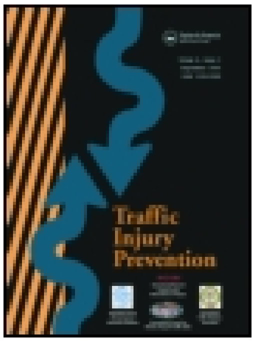

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Chest injuries of elderly postmortem human surrogates (PMHSs) under seat belt and airbag loading in frontal sled impacts: Comparison to matching THOR tests

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Chest injuries of elderly postmortem human surrogates (PMHSs) under seat belt and airbag loading in frontal sled impacts: Comparison to matching THOR tests

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ABSTRACT

Objective: The goal of the study was to develop experimental chest loading conditions that would cause up to Abbreviated Injury Scale (AIS) 2 chest injuries in elderly occupants in moderate-speed frontal crashes. The new set of experimental data was also intended to be used in the benchmark of existing thoracic injury criteria in lower-speed collision conditions.
Methods: Six male elderly (age >63) postmortem human subjects (PMHS) were exposed to a 35 km/h (nominal) frontal sled impact. The test fixture consisted of a rigid seat, rigid footrest, and cable seat back. Two restraint conditions (A and B) were compared. Occupants were restrained by a force-limited (2.5 kN [A] and 2 kN [B]) seat belt and a preinflated (16 kPa [A] and 11 kPa [B]; airbag). Condition B also incorporated increased seat friction. Matching sled tests were carried out with the THOR-M dummy. Infra-red telescoping rod for the assessment of chest compression (IRTRACC) readings were used to compute chest injury risk. PMHSs were exposed to a posttest injury assessment. Tests were carried out in 2 stages, using the outcome of the first one combined with a parametric study using the THUMS model to adjust the test conditions in the second. All procedures were approved by the relevant ethics board.
Results: Restraint condition A resulted in an unexpected high number of rib fractures (fx; 10, 14, 15 fx). Under condition B, the adjustment of the relative airbag/occupant position combined with a lower airbag pressure and lower seat belt load limit resulted in a reduced pelvic excursion (85 vs. 110 mm), increased torso pitch and a substantially lower number of rib fractures (1, 0, 4 fx) as intended.
Conclusions: The predicted risk of rib fractures provided by the THOR dummy using the C_{max} and PC Score injury criteria were lower than the actual injuries observed in the PMHS tests (especially in restraint condition A). However, the THOR dummy was capable of discriminating between the 2 restraint scenarios. Similar results were obtained in the parametric study with the THUMS model.

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Introduction

Seventeen percent of Europeans were aged 65 and older in 2012, and this proportion will rise to 28% in 2020 (European Commission 2011). Protecting older occupants is becoming a priority in many countries in the world. But developing restraint systems capable of preventing injuries to older occupants poses a significant challenge because elderly people are exposed to a higher risk of injury for a given magnitude of loading and to a higher risk of worse outcome for the same Abbreviated Injury Scale (AIS)-level injury (Kent et al. 2009). Recovery time is longer, and the disability risk is higher compared to that of the younger population (Schoell et al. 2016).

Identifying injury thresholds relies on biomechanical experiments in which different surrogates are used to represent the living human (animals, crash test dummies or anthropomorphic test devices [ATDs], and postmortem human surrogates [PMHS]). A recent review of the biomechanical experiments performed over the last decades showed that a substantial proportion of the studies have investigated the effects of advanced age on injury tolerances (Forman et al. 2015), largely focusing on the chest and rib cage. Despite all of this research, it has been shown that the thorax continues to be the most critical body region for older car occupants because they present the highest share of AIS 3+ injuries (Wisch et al. 2017), which prompted the European Commission to fund the SENIORS (Safety Enhanced Innovations for Older Road userS) project aiming to improve the safe mobility of the elderly. SENIORS could be considered a follow-up of the research performed in the

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THORAX project, also funded by the European Commission, where the development and use of multichest deflection injury criteria with the THOR ATD in combination with the use of computational human body models was explored (Davidsson et al. 2014) as an assessment tool to develop more effective restraint systems.

The need for incorporating factors that influence injury occurrence (such as age or size of the individual) has been recognized in several studies that investigated how to use injury criteria with different types of ATDs (Kent and Patrie 2005; Laituri et al. 2005). With the recent release of a draft version of the *Qualification Procedures Manual* of the THOR 50th percentile male dummy in August 2016 (NHTSA 2016), organizations like Euro NCAP are moving toward adopting the THOR dummy in their test protocols (Ellway 2017). In parallel, contemporary research has proposed chest injury criteria based on the multipoint chest deformation measuring capabilities of the ATD (Poplin et al. 2017), including age modifiers in the injury functions. This research has pointed out the need for validation of the proposed injury criteria with an independent experimental data set of matching THOR and PMHS tests. With the aim of developing a robust injury risk function that would not be sensitive to experimental conditions (Kent et al. 2003; Petitjean et al. 2003), the aforementioned study included a sample of matching THOR and PMHS tests including different types of restraints, several seating positions, and impact speeds. However, just a few cases in the data set used incorporated an airbag, which is mandatory in all current vehicles in developed countries.

In addition, though most of the previous research has addressed AIS 3+ thoracic injuries, it is expected that in the near future automated features in passenger cars will reduce crash speeds and consequently the associated injury severity.

The goal was to develop experimental chest loading conditions that would cause up to AIS 2 chest injuries in elderly occupants in moderate-speed frontal crashes. The new set of experimental data was also intended to be used as benchmark of the proposed thoracic injury criteria in lower-speed collision conditions and including state-of-the-art restraints like force-limited seat belts and frontal airbags. To this end, 6 frontal sled tests with the THOR ATD and 6 elderly (>65 years old) PMHSs were performed at 35 km/h.

Methods

Overall approach

The study consisted of 2 separate rounds of testing involving both PMHS and the THOR ATD as test surrogates at each round. Because the goal was to assess the ability of existing THOR