Study of the Kinematics of the THOR dummy in Nearside Oblique Impacts

Bengt Pipkorn, Francisco J. Lopez-Valdes, Oscar Juste-Lorente, Mario Maza and Cecilia Sunnevång

Abstract Oblique and small-overlap crashes are the second most common frontal crash type leading to fatal outcome. This study discusses a simplified test rig suitable to analyse the performance of the THOR dummy in oblique impacts. Secondly, this paper compares the kinematics and dynamics of the THOR dummy under the loading of two types of seat belts. Last, the study compares the response of the THOR finite element (FE) model to the one of the physical dummy. By means of mathematical simulations with the THOR FE model different seat designs were evaluated so that the dummy kinematics could approximate those observed in real vehicles. Thereafter two different three-point seat belt systems were evaluated via physical and computer-modelled sled tests: a pretensioned (shoulder retractor and lap) force-limiting seat belt (reference seat belt) and an innovative belt in which the shoulder and the lap bands were split (split buckle). The study shows that THOR pelvic displacement was significantly reduced in a realistic manner by using a modified angled seat in comparison to the originally flat seat of the test fixture. The THOR dummy was able to discriminate between the two seat belt systems and the results suggest that the split buckle restraint has the potential to achieve significant injury reducing benefits in the oblique loading condition. In the comparison of the THOR mathematical and mechanical models, a total CORA score of 0.62 was obtained for the reference seat belt comparison and a score of 0.60 was obtained for the split buckle comparison.

Keywords FE-model, gold standard, near-side, oblique, THOR

I. INTRODUCTION

Oblique and small-overlap crashes are the second most common frontal crash type leading to fatal outcome after crashes with a large change in velocity (high delta V) [1]. For an occupant seated on the near-side adjacent to the impacted side of the vehicle there is a risk of serious injuries to the head and chest from contact with the A-pillar, instrument panel, intruding door, steering wheel or seat belt load [2-4]. When exposed to an oblique or small-overlap crash the occupant moves in the forward-lateral direction. It was hypothesised that the occupant is directed towards the outboard vehicle components such as the A-pillar and that the trajectory may not be optimal for the existing belt and airbag restraint systems [2]. To enhance occupant protection in oblique and small overlap type of crashes, the Insurance Institute for Highway Safety (IIHS) introduced the small overlap load case in their consumer rating portfolio [5] and NHTSA is proposing an oblique load case in the US NCAP (MY19) upgrade. In the IIHS small overlap test the vehicle is crashed into a rigid barrier at 64.4 km/h with 25% overlap using the Hybrid III (HIII) 50% male for injury assessment (IIHS 2014). In the NHTSA proposal a moving deformable barrier is crashed at a 15 degree angle with a 35% overlap into a stationary vehicle at 90 km/h. The THOR-M dummy in the driver and passenger seat is proposed for injury assessment [6]. The aforementioned test protocols use two different types of anthropomorphic test devices (ATDs) for injury assessment in oblique and small overlap crashes. A previous comparison between the Hybrid III (HIII) and THOR in the IIHS small overlap crash test showed no difference in injury outcome [3]. However in a sled test comparison using a pre deformed door and small overlap crash pulse, a difference in dummy kinematics and potential injury caused by the contact to the door was found between the HIII and modified THOR (THORAX Thor similar to THOR Mod-Kit with SD3 shoulder) [7]. The comparison of the THOR ATD to the HIII and Post Mortem Human Surrogate (PMHS) tests in frontal impacts has shown that THOR exhibits a more human-like behaviour [8-10]. With the more

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biofidelic kinematic behaviour and increased thoracic sensitivity of THOR-M it has been suggested that the THOR-M is a suitable tool for evaluating occupant injury risk in oblique impacts [7]. In recent years, a generic test rig was developed to be used in the assessment of ATD biofidelity and in the development of a multi-point thoracic injury criterion for the THOR dummy. The test fixture (called Gold Standard) has been used elsewhere to evaluate ATD biofidelity and to develop thoracic injury criteria [11-13]. The advantage is that the rig is generic, can easily be reproduced and it allows complete visual access to the occupant. However, due to the fact that the seat consists of a horizontal rigid plate the kinematics of the pelvis differ from the kinematics of the pelvis when seated in a real vehicle seat. This effect influences the performance of the restraint systems used in the dummy evaluations with the generic rig [13]. In addition, the rig has been used with a knee bar not allowing any forward excursion of the pelvis in some of the previous studies [11-12]. Due to the complexity of a crash, with potential intrusion affecting the injury outcome, as well as interaction with seat, airbags and seat belt it is difficult to make an overall assessment of the suitability of THOR in nearside oblique impacts. The aim of this study was therefore three-fold. The primary aim was to modify the Gold Standard test fixture so that pelvis interaction with the generic seat structure will be similar to the interaction between the pelvis and a state of the art vehicle seat. The secondary aim was to evaluate THOR responses in oblique impacts using different seat belt configurations. The third aim was to compare the THOR physical dummy response with the THOR mathematical (or finite element) model response.

