Investigation of Pelvis Kinematics for Various Lap Belt Positions and an Inflatable Pelvis Restraint Cushion Using a Human Body Model of a Female Occupant

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ABSTRACT

A human body model of a female post-mortem human subject (PMHS) was created by anthropometric scaling of the THUMS adult male 50th perc. finite element model. The kinematic response of the scaled human model was correlated by means of PMHS sled tests. The force-displacement responses of the seat, the seat belt and an inflatable pelvis restraint cushion (PRC) of the finite element sled model were correlated by means of Hybrid III 50th perc. mechanical sled tests.

The scaled THUMS model was positioned in the sled model and its response correlated in 56km/h by means of one PMHS test with a standard seat and two PMHS tests with a seat-mounted PRC. Accelerations and displacements in the head, chest and pelvis together with pelvis rotations, belt forces and seat forces from the model were compared to that of three PMHS sled tests. For the scaled THUMS models, a CORA rating of 0.75 was obtained using the standard seat and 0.76 using the seat-mounted PRC.

The correlated scaled THUMS model was then used for investigating how the lap belt position and a seat-mounted PRC affects pelvis kinematics and the risk of submarining. The investigation was carried out for a belted passenger side occupant in the vehicle interior of a mid-sized sedan. The risk for submarining was measured by recording the distance between the pelvic bone anterior superior iliac spine (ASIS) points to three points on the lap belt.

Lap belt positions with the belt midpoint 55mm (baseline) and 86mm (upper) above ASIS were investigated. In general, increased pelvis displacements and increased risk of submarining was obtained for the upper compared to the baseline lap belt position. Compared to a system without lap belt pretensioner and PRC, pelvis displacements were reduced by 12% and 9% using a lap belt pretensioner and by 61% using the PRC for the baseline and upper positions respectively. Rearward pelvis rotations were reduced by 56% using the PRC for both lap belt positions while slightly increased rearward pelvis rotations was obtained using the lap pretensioner. Using both the lap pretensioner and the PRC, pelvis displacements were reduced by 71% for the baseline position and by 70% for the upper position. Based on the submarining distance measurement, submarining was prevented using the PRC for both lap belt positions. Additional reduction in the risk of submarining was obtained by combining lap pretensioning with the PRC.

INTRODUCTION

Submarining is the phenomenon of the pelvis sliding under the lap portion of the seat belt in a vehicle crash. The sliding of the lap belt over the pelvis and the following loading to the abdomen was suggested as the injury mechanism causing injuries to the hollow abdominal organs such as the small interstine, large intestine and mesentery [1]. It was also found that the risk of AIS2+ injuries to the abdominal organs inceased with the increase in ΔV, age and, although not statistically significant, BMI. No association with submarining-related injuries was found for occupant seating location and gender.

It has been shown that most occupants in the vehicle wear the lap belt well superior of the anterior superior iliac spines (ASIS) of the pelvis [2]. Especially for older and overweight occupants, the amount of soft tissue in the lower abdomen and femur prevents fitting of the lap belt in the optimal position relative to the pelvic bone.

The pelvis restraint cushion (PRC) is a folded metallic sheet metal device which is mounted between the seat structure and the seat foam, Figure 3. The PRC is designed to add restraining support to the pelvis in the inflated state without affecting the seat comfort in the folded state. A metallic inflatable cushion was evaluated by means of static deployment tests using HIII 5th perc. small female dummy, the HIII 50th perc. male dummy and PMHS [3]. In the tested occupant positions, in-position and out-of-position, low Hybrid III dummy lumbar spine forces and moments were measured and no injuries in the PMHS were observed.

The importance of controlling the pelvis rotation was identified using dummy tests and Madymo simulations [4]. Submarining was found likely to occur when a critical angle between the pelvic bone and the lap belt is reached. In addition to the lap belt versus pelvic bone angle, increased lap belt force resulted in reduced risk of submarining [5].

One of several mathematical models of humans which have been developed to improve the understanding of human impact response and injury mechanisms is the Total Human Model for Safety (THUMS) finite element model [6]. The THUMS model represents an adult mid-sized male with respect to anthropometry and biomechanical properties such as bone stiffness and skin flexibility. The bony body parts are modelled using solid elements for the trabecular bone and shell elements for the cortical bone. Internal organs are modelled in a simplified manner by upper abdomen, lower abdomen and lungs. The superficial soft tissues are modelled using solid elements and the skin using shell elements.

The Autoliv THUMS model was derived from the THUMS model version 1.4. In-house validations and modifications have been carried to improve its biofidelity based on results from PMHS tests. The predictability of whole-body kinematics of the THUMS model was evaluated by means of frontal sled tests [7]. The thorax of the THUMS model was validated in four table-top, hub, diagonal belt, distributed and criss-cross belt [8].

In this study, the first objective was to correlate a human body finite element model of a female subject with respect to the kinematic response and secondly, to use the correlated model for investigating how the lap belt position and the use of a seat-mounted inflatable pelvis restraint cushion affects pelvis kinematics and the risk of submarining.

METHOD

Correlation of the System FE-Model
The finite element system model consisted of a front passenger compartment of a 2014 Hyundai Elantra body-in-white (BiW) with an instrument panel, a front seat and a double pretensioned and load limited 3-point belt system, Figure 1.
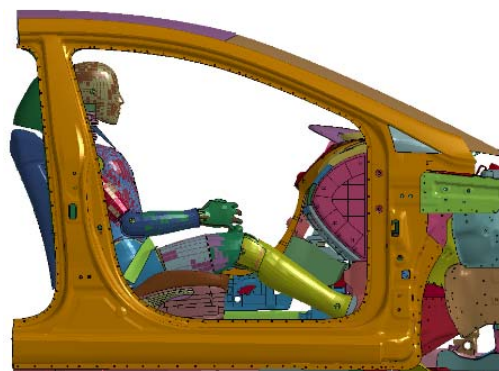

Figure 1. Passenger side system model

The standard seat was modified to incorporate an inflatable metal pelvis restraint cushion (PRC, Figure 2) by reinforcements to the seat frame and the seat rails. The folded PRC was inflated using a pyrotechnic gas generator, Figure 3.

Figure 2. Metal pelvis restraint cushion (PRC) in the front seat (post test).

The seat, seat belt and PRC models of the system FE-model were correlated by means of two Hybrid III mechanical sled tests in 56km/h using the Humanetics Hybrid III 50th %-ile FE-model Version 7.1.8. The crash pulse approximated that of the 2013 Hyundai Elantra USNCAP frontal pulse with a peak acceleration of 38g. Sled test 284 was carried out with the standard seat and sled test 287 with the seat mounted PRC [9]. Both tests were carried out with the seat in the most rear position using a 3-point belt system with retractor pretensioner, 4kN load limiting and lap belt pretensioner (PLP). No passenger airbag was used.
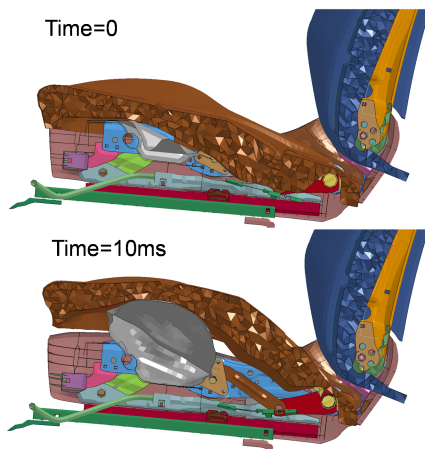

Figure 3. Folded and inflated PRC in the seat FE-model.

