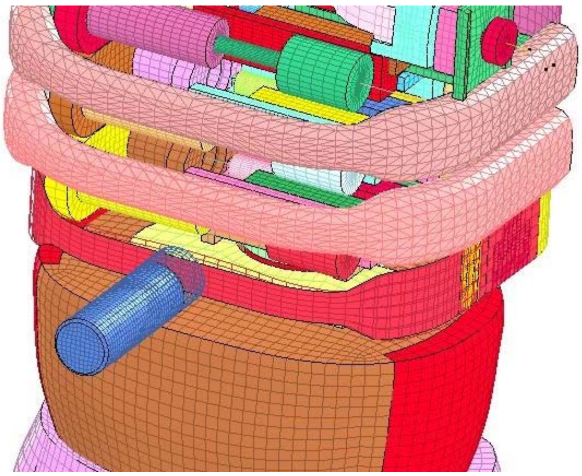

Figure 13: ES-2re subjected to LP_40 impact condition (Lower rib – P1 location)

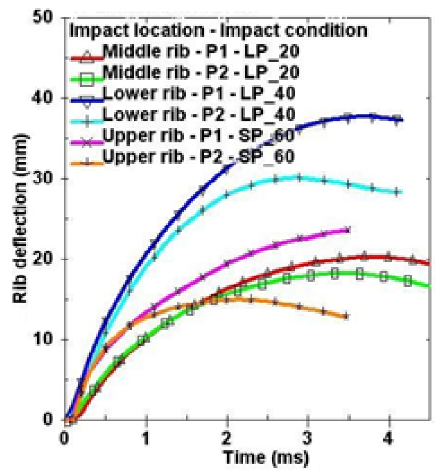

Figure 14: Dynamic deflection response for all 3 impact conditions

Using the maximum rib deflections from the output of the impact simulations and Equations (2) and (3), probabilities for AIS3+ and AIS4+ injuries and VC_{max} were evaluated and presented in the Table 3.

Table 3: Probabilities of AIS3+ and AIS4+ injuries

Impact Location / Impact condition	p(AIS3+)	p(AIS4+)	VC_{max} using Equation 1
Middle rib – P1 - LP_20	0.24	0.08	0.64
Middle rib – P2 – LP_20	0.23	0.07	0.66
Lower rib – P1 – LP_40	0.44	0.17	2.44
Lower rib – P2 – LP_40	0.35	0.12	2.00
Upper rib – P1 – SP_60	0.27	0.09	0.95
Upper rib – P2 – SP_60	0.20	0.06	0.71

Using the correlation between VC_{max} and AIS, probabilities for AIS3+ and AIS4+ injuries (Gennarelli *et al* [17], States [18], States *et al* [19]) can be useful for the quantifying the blunt thoracic trauma. For instance, p(AIS3+) = 0.25 corresponds to VC_{max} of 1 m/s. As per cadaver test results presented by Bir

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[20], LP_20, LP_40 and SP_60 impact cases produced VC_{max} values 0.34, 1.63 and 0.37 respectively. Therefore, from the study, it is evident that VC_{max} values that correspond to p(AIS3+) and p(AIS4+) and VC_{max} values evaluated using the equation 1, were not in correlation with the cadaver test results presented by Bir *et al* [7]. VC_{max} value obtained for ES-2re for the LP_20 impact condition and impact point P2 was very close to that obtained from the cadaver tests.

3. Conclusions and recommendations

The following conclusions were drawn from the mechanical responses obtained from the thoraces of 4 ATDs subjected to LP_20, LP_40 and SP_60 impact conditions,

- It was evident that three thoraces of the Hybrid III were very stiff and didn't yield any realistic force response.
- Thorax of the ES-2re dummy gave reasonable and realistic responses. However, VC_{max} values calculated from the dynamic deflection plots were way too high when compared to those obtained from the cadaveric experiments. In all impact cases pertaining to the ES-2Re side impact dummy, no measurable spinal deflections and accelerations were found, and it is an indication that the deformation is local and also the thorax was stiff.
- VC_{max} values evaluated using the probability for AIS3+ and AIS4+ injuries were also not in agreement with the cadaver tests data.
- In some impact cases, though the maximum rib deflections and maximum chest deflections were smaller in magnitude, velocity of maximum deformation was very high. In all cases projectile lost contact with the thorax within 2 ms time. In the case of SP_60 impact case, the contact time was less than 1 ms.
- None of the impact cases yielded any measurable spinal acceleration. Therefore, the force-time and deflection-time responses were only local, and not really responses of the thoraces of the ATDs.

None of the material data or design parameters pertaining to the ATDs were altered in the present study. By altering the material data or design parameters or attaching a thick soft, foam bib in front of the thorax might have made the thoraces to emulate the cadavers

In a nutshell, none of the thoraces of the ATDs under review that are useful for the simulated automotive crash applications can be used for the evaluation of the thoracic trauma caused by blunt ballistics (such as impacts from non-lethal projectiles, solid sports ball impacts, etc.). The same may be true for various other ATDs (both physical and numerical models) as every one of them got correlated with biomechanical response corridors developed for the impacts pertinent to the automotive crashes. Therefore, there is a necessity for the development of a fast solving and easy to use FE model thorax for the evaluation of blunt thoracic trauma.

Acknowledgements

The study presented in the paper is a part of a major project 'Development and validation of a Mechanical THOrax for Trauma Assessment (MTHOTA)'. Principal author thanks 'Livermore Software Technology Corporation, USA' for providing the educational license for four months. Also, thanks 'Mindglow India Private Limited, Bangalore, India' for providing resources and 'Amerigo Structural Engineers Private Limited, Bangalore' for providing necessary funds for the successful completion of the project.

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