II. METHODS

The test and simulation matrix can be found in Table I. A generic test rig was used as the basis for the development of the fixture to be used in the subsequent oblique sled tests. The generic fixture (the so called Gold Standard) consisted of a rigid metallic frame mimicking the basic geometry of a standard seating position in a passenger car while allowing direct visualization of the kinematics of the occupant. The fixture has been used in several studies focusing on the development of a thoracic injury criterion applicable to the THOR dummy and on the kinematics of the spine [11-13]. The rigid knee bolster used in the previously mentioned studies was removed from the test fixture. Additional restraint to the occupant's pelvic motion was achieved by modifying the initially flat seat of the Gold Standard rig. The redesign of the seat (SAFER seat) was carried out by means of mathematical simulations with the THOR v1.0 dummy model. Pelvic motion was arrested by adding an inclined stiff plane around the pelvis of the dummy. The incline and height of the stiff plane were varied until a proper design was obtained. Also care was taken that the penetration of the stiff plane into the thigh was considered acceptable meaning that the modified seat would not be too uncomfortable for a human. The predicted pelvis kinematics with the redesigned seat fixture was compared with the predictions with matched simulations with a model of a real vehicle seat that included foam, fabric, etc. The design that produced pelvis kinematics similar to the kinematics observed in simulations with a real vehicle seat was selected as a reasonable approximation of a real vehicle occupant environment [14]. The redesigned test fixture was used to study occupant kinematics in oblique near side impacts. Four mechanical sled tests and mathematical simulations in matching conditions with the THOR dummy were performed at 35km/h with a peak acceleration of 16-19g, a duration of approximately 80ms and at a 30 degrees angle (passenger seat belt configuration). A similar crash pulse was used in a study by Forman in PMHS sled tests in far-side oblique impacts [15]. The crash pulse from these oblique impacts was selected for this study because the tests included here were part of a larger scope project aiming to compare the performance of the same restraint systems in frontal and oblique impacts. Only the results from the oblique impacts are included in this study.

The THOR dummy used in this study was one of the demonstrator dummies developed within the EC Seventh Framework project THORAX (EU-THORAX). In EU-THORAX the THOR-NT dummy was upgraded with a new thorax and shoulder [16-17]. The upgraded THOR is comparable to the NHTSA THOR Mod Kit dummy with an SD3 shoulder (Mod-Kit_SD3) and the design was then used as the basis for building the THOR-M. The difference between THOR Mod-Kit SD3 and THOR-M is that the Mod-Kit is an upgrade from THOR-NT and the THOR-M is built from scratch using metric fasteners. A biofidelity evaluation performed by NHTSA showed improved biofidelity of the THOR Mod Kit with an SD3 shoulder compared to previous versions of the THOR dummy, and also similar to the THOR-M [18].

The three-dimensional displacement of selected locations of the THOR dummy were recorded by a motion capture system operating at 1,000 Hz. Data included in the study corresponded to the approximate location of the ATD head center of gravity (CG) (calculated as the mid-point between two markers located bilaterally on the head) and the mid-point between the two bilateral H-points of the dummy. ATD chest instrumentation included four 3D IR-TRACCs. Two different three-point seat belt systems were evaluated: a pretensioned (shoulder retractor and lap) force-limiting seat belt (reference seat belt) and a new prototype belt system in which the shoulder band and the lap band were split (split buckle seat belt) (Fig. 1). The lab belt and diagonal belt are independent from one another. The reference belt system comprised a shoulder (1.5kN) and lap (2kN) pretensioned, force-limiting (4kN) belt (PT+FL) seatbelt. In the mechanical tests the belt was replaced after each test. The split buckle seat belt system incorporated pretensioners at the shoulder retractor, and at the lap buckle and anchor (bilaterally on the lap band). The lower anchor point of the shoulder band was moved 150 mm forward of the lap anchor point (Fig. 1). The shoulder belt force was measured at an intermediate position between the shoulder of the occupant and the D-ring. By splitting the belt system and moving the lower attachment point of the diagonal belt forward in the vehicle the loading from the belt is reduced on the lower part of the thorax and increased in the upper part (clavicle) of the thorax leading to reduced chest deflection. All sensor data were recorded at 10,000Hz. All results are reported in a coordinate system oriented according to the SAE J211 recommendations, with the x-axis pointing forwards, the z-axis pointing downwards and the y-axis oriented to complete a right-hand oriented coordinate system. Displacements are given with respect to the reference system attached to the seat.

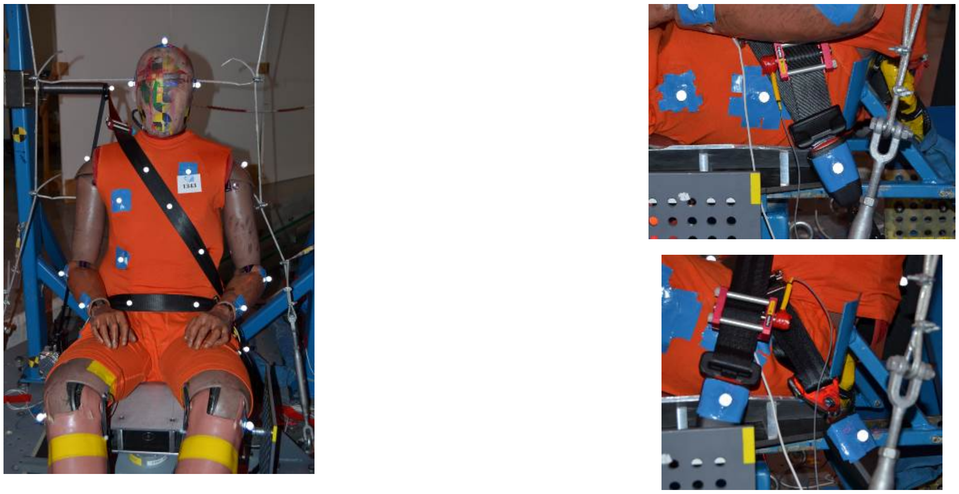


Fig. 1. Left: overall view of the seat belt fit (reference) over the THOR torso. Right: detail of inner side belt buckle. The upper picture shows the reference belt buckle and the bottom one the two independent bands of the split buckle system.

The comparison between the mechanical THOR dummy and the mathematical THOR model was carried out using a CORA (correlation and analysis) analysis [19]. CORA uses two different methods to assess the correlation of signals. While the corridor method calculates the deviation between curves by using corridors, the cross correlation method analyses specific curve characteristics like phase shift or shape of the signals. The rating results ranges from “0” (no correlation) to “1” (perfect match).