Anthropometric Scaling of the THUMS AM50 Model to a Female PMHS

A female post mortem human subject (PMHS 654) was chosen as the target subject for the anthropometric scaling of the Autoliv THUMS adult male 50th FE-model. This subject was estimated suitable as target subject due to its high BMI (27) and thus likely increased susceptable to submarine because of poor initial belt fit [1,2].

Target subject anthropometric measurement according to Table 1 was used to extract a detailed target subject from the RAMSIS anthropometric database [10], Figure 4. In Table 1, sitting height, neck length, upper arm length and buttock knee length were not known for the target subject. Instead these measures were taken from RAMSIS database "Germany 2004" for females 50-70yrs and reference year 2013. Shoulder width deltoidal, hip width and knee height were extracted from CT-scan measurement of the target subject.

**Table 1.
Target Subject Definition for RAMSIS**

Num	Body Dimension	Subject 654 (mm)
1	Body height	1665
2	Sitting height	880
3	Head height	210
4	Head width	145
5	Head depth	185
6	Neck length	90
7	Shoulder width deltoidal	441
8	Upper arm length	298
9	Forearm length with hand	425
10	Forearm circumference	240
11	Chest width	315
12	Chest depth	215
13	Waist circumference	925
14	Pelvis width	360
15	Hip width	406
16	Buttock knee length	606
17	Knee height sitting	509
18	Foot height	70
19	Foot length	230
20	Foot width (breadth)	82
21	Upper arm circumference	315
22	Calf circumference	370
23	Thigh circumference	570
	Weight (kg)	74
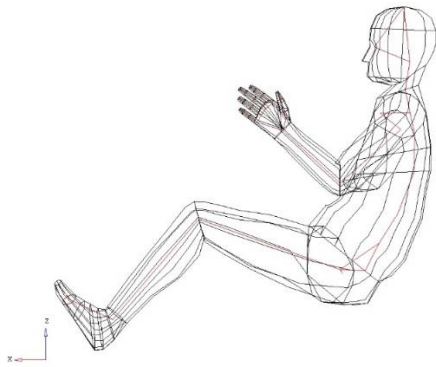
Figure 4. RAMSIS CAD-model of the target subject PMHS 654 (in THUMS posture).

Figure 5. Passenger side system model with scaled THUMS.

Using the detailed anthropometric description of the target subject (Figure 4), the scaling of the THUMS was carried out in four scaling steps:

Step 1: Each body segment was scaled by the ratio of its characteristic depth, width and length of THUMS to the RAMSIS target subject. Step 2: The morphing of the superficial soft tissues for each segment of the THUMS was carried out to account for the shape of the skin. Step 3: The morphing of the pelvic bone was carried out to account for the female anthropometry of the PMHS. Step 4: The whole body mass of THUMS was scaled to match the whole body mass of the RAMSIS target subject.

In order to improve the stability of the scaled THUMS model in belt to pelvis interactions, the pelvis external soft tissue material model was replaced by a material model of adipose (fat) tissue [11].

Model Correlation Using the Scaled THUMS model to PMHS Sled Tests
The scaled THUMS model was positioned in the correlated system sled model, Figure 5. The responses of the THUMS system model was correlated by means of PMHS sled tests in 56km/h [12, 13]. One sled test was carried out using a standard seat and two sled tests with the seat-mounted PRC, Table 2. All tested PMHS were females with a BMI of 22 to 23. Compared to the scaled THUMS, the stature of the tested PMHS were similar and the body mass lower.
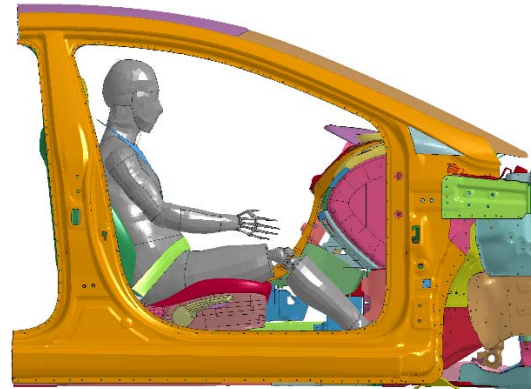
Table 2.
PMHS sled tests in 56km/h.

Test	PMHS	DV (kph)	Mass (kg)	Stature (cm)	Age	PRC	Sub
— 299	655	56	66,2	171,5	64	No	Yes
354	738	56	60,3	167,0	67	Yes	No
358	753	56	64,4	167,0	64	Yes	Yes

All PMHS tests were carried out with the seat in the mid position using a 3-point belt system with a retractor pretensioner, 4kN load limiting and a lap pretensioner. No passenger airbag was used.

Submarining was observed for the PMHS in test 299. For the two sled tests with the PRC, no submarining was obtained in test 354 and a submarining unlikely to be injurious in test 358 [13].

Pelvis and Lap Belt Positions The whole-body of THUMS was positioned in the average position from the three PMHS. Average positions of PMHS anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS) and pubic symphysis (PS) VICON measured points were used to position the pelvic bone of the scaled THUMS to the tested conditions, Figure 6.
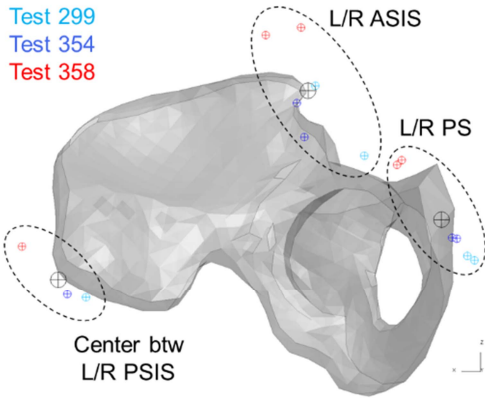
Figure 6. Pelvis position of the scaled THUMS model compared to test data. Average positions are indicated with large black circles.

Lap belt angle were calculated using a projection into the sagittal (XY) plane of the lap belt attachment point and the webbing midpoint, Figure 7. Pelvic angle was calculated from the center between left and right ASIS to the PS, with both points projected to the sagittal plane. Lap belt position relative ASIS was calculated from the center between left and right ASIS to the belt webbing midpoint, with both points projected to the sagittal plane. Geometry data for the mechanical tests were calculated from processed VICON measurements.
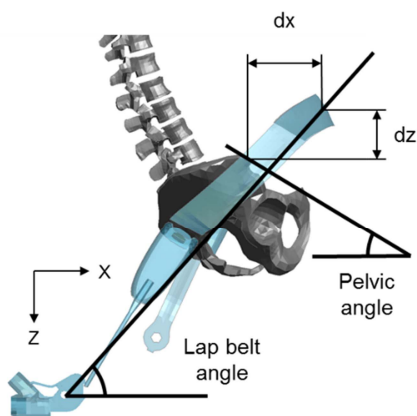
Figure 7. Definition of pelvic angle, lap belt angle and lap belt position relative pelvic bone.

A close agreement was obtained for the lap belt angles and the lap belt position relative ASIS for the THUMS system model compared to the average of the tests, Table 3. Initial angle of the

THUMS pelvic bone was close to the PMHS in test 354 but smaller than that of the other tested PMHS.

Table 3.
Lap belt geometry and position relative pelvic bone.

PMHS Test, Model	Lap belt to ASIS dx (mm)	Lap belt to ASIS dz (mm)	Lap belt outboard angle (deg)	Lap belt inboard angle (deg)	Pelvic angle (deg)
299	66	89	54	55	46
354	108	51	48	50	37
358	90	17	52	54	48
Aver.	88	52	51	53	44
THUMS	101	55	51	57	33

Submarining Distance In order to quantify the position of the pelvis relative to the lap belt, the parameter "Submarining Distance" was used [13], Figure 8. In [13] the submarining distance was defined as the X-axis position of the right ASIS of the pelvis relative to the X-axis position of the lap belt at the midline of the subject. In this study, the corresponding distance is measured at two additional planes, left and right ASIS sagittal planes, Figure 9. For all three measurement definitions, positive values of the submarining distance indicate that the ASIS is forward of the lap belt and thus the occurrence of submarining.
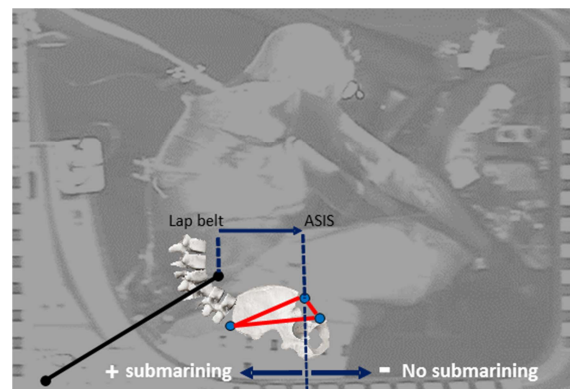

Figure 8. Submarining distance [9]. Positive values indicate submarining.

Figure 9. Definitions of measurement points for calculating the submarining distance.

CORA Rating

The correlation of seat, seat belt and PRC responses of the system FE-model was assessed using the CORA (CORrelation and Analysis) method [14]. The scaled THUMS was then positioned in the correlated system model and its responses assessed using CORA.

Using this method, the total rating is calculated using two correlation metrics, cross-correlation and corridor. The cross-correlation metric quantifies the correlation of the phase, size and shape of the model response to that of the test. In the corridor metric, the degree of fit of the model response to a corridor, derived from the test response, is evaluated.

In this study, the CORA rating for the (Hybrid III) system model was derived using 9 responses and for the THUMS system model using 11 responses (Table 4). The evaluation time window of 0-90ms was chosen to avoid the influence on the result from the occupant head to the instrument panel impact. A total CORA rating was calculated from two subcases, occupant response and boundary conditions.

Parameter Study

A parameter study was carried out to investigate the influence of the PRC, the lap pretensioner (PLP) and the lap belt position on the risk of submarining in 56km/h. The risk of submarining was measured using the submarining distance parameter.

The three parameters were combined according to Table 5. The upper lap belt position (86mm) corresponded to a displacement of app. one standard deviation from the tested lap belt

geometries. This distance is also close to the highest positioned lap belt (Test 299).

Table 4.
Hybrid III and THUMS system model responses in the CORA rating evaluation

	Hybrid III		THUMS
1	Head Res. Acc.	1	Head Res. Acc.
2	Chest Res. Acc.	2	Chest Res. Acc.
3	Pelvis Res. Acc.	3	Pelvis Res. Acc.
4	Lumbar X-Force	4	Head X-Disp.
5	Lumbar Z-Force	5	Chest X-Disp.
6	Lumbar Y-Moment	6	Pelvis X-Disp.
7	Belt Force Shoulder B3	7	Pelvis Y-Rot.
8	Belt Force Buckle B4	8	Belt Force Shoulder B3
9	Belt Force Lap B6	9	Belt Force Buckle B4
		10	Belt Force Lap B6
		11	Seat Res. Force

Table 5.
Parameter study 56km/h

Num	PLP	PRC	Lap belt to ASIS dz (mm)
1	PLP	-	55
2	PLP	PRC	55
3	-	-	55
4	-	PRC	55
5	PLP	-	86
6	PLP	PRC	86
7	-	-	86
8	-	PRC	86

RESULTS

Correlation of the System FE-Model

A total CORA rating of 0.82 to 0.88 was obtained for the Hybrid III system model, Figure 10 and Appendix 1. For the boundary conditions (i.e. belt forces), a rating of 0.86 to 0.91 was obtained. The total rating was lower for the seat-mounted PRC compared to the standard seat.
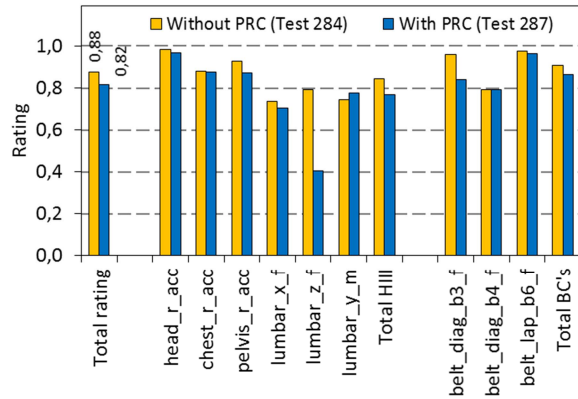
Figure 10. CORA rating for HIII in 56km/h with and without the metal PRC.

Anthropometric Scaling of the THUMS AM50

The main anthropometric body dimensions of the scaled THUMS are shown in Table 6. Compared to the THUMS AM50, the scaled THUMS was shorter in height with larger hip width and slightly smaller weight, Figure 11 and Figure 12.

Table 6.
Body dimensions for THUMS AM50 and scaled THUMS.

Body Dimension	THUMS AM50 (mm)	Scaled THUMS (mm)	Scaled THUMS Perc. (%)
Body height	1763	1665	77
Sitting height	915	880	86
Waist circumference	935	925	69
Hip width	374	406	70
Weight (kg)	76	74	-