TABLE I
SIMULATION AND TEST MATRIX

Occupant Substitute	Mech Test/Math Model	Restraint	Impact Vel (km/h)	Seat	Angle (Deg)
Aim 1: Test fixture design					
THOR	Math Model	3-pt FL PT Belt	35	Flat	0
THOR	Math Model	3-pt FL PT Belt	35	SAFER	0
THOR	Math Model	3-pt FL PT Belt	35	Vehicle Seat	0
Aim 2: THOR performance in oblique impacts					
THOR	Mech Test (1343, 1344, 1345)	3-pt FL PT Belt	35	SAFER	-30
THOR	Mech Test (1346)	Split Buckle	35	SAFER	-30
Aim 3: Comparison mechanical THOR dummy vs mathematical THOR model + tests from aim 2					
THOR	Math Model	3-pt FL PT Belt	35	SAFER	-30
THOR	Math Model	Split Buckle	35	SAFER	-30

The mechanical THOR dummy used in the tests was the THORAX demonstrator [20]. The THORAX demonstrator is an upgraded THOR-NT with modified shoulder design (SD3), rib cage and pelvis/hip modification kit, similar to THOR Mod-Kit with SD3. The numerical model (FE-THOR) was the THOR-M version 1.0. Thoracic injury risk was evaluated using injury risk functions proposed to be used for occupant injury assessment in future US NCAP (MY19) [6].

III. RESULTS

Seat Modification for Oblique Near Side Evaluation

The redesigned seat (from here onwards, referred to as the SAFER seat) included a 50mm edge around the seat and a 50mm ramp in the posterior/anterior direction (Fig. 2). In the full frontal impact the pelvis stayed on the seat. The pelvis kinematics in x- and z-direction with the SAFER seat were similar to the pelvis kinematics in the vehicle seat (Fig 3). In full frontal impact the redesigned seat reduced peak x-displacement for the pelvis from 110mm to 82mm relative to the original flat seat. In z-direction pelvis peak displacement was reduced from 20mm to 10mm (Fig 3).

Fig. 2. Seat modification a) THOR in SAFER seat, b) FE seat model, c) seat hardware

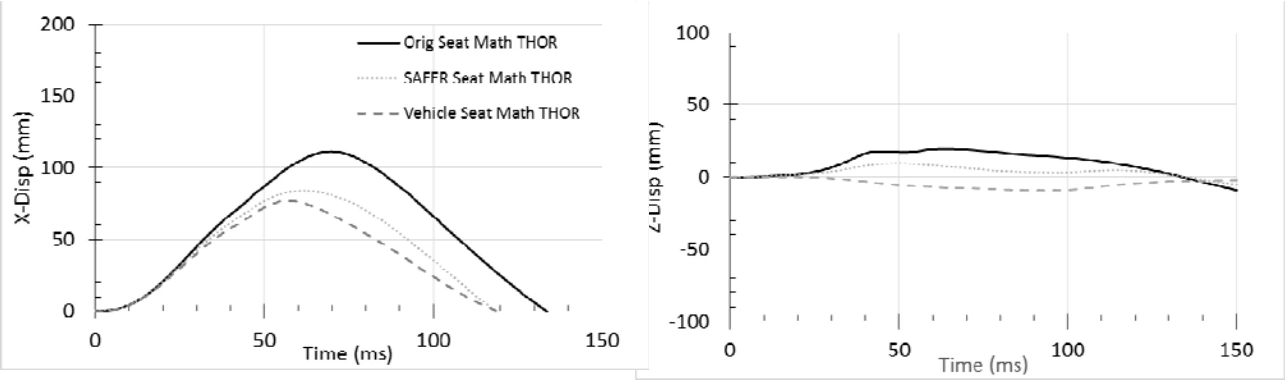


Fig 3. THOR Pelvis displacement for original gold standard seat and SAFER seat. Frontal impacts.

Mechanical THOR Dummy Evaluation in Oblique Near Side Impacts

Overall, similar kinematics for the occupant in the 3-pt FL PT (reference) and split buckle configurations were observed.

Pelvis x-, and y-displacements were greater for the reference configuration than for the split buckle while the z-displacement was small for both configurations (Fig. 4). .

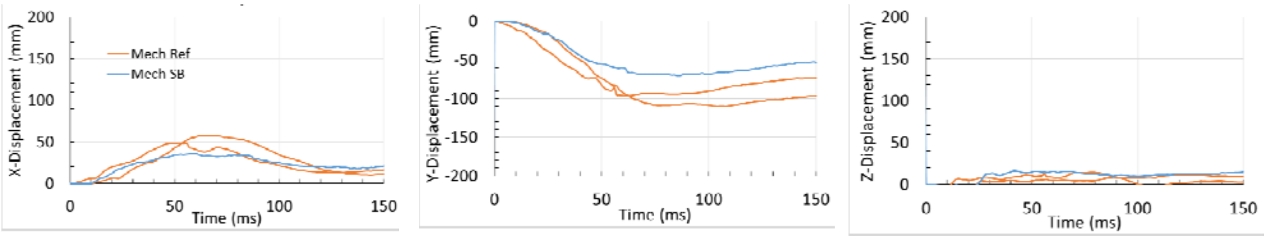


Fig. 4. Pelvis CG displacement from both model and test (x, y and z direction)

For the head center of gravity the peak displacement in x-direction was for the reference configuration 250 mm and for the split buckle configuration 220 mm. The peak displacement in y- and z-direction were 350 mm and 310 mm for the reference and split buckle configurations respectively (Fig. 5).

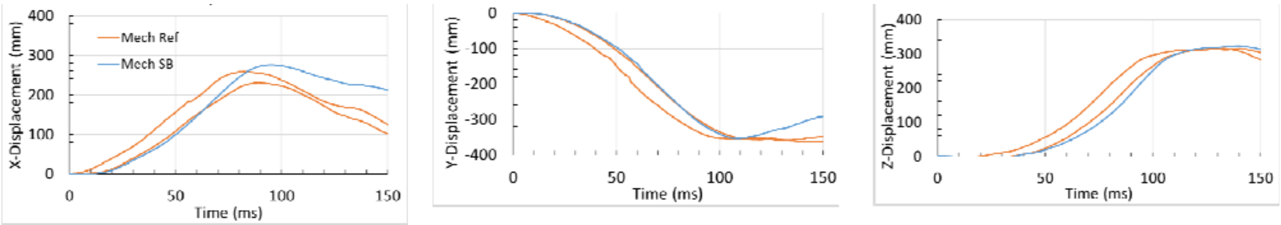


Fig. 5. Head CG displacement for both model and test (x, y and z direction)

Upper shoulder belt force-time history is shown in Fig. 6. The belt forces started to build at approximately 30ms. The pretensioning force in the reference tests was approximately 2kN and the peak force was 5kN. For the split buckle configuration the pretensioning force was 3kN and peak force was 6kN. In addition the duration of the force in the split buckle configuration was greater than in the reference configuration... Peak forces were reached at approximately 80ms.