Compared to THUMS AM50, the morphed pelvic bone of the scaled THUMS was app. 18mm smaller in the areas of the pelvic wings and the pubic arch, Figure 13.
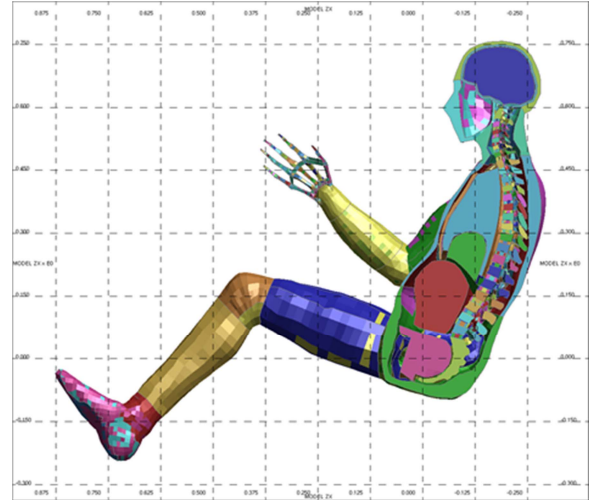
Figure 11. Anthropometry of the THUMS AM50 model.
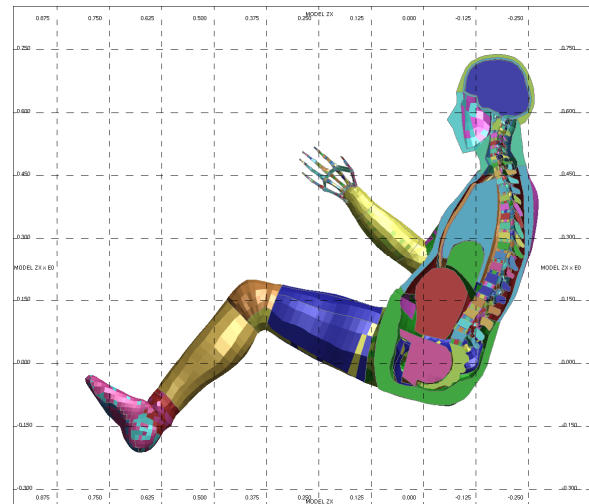
Figure 12. Anthropometry of the Scaled THUMS model.
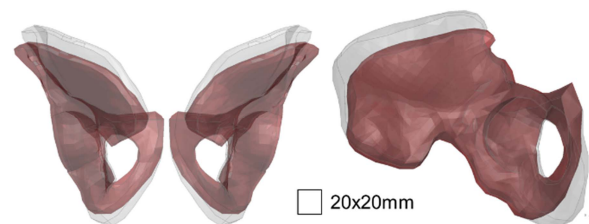
Figure 13. Anthropometry of the pelvic bone for the scaled THUMS (in red) compared to THUMS AM50 (in grey).

Model Correlation using THUMS

A total correlation rating of 0.75 was obtained for the THUMS system model using the standard seat and 0.76 using the seat-mounted PRC, Figure 14 and Appendix 2. Lowest rating was obtained for the pelvis y-rotation.
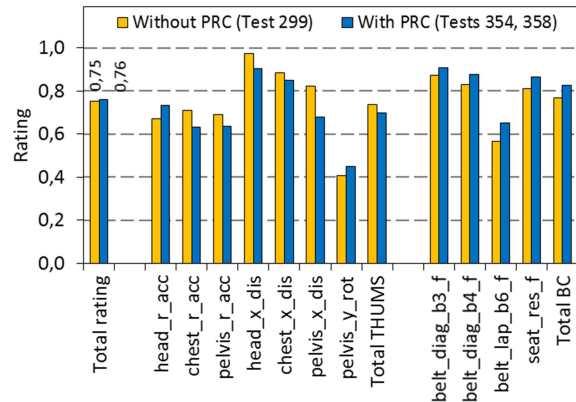
Figure 14. CORA rating for scaled THUMS in 56km/h with and without the metal PRC

For the standard seat, a forward-downward trajectory of the upper body and pelvis was obtained, Figure 15. For the seat-mounted PRC, forward-upward trajectory of the upper body and pelvis was obtained, Figure 16. With the seat-mounted PRC, pelvis x-displacements were reduced by 64% in the tests and by 67% in the FE-model.
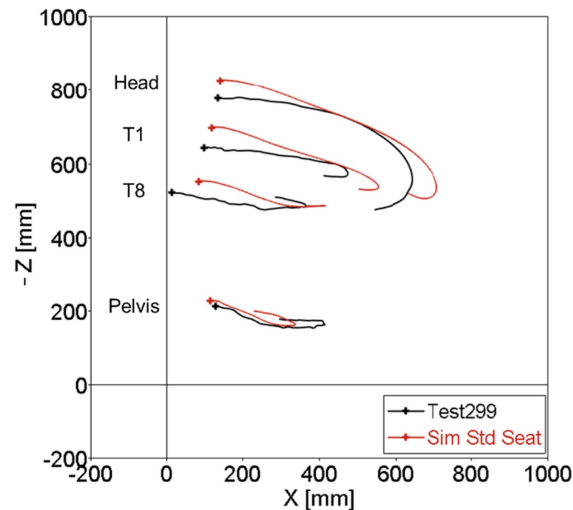
Figure 15. Head, T1, T8 and pelvis trajectories in the sagittal (XZ) plane for the test and FE-model with standard seat in 56km/h.
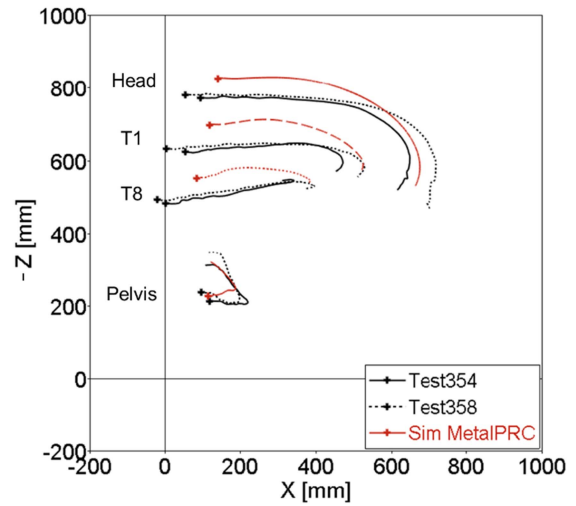
Figure 16. Head, T1, T8 and pelvis trajectories in the sagittal (XZ) plane for the tests and FE-model with seat-mounted metal PRC in 56km/h.

For the seat-mounted PRC, reduced pelvis rearward rotation, reduced lap belt force (tests only) and increased seat forces was obtained, Figure 17 to Figure 19.
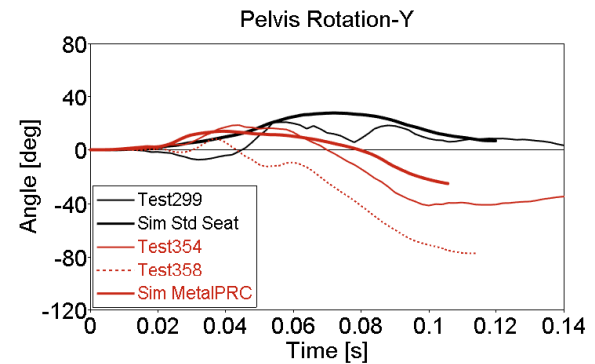
Figure 17. Pelvis rotations for standard seat compared to seat-mounted PRC (+ rearward rotation, - forward rotation).
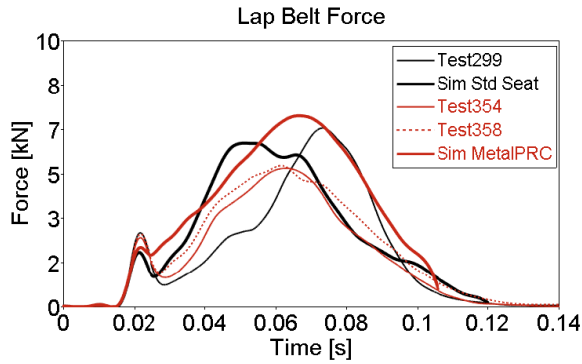
Figure 18. Lap belt force at sill for standard seat compared to seat-mounted PRC.
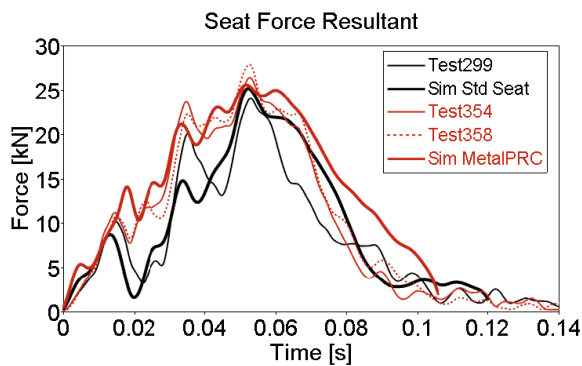

Figure 19. Seat force for standard seat compared to seat-mounted PRC.

The submarining distance was reduced from 182mm (indicating submarining) to negative 12mm (no submarining) and 40mm in the PMHS tests,
Figure **20**. For the THUMS model, the submarining distance was reduced from 92mm to negative values of 22 to 41mm, indicating no submarining.

Belt to pelvis interaction for the standard seat compared to the seat-mounted PRC is shown in Figure 21.
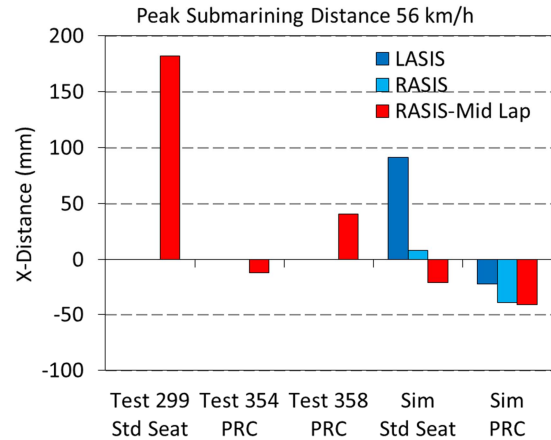
Figure 20. Peak submarining distance for standard seat compared to seat-mounted PRC.
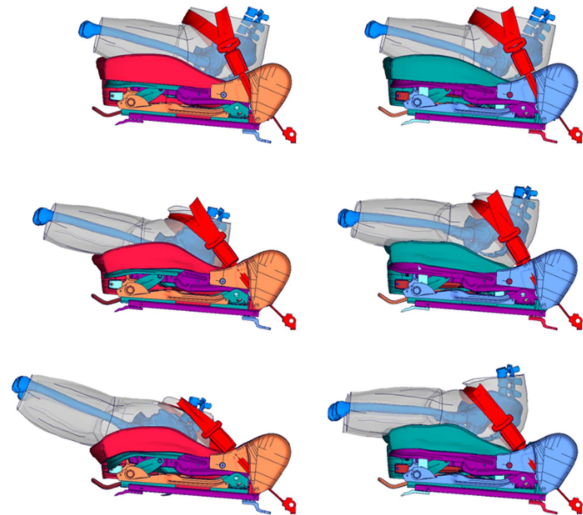
Figure 21. Belt to Pelvis Interaction at the time of 0ms, 50ms and 70ms (standard seat left, seat-mounted PRC right).

Parameter Study

Increased pelvis displacements and increased pelvis rotations was obtained for the upper (86mm) compared to baseline (55mm) lap belt position, Table 7 and Appendix 3.

Compared to the "no PLP, no PRC" combination, pelvis displacements were reduced by 12% using the PLP and by 61% using the PRC for the baseline lap belt position. The corresponding values of 9%

and 61% was obtained for the upper lap belt position.

For both lap belt positions, larger reduction in rearward pelvis rotation was obtained for the PRC compared to the PLP, Table 7.

Table 7.
Peak pelvis displacements and rotations for combinations of PLP and PRC (baseline and upper lap belt positions). Reduction values (%) are calculated with respect to the "No PLP, No PRC" combination.

Lap belt dz (mm)	PLP/PRC	Pelvis X-Disp (mm)	Pelvis Y-Rot (deg)
55	PLP only	224 (-12%)	28 (+4%)
55	PLP+PRC	73 (-71%)	14 (-48%)
55	No PLP, No PRC	254	27
55	PRC only	100 (-61%)	12 (-56%)
86	PLP only	256 (-9%)	30 (+11%)
86	PLP+PRC	83 (-70%)	15 (-44%)
86	No PLP, No PRC	280	27
86	PRC only	108 (-61%)	12 (-56%)

For both the baseline and the upper lap belt position, the submarining distance increased when removing the lap pretensioner (PLP), Figure 22 and Figure 23. For both lap belt positions, the PRC alone was enough to prevent submarining and a reduced risk of submarining was obtained by the addition of the PLP to the PRC.

In general, the submarining distance increased for the upper compared to the baseline lap belt position. For all cases, the largest submarining distance was obtained for the buckle side measurement point (LASIS).
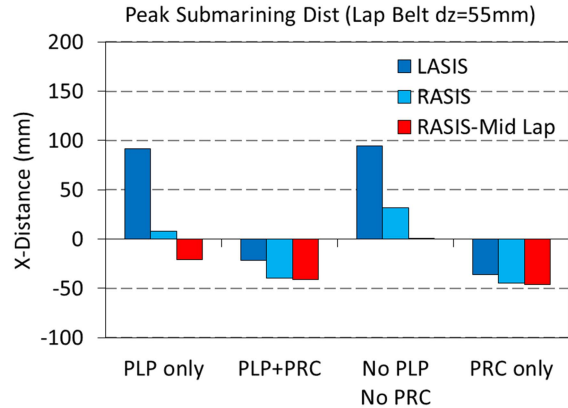

Figure 22. Peak submarining distances for the baseline lap belt position (dz=55mm)
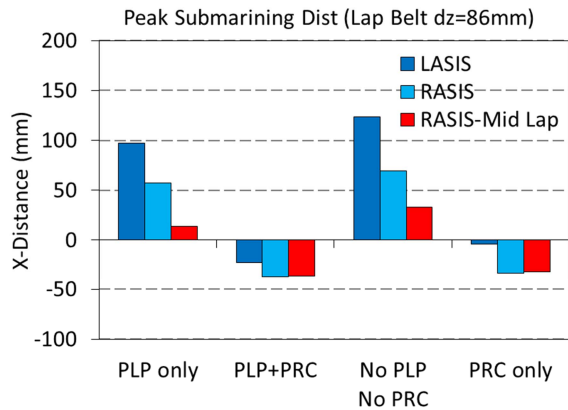

Figure 23. Peak submarining distances for the upper lap belt position (dz=86mm)

DISCUSSION

A female human body model was created by anthropometric scaling of the THUMS adult male 50th perc. finite element model. The kinematic response of the scaled model was correlated by means of PMHS sled tests and used for investigating geometry and restraint parameters potentially influencing the risk of submarining.