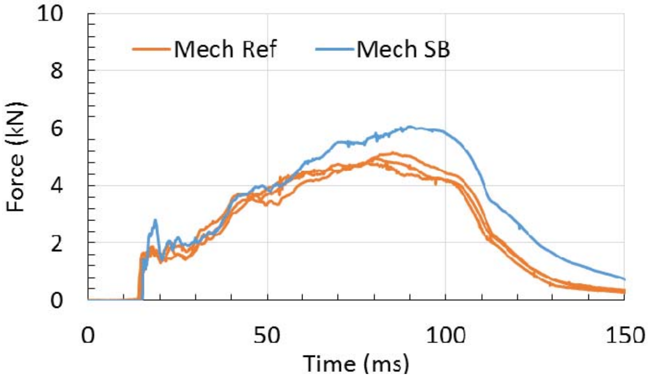


Fig. 6. Shoulder belt force for mechanical test and mathematical model. Reference seat belt.

For both the reference and split buckle configurations greatest resultant and x-direction chest deflection was found at the upper left IR-TRACC (Fig. 7). Peak resultant and x-direction chest deflections for the reference configuration were 35mm and 33mm respectively. For the split buckle configuration peak resultant and x-direction deflections were 25mm and 24mm respectively. Based on the resultant chest deflection the mechanical THOR tests using the reference belt system resulted in 11% risk of AIS3+ thoracic injury for a 45 year old occupant. Corresponding risk for a 65 year old occupant was 31%. Based on the resultant deflection for the mechanical THOR tests using the split buckle restraint system resulted in 2% risk of AIS3+ thoracic injury for a 45 year old occupant. Corresponding risk for a 65 year old occupant was 7%.

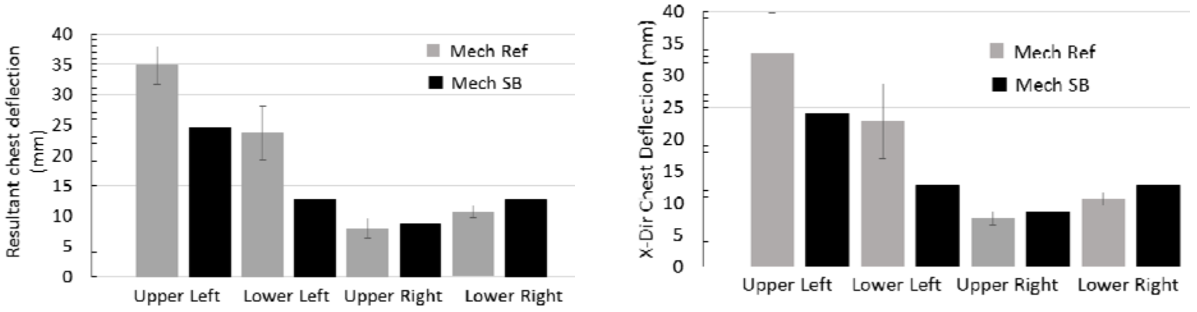
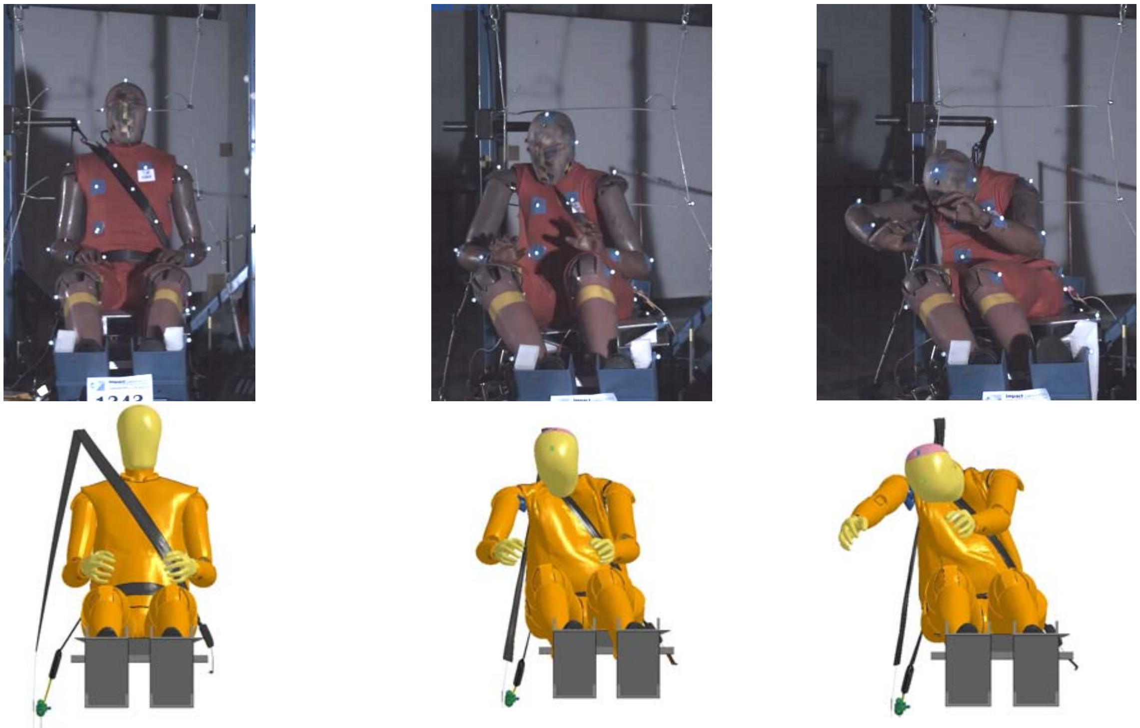


Fig. 7. Resultant and x-direction chest deflection for both mechanical THOR in reference and split buckle configurations. Error bars correspond to ±1 standard deviation for the three mechanical tests in the reference configuration.

Comparison Mechanical THOR dummy Response to Mathematical THOR Model Response

Overall similar predicted and measured kinematics for the occupant in the reference and split buckle configurations were observed (Fig. 8). However, there were some differences in the arm and lower leg kinematics between the mechanical THOR and the mathematical THOR model. The arms in the mathematical THOR were straighter than the arms in the mechanical THOR and the lateral displacement of the knees for the mathematical THOR was smaller than for the mechanical THOR.



0ms 75ms 100ms

Fig. 8. Frontal view of THOR kinematics for the mechanical test as well as the mathematical model at 0, 75 and 100ms.

The predicted pelvis displacement was greater than the measured for both the reference and split buckle configurations (Fig. 9). In y-direction there was agreement between the predicted and measured pelvis displacements for the reference configuration. For the split buckle configuration the predicted y-displacement was greater than the measured one. For both the reference and split buckle configurations the predicted and measured pelvis displacements in z-direction were small.

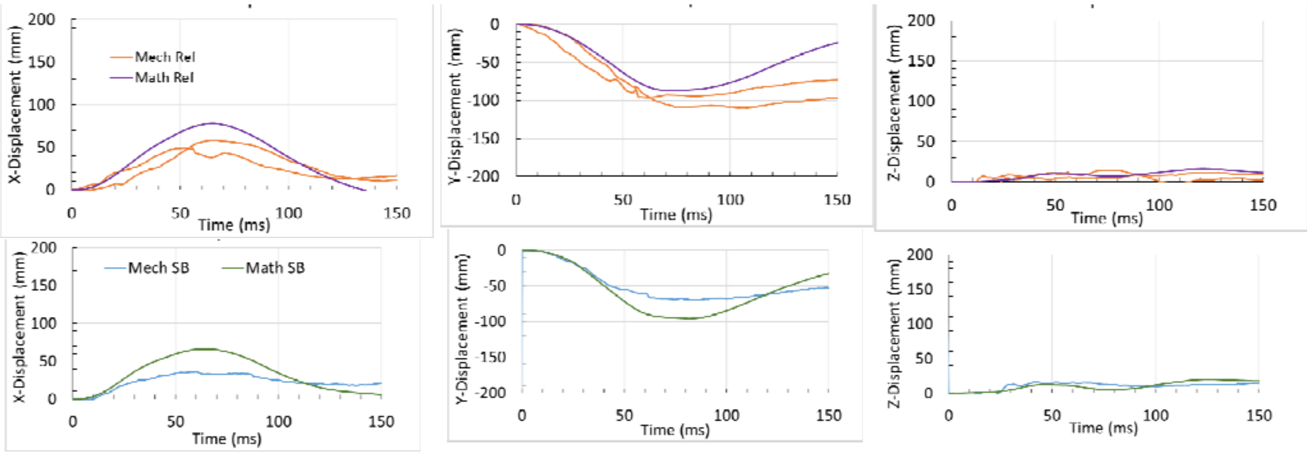


Fig. 9. Pelvis CG displacement for reference configuration (top row) and split buckle configuration (bottom row) comparison (X, Y and Z direction).

For both the reference and split buckle configurations there was agreement between the predicted and measured head displacement in x-direction (Fig. 10). In y- and z-directions the predicted displacements were smaller than the measured for both configurations.

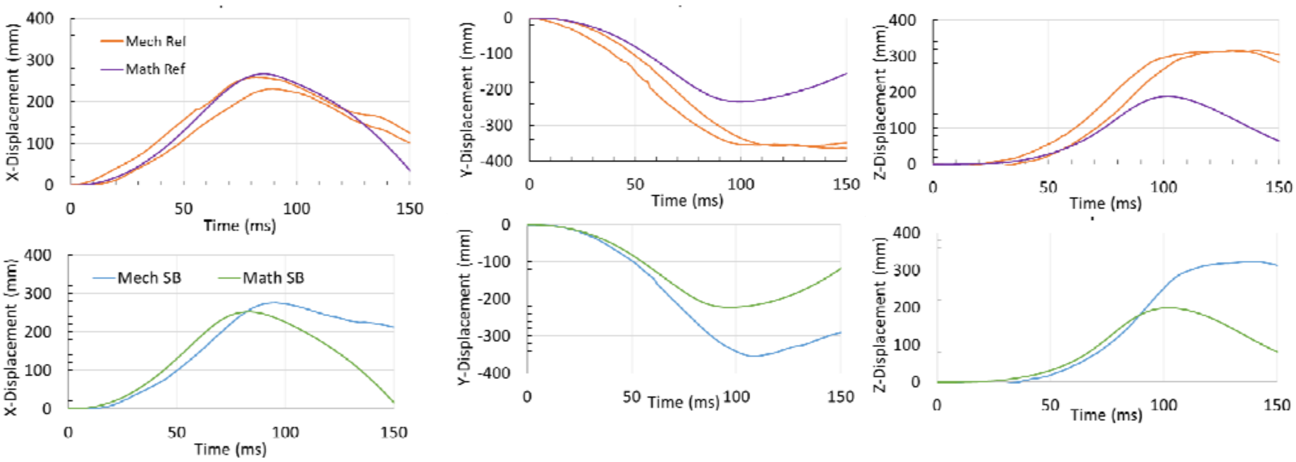


Fig. 10. Head CG displacement for both model and test (X, Y and Z direction)..

Upper shoulder belt force-time history comparison is shown in Fig. 11. The pretensioning force was predicted for both configurations. However, the predicted peak force was less than the measured one. In addition the duration of the predicted forces for both configurations were shorter than the measured.

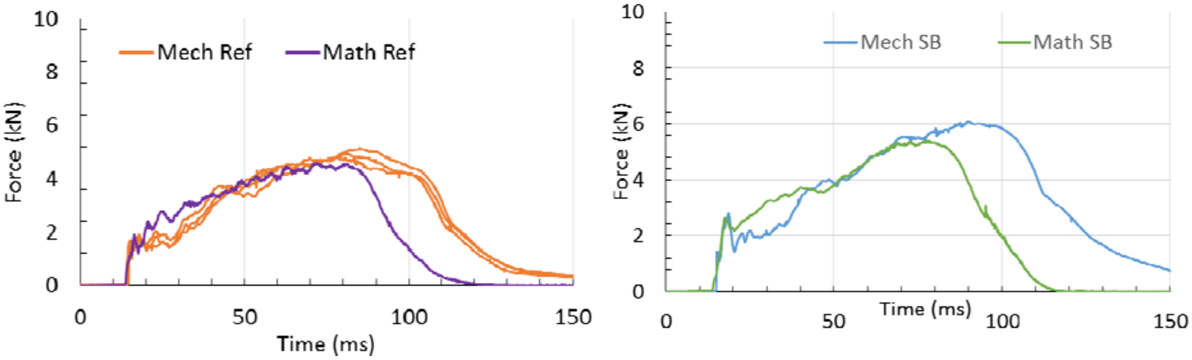


Fig. 11. Shoulder belt force for the reference configuration and split buckle configuration.

The CORA score for both models is shown in Fig. 12. The total score was 0.64 for the reference configuration while for the split buckle the score was 0.60 (Fig. 12). Highest score for both configurations was for the head displacement. High score was also obtained for the pelvis displacement. For the split buckle configuration low score was obtained for chest deflection. The score for the boundary condition belt force was 0.9 for both configurations.

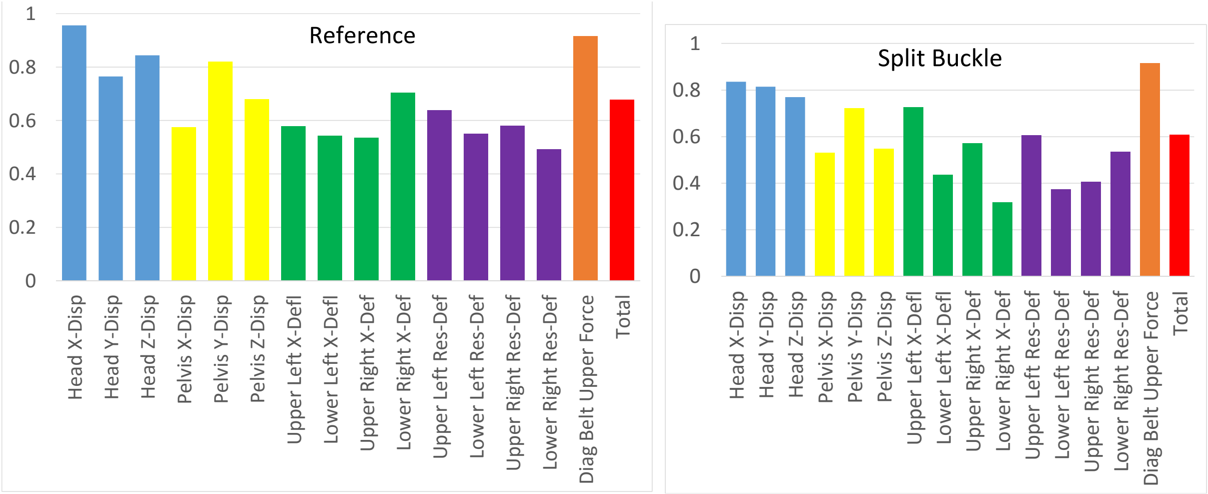


Fig. 12. Cora score for reference and split buckle configurations.

IV. DISCUSSION

The rigid steel fixture used in the tests and simulations was developed for biofidelic evaluations and development of ATDs (crash test dummies). However, due to the fact that the seat is rigid, excessive pelvis x-displacement was observed in frontal crash testing the seat was modified with an edge to limit pelvis x-displacement. The pelvis displacement observed in testing with the rigid steel fixture was greater than observed in tests with vehicle seats. In addition, for oblique impacts it was feared that the dummy would slide off the seat in the tests. The modified seat reduced pelvis excursion in both x- and y-direction. The displacement was found to be more similar to the displacement of the pelvis in a vehicle seat. Thus, the results included here support the use of the modified Gold Standard fixture in further biofidelity analyses of human surrogates using different types of restraints. The new seat geometry provided additional restraint to the pelvis and, as consequence, the knee bolster could be eliminated from the test fixture. The THOR dummy is proposed by NHTSA to be used in the recently developed oblique testing configuration [6]. There is a need of assessing THOR's mechanical behaviour under oblique loading and to check whether the dummy is able to discriminate between different types of restraints. In addition, it is also necessary to benchmark the predictions given by the FE-model of THOR against the results of actual sled tests. Thus, this study evaluated THOR kinematics in oblique impacts for two different restraint systems. The evaluation included both physical tests and computer modelling. One restraint system consisted of a standard belt system with a pretensioner and load limiter. In the other restraint, the diagonal belt and lap belt were separated with pretensioner at the diagonal belt and dual pretensioners at the lap belt. Studies of real-life data have shown that in combination with head injuries, chest injuries are common in oblique crashes [21-22]. The current study aimed to evaluate the kinematics and also the load to the occupant from the seat belt in near-side oblique frontal impacts. For the test conditions in which repeated tests were run (reference seat belt), the THOR dummy showed repeatable results in the displacement of the head and pelvis, thoracic deflection and measured shoulder belt force. Regarding the head, the physical tests showed that the displacement of the head CG was greater in the lateral direction (in the range of 350 mm) than in the fontal direction (around 250 mm), regardless of the seat belt used. A similar result had been observed in PMHS tests exposed to the same loading conditions in the reference belt configuration [23]. Previous PMHS sled tests exposed to approximately the same deceleration pulse but using different seats and seatbelts had already shown a very important lateral component to this loading condition [24]. The first consideration is that the THOR physical dummy was in agreement with the kinematics observed in the PMHS tests. The second one is that such a significant lateral head excursion makes it necessary to pay attention to side airbag designs in these small overlap or nearside oblique impacts. The simulations performed with the THOR dummy model showed that the model slightly over-predicted the peak head excursion in the x-direction but under-predicted the lateral head excursion of the physical dummy.. A contributing factor to these differences can be that in the model the location of the head and pelvis accelerometers were used to calculate the displacement, while in the mechanical tests the displacement of head CG location and pelvis internal location were computed based on external bilateral markers attached to the H-point of the subject. Also, there might be small differences in the design of the pelvis between the THOR-M and the THORAX THOR, although these differences have been never quantified. Despite of it, the differences observed in the predicted displacement indicate the need for further improvement of the mathematical model of the THOR dummy if it is to be used as surrogate in this type of oblique loading. As for the thorax response, chest injury reducing benefits with the split buckle system had been reported in pure frontal impacts [14]. In this study, chest injury reducing benefits were also obtained with the split buckle system in near side oblique impacts. In the mechanical tests peak chest deflection in x-direction (upper left) was reduced from 35mm to 24mm with the split buckle system. In the mathematical model chest deflection was reduced from 41 to 29mm. The reason for the difference in chest deflection between the mechanical THOR dummy and the mathematical THOR FE-model is not clear, although both surrogates predicted a similar reduction of deflection. The split buckle system alters the load distribution on the body from the lower part of the chest towards the shoulder area providing the same restraining effect in terms of excursion but reducing the loading of the rib cage, which consequently reduced the injury risk. However, the effect of increased load to the shoulder has to be investigated in more detail in future studies.

The simulations with the THOR model allowed identifying differences in the belt motion over the occupant's torso between the reference belt system and the split buckle system (Fig. 13). Initially the routing of the diagonal belt across the chest of the occupant was similar. However, between 40 and 50ms the diagonal belt for the reference system slided off the clavicle and loaded the sternal plate. For the split buckle system, the belt also slided off the clavicle but later in the crash sequence (60ms). Therefore, the split buckle system can increase the load on the clavicle of the occupant. Again, this modification of the loading path requires further study.

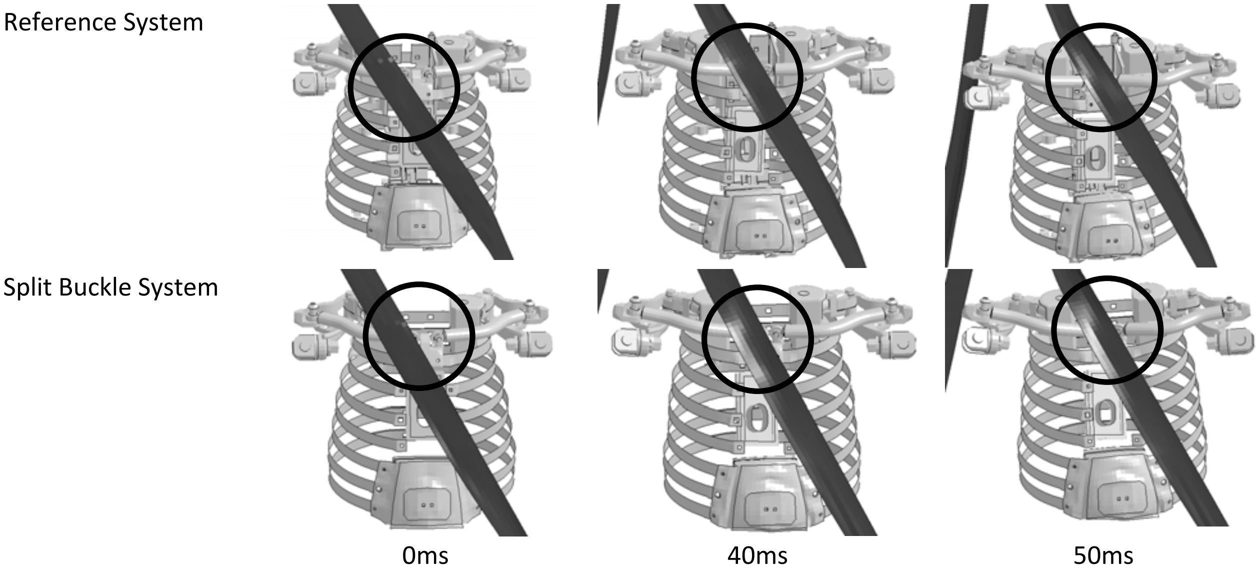


Fig. 13. Diagonal belt kinematics

Based on experience for a signal comparison with a CORA score of clearly better than 0.8 good correlation can be assumed [25]. Correlations with a score of 0.7 or higher can also be assumed as good. In the comparison between the mechanical THOR dummy and the mathematical THOR dummy model the CORA score for almost all signal comparisons were below 0.7. Only head displacements and the boundary conditions (belt forces) for both configurations were greater than 0.7. Therefore additional development and validation efforts for the THOR dummy model seems necessary.

V. CONCLUSIONS

The modified test seat provided more vehicle-like pelvis kinematics than the original Gold Standard seat design. Both the physical and the computational THOR ATDs were able to discriminate between two different types of seat belt (reference and split buckle). The THOR dummy showed good repeatability for the displacement of the head and pelvis, shoulder belt forces and thoracic deflection with the reference seat belt, which was the only condition for which repeated tests were run. The split buckle restraint demonstrated significant injury reducing benefits in the oblique loading condition. Based on the CORA score, the THOR mathematical model head displacement predictions were the only predictions with good correlation.

VI. ACKNOWLEDGEMENT

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VII. REFERENCES

[1] Bean, J, Kahane, C, Mynatt, M. Fatalities in frontal crashes despite seat belts and air bags - Review of all CDS Cases - Model and Calendar Years 2000-2007 - 122 Fatalities. NHTSA Technical Report DOT HS 811 202. 2009.

[2] Hallman, J, Yoganandan, N, Pintar, F, Maiman, D. Injury difference between small and large overlap frontal crashes. Annual Proceedings of the Association of the Advancement of Automotive Medicine (AAAM) 2011.

2011. Paris, France.

[3] Mueller, B, Sherwood, C, Arbelaz, R, Zuby, D, Nolan, J. Comparison of Hybrid III and THOR dummies in paired small overlap tests. STAPP Car Crash Journal. 2011;55:379-409, 2011.

[4] Rudd, R, Scarboro, M, Saunders, J. Injury analysis of real-world small overlap and oblique frontal crashes. 22nd ESV Conference. 2011. Seoul, Korea.

[5] IIHS. Small overlap frontal crashworthiness evaluation crash test protocol (Version II). Rating protocol from Insurance Institute of Highway Safety. 2012.

[6] Saunders J, Ames E. NHTSA oblique crash test results: vehicle performance and occupant injury risk assessment in vehicles with small overlap countermeasures. Proceedings of the 24th ESV Conference, paper No 15-0108, 2015. Gothenburg, Sweden.

[7] Sunnevång C, Hynd D, Carroll, J, Kruse, D, Boström, O, Evaluation of near-side oblique frontal impacts using THOR with SD3 shoulder. Traffic Inj. Prev. 2014;15, 2014.

[8] Parent, D, Craig, M, Ridella, S, McFadden, J, Thoracic biofidelity assessment of the THOR Mod Kit ATD. Proceedings of the 23rd ESV, 2013. Paper No 13-0327.

[9] Shaw, G, Crandall, J, Butcher, J. Biofidelity evaluation of the THOR advanced frontal crash dummy. Proceedings of the IRCOBI Conference. 2000. Montpellier; France.

[10] Yoganandan, N, Schlick, M, Moore, J, Maiman, D. Comparison of head-neck responses in frontal impacts using restrained human surrogates. Annual Proceedings of the Association of the Advancement of Automotive Medicine (AAAM). 2011;55:181-91, 2011.

[11] Lopez-Valdes, F, Lau, J.J., Lamp, J. Analysis of spinal motion and loads during frontal impacts, comparison between PMHS and ATD. Annual Proceedings of the Association of the Advancement of Automotive Medicine (AAAM) 2010:54. 2010.

[12] Shaw, G, Parent, D, Purtsezov, S. Impact response of restrained PMHS in frontal sled tests: Skeletal deformation patterns under seat belt loading. Stapp Car Crash Journal 2009, 53:1-48, 2009.

[13] Lopez-Valdes, F, J, Juste, O, Pipkorn, B, Garcia-Munoz, I, Sunnevang, C, Dahlgren, M, Alba, J, J, A. Comparison of the performance of two advanced restraint systems in frontal impacts. Traffic Injury Prevention 15 Suppl 1, S119-25, 2014.

[14] Pipkorn, B, Lopez-Valdes, F, Juste-Lorente, O, Insausti, R, Lundgren, C, Sunnevång, C. Assessment of an Innovative Seatbelt with Independent Control of the Shoulder and Lap Portions Using THOR Tests, the THUMS Model and PMHS Tests. Annual Proceedings of the Association of the Advancement of Automotive Medicine (AAAM) 2016 2016. *Under review*.

[15] Forman, J, Lopez-Valdes, F, Lessley, D, Riley, P, Sochor, M, Heltzel, S, Ash, J, Perz, R, Kent, R. Occupant kinematics and shoulder belt retention in far-side lateral and oblique collisions: A parametric study. Proceedings of the 57th Stapp Car Crash Conference

[16] Lemmen P, Been B, et al. Development of an advanced frontal dummy thorax demonstrator. Proceedings of the IRCOBI Conference, 2012, Dublin, Ireland.

[17] Lemmen P, et al. An advanced thorax-shoulder design for the THOR dummy. Proceedings of the 23rd ESV Conference, 2013, Seoul, South Korea.

[18] Parent D, Craig M, Ridella S, MacFadden J. Thoracic biofidelity assessment of the THOR Mod Kit ATD. Proceedings of the 23rd ESV Conference, 2013, Seoul, South Korea.

[19] Gehre, C, Gades, H, Wernicke, P. Objective rating of signals using test and simulation responses. Proceedings of the 21:st ESV, 2009.

[20] Lemmen, P, Carroll, J, Hynd, D, Davidsson, J, Martinez, L and Eggers A. An advanced thorax-shoulder design for the THOR dummy. Proceedings of the 23rd ESV Conference, Paper No. 13-0171. 2013.

[21] Brumbelow, M, Zuby, E. Impact and injury patterns in frontal crashes of vehicles with good ratings for frontal crash protection. Proceedings of the 21:st ESV Conference. 2009.

[22] Lindqvist, M, Hall, A, Björnstig, U. Kinematics of belted fatalities in frontal collisions: A new approach in deep studies of injury mechanisms. J Trauma 2006;61:1506-1516, 2006.

[23] Lopez-Valdes, F,J, Juste-Lorente, O, Maza-Frechin, M, Pipkorn, B, Sunnevang, C, Lorente, A, Aso, A, Davidsson, J. Analysis of occupant kinematics and dynamics in nearside oblique impacts. Traffic Injury Prevention (2016 AAAM Conference), Special Issue. 2016. *Under review.*

[24] Tornvall, F, V, Svensson, M, Y, Davidsson, J, Flogard, A, Kallieris, D, Haland, Y. Frontal impact dummy kinematics in oblique frontal collisions: evaluation against post mortem human subject test data. Traffic Injury Prevention 6, 340-350, 2005.

[25] Gehre, C., Stahlschmidt, S. Assessment of dummy modes by using objective rating methods. Proceedings of the 22nd ESV Conference. 2011. Seoul, Korea.