With the PRC, increased seat forces and reduced lap belt forces (PMHS tests only) leading to reduced pelvis displacements and reduced rearward pelvis rotations was obtained. Reduced submarining distance indicated less risk of the lap belt sliding in to the abdomen and thus reduced

risk of submarining. The benefit of the PRC was also observed in parameter study where the PRC prevented submarining for both the baseline and for an upper (30mm raised) lap belt position.

The effect from the PRC was also evaluated in 20km/h PMHS sled tests for two front seat positions, mid- and rearmost [16]. Also in these configurations, reduced pelvis displacements and reduced risk of submarining was obtained for the PRC compared to a standard seat.

Although no effect was found from gender on the belt fit nor on the risk of submarining-related injuries [2], a female anthropometry was used in this study. The effect of larger pelvic size for males compared to females should be investigated in a future study.

The two lap belt positions investigated in this study were both forward and higher than the mean position from [2], Figure 24. These positions thus covered the lap belt geometry for most of the occupants.
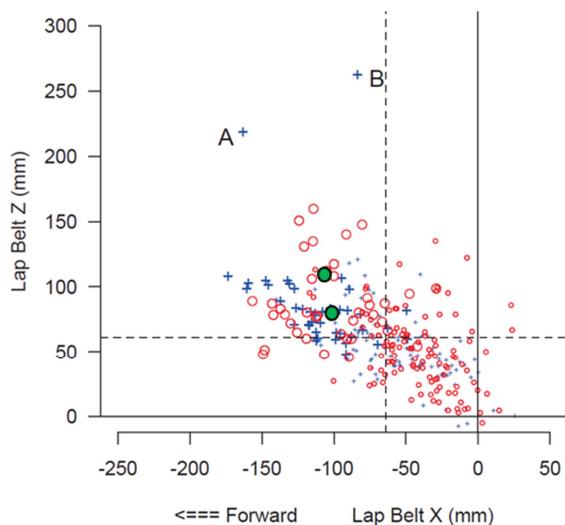
Figure 24. Lap belt location for males (+) and females (o) [2]. The data points are the location of the <u>upper edge</u> of the lap belt. Baseline and upper lap belt positions used in this study are marked with solid green circles.

Using the sliding scale in [15], a good to excellent biofidelity rating was obtained for the Hybrid III models (CORA 0.82-0.88) and a good biofidelity rating for the THUMS models (CORA 0.75-0.76).

Low rating was obtained for the head, chest and pelvis accelerations due to the noisy signals from the THUMS model. Low rating was also obtained for the pelvis rotation which can depend on the smaller initial pelvic angle (33deg) for THUMS compared to the tested PMHS (37-48deg), Table 3. The effect of the higher body weight of the scaled THUMS (74kg) compared to the tested PMHS (60-66kg) should also be investigated.

The scaled THUMS corresponded to a 69th perc. with respect to waist circumference and to a 70th perc. with respect to hip width according to RAMSIS anthropometric database "Germany 2004" for females 50-70yrs and reference year 2013, Table 6.

The standard seat was reinforced to allow installation of the PRC. The effect from the reinforcement has not been evaluated.

The results from this study indicate the importance of the seat response on the restraining of the pelvis for preventing submarining. The study also gives important insight in the restraining of the lower body for future sitting positions in highly automated driving (HAD) vehicles where more slouched, and even sleeping, occupant positions might be common.

CONCLUSIONS

Using the pelvis restraint cushion (PRC), pelvis displacements were reduced by 61% and rearward pelvis rotations by 56%.

Using both the PRC and the lap pretensioner, pelvis displacements were reduced by 70%.

The PRC was effective in preventing submarining (based on the submarining distance measure).

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the PMHS tests, processed the test data and contributed with valuable knowledge in the study.

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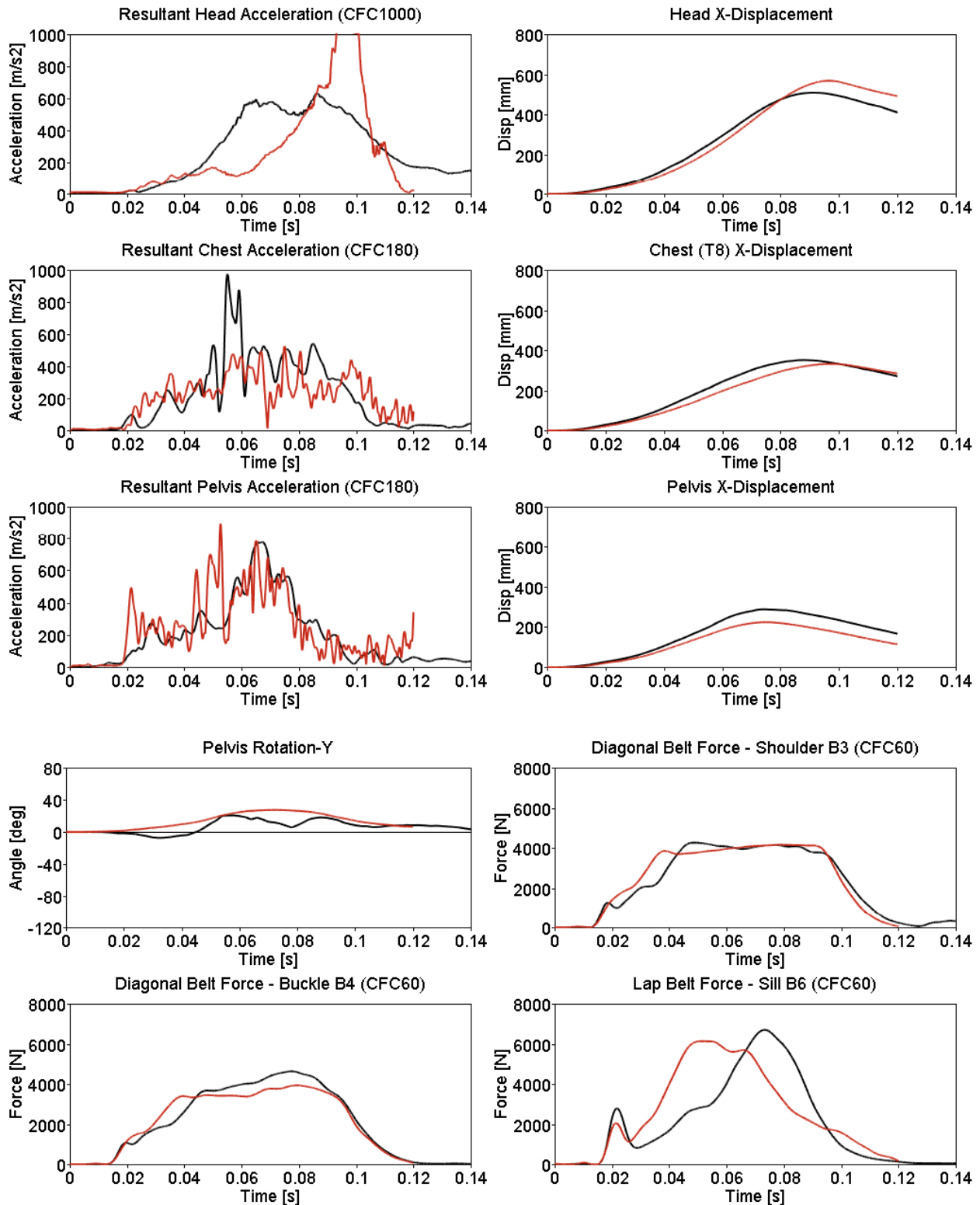## APPENDIX 1 – HYBRID III TESTS AND HYBRID III SIMULATION RESULTS

Test284 Std Seat ·········   Sim Std Seat ——— (red)
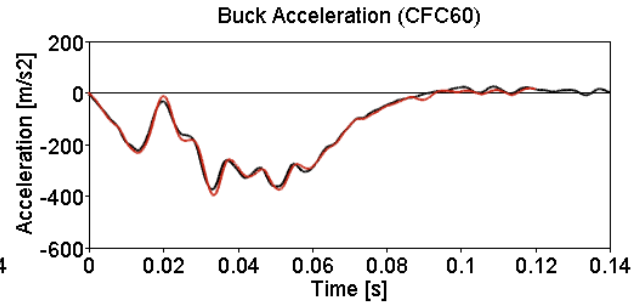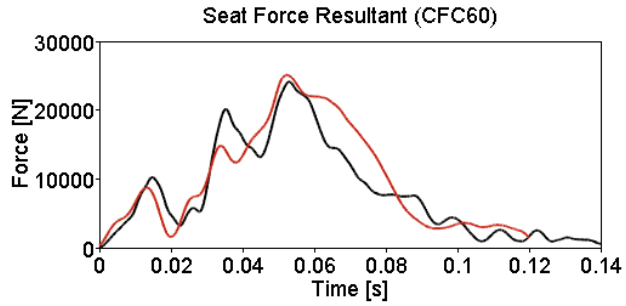Test287 MetalPRC ·········   Sim MetalPRC ——— (black)
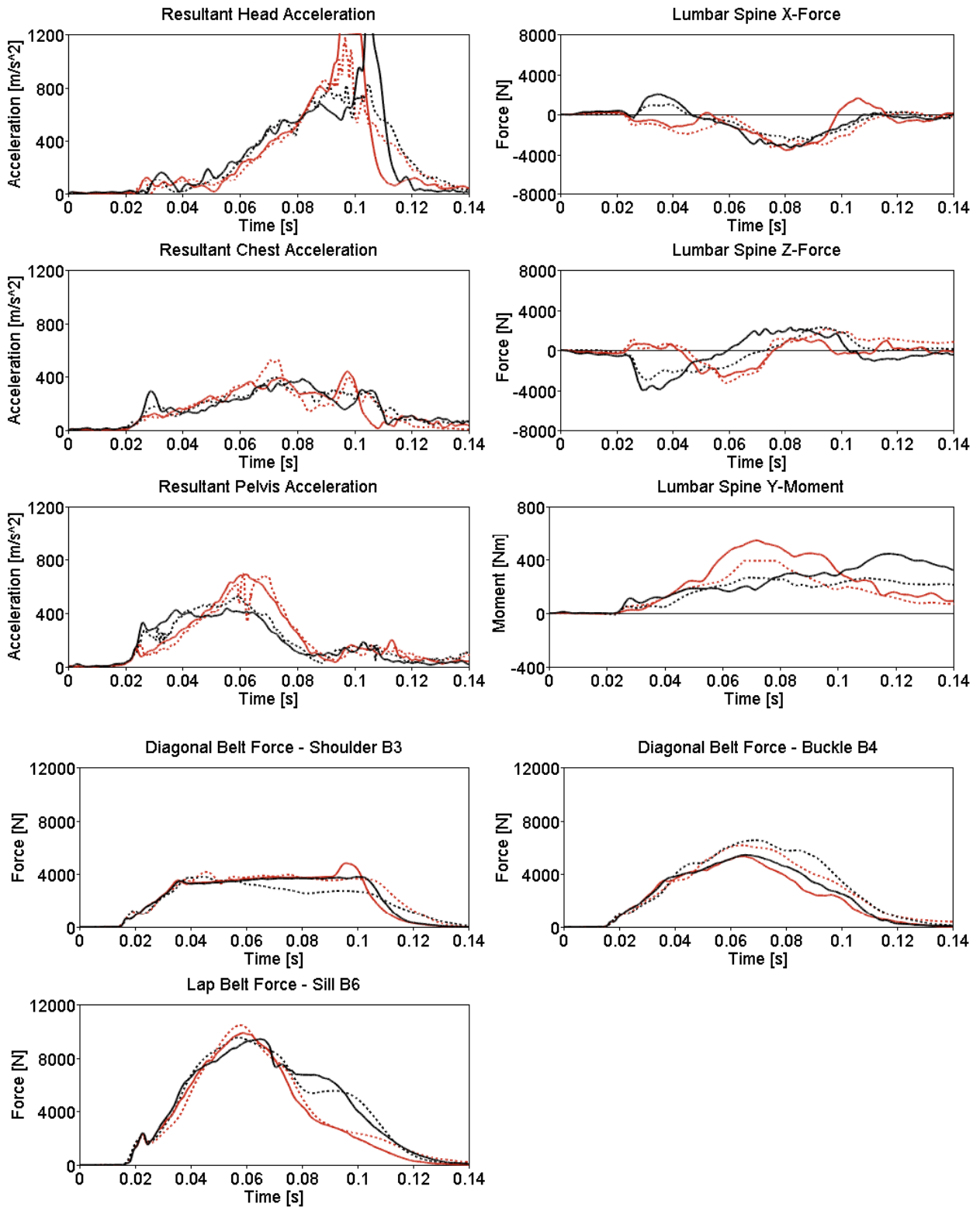
APPENDIX 2 - PMHS TEST AND THUMS SIMULATION RESULTS

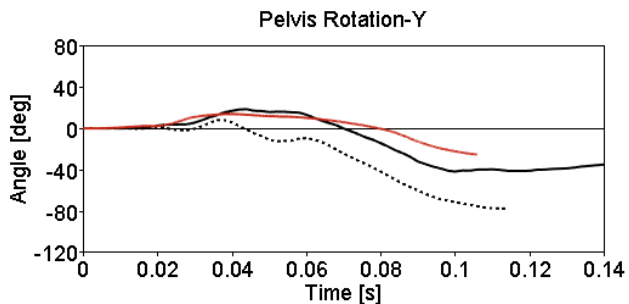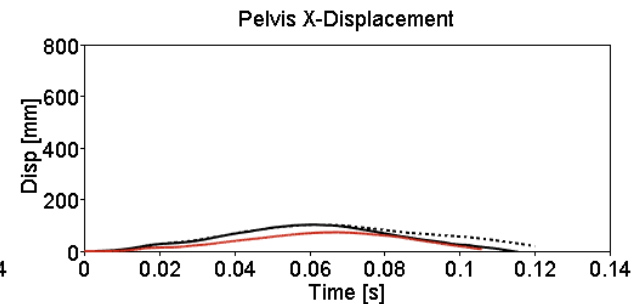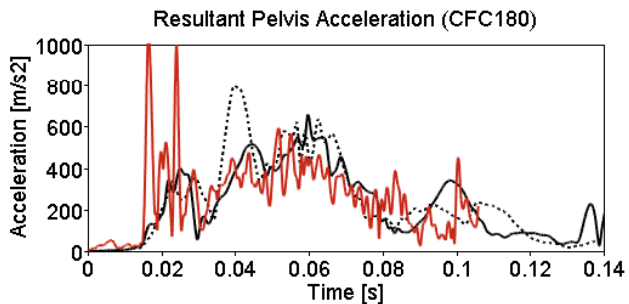**56km/h without Metal-PRC**

56km/h with Metal-PRC

Test354   Test358   Sim MetalPRC

Diagonal Belt Force - Buckle B4 (CFC60)

Lap Belt Force - Sill B6 (CFC60)

Seat Force Resultant (CFC60)

Buck Acceleration (CFC60)
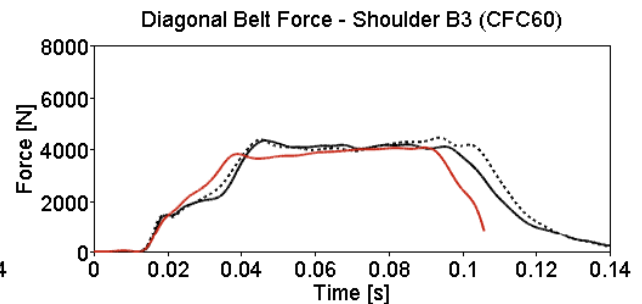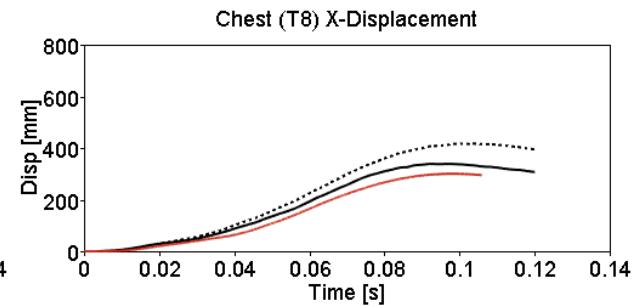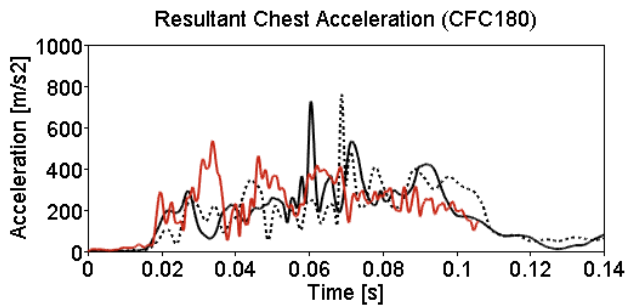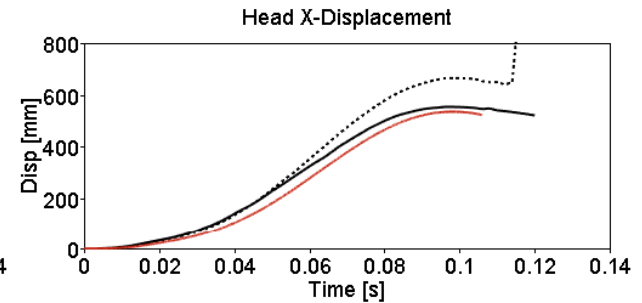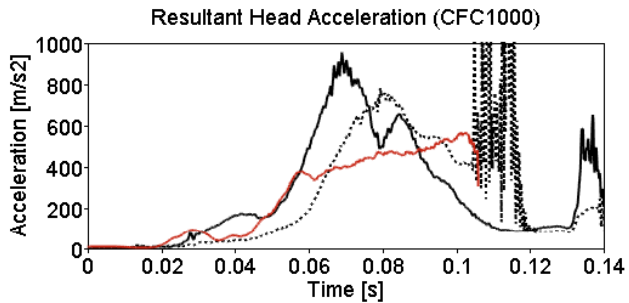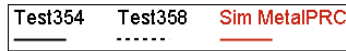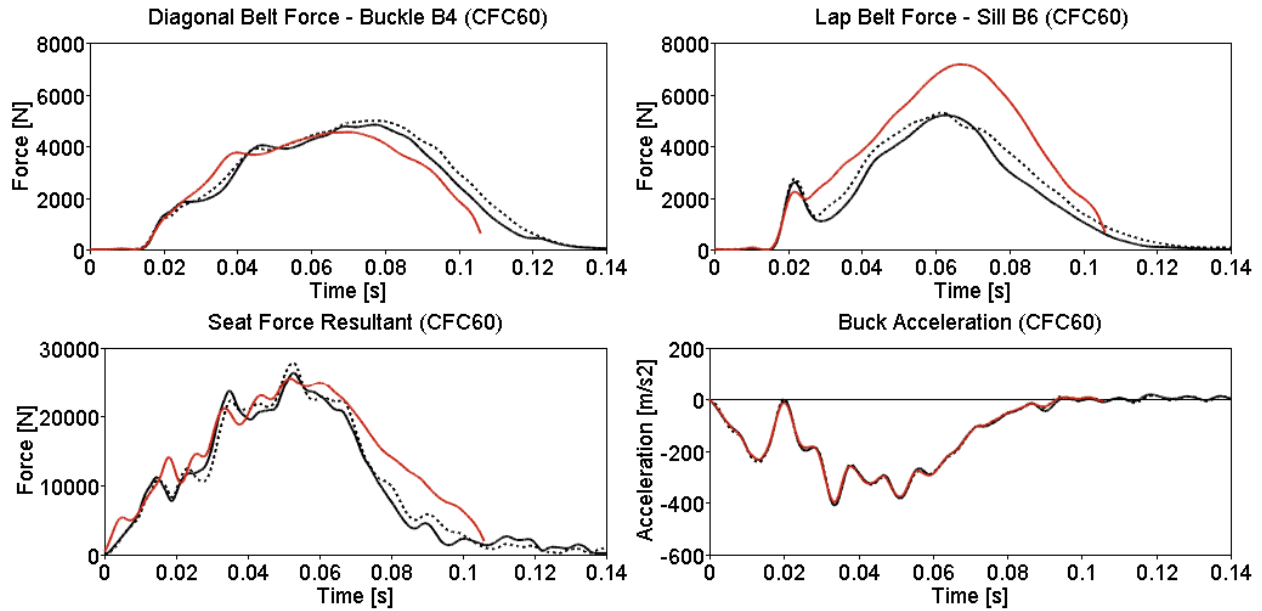
APPENDIX 3 – PARAMETER STUDY - THUMS SIMULATION RESULTS

Pelvis X-Displacement

Pelvis Rotation-Y

| 55mm PLP only | 55mm PLP+PRC | 55mm No PLP, No PRC | 55mm PRC only |
| 86mm PLP only | 86mm PLP+PRC | 86mm No PLP, No PRC | 86mm PRC only |

Lap Belt Force - Sill B6 (CFC60)

| 55mm PLP only | 55mm PLP+PRC | 55mm No PLP, No PRC | 55mm PRC only |
| 86mm PLP only | 86mm PLP+PRC | 86mm No PLP, No PRC | 86mm PRC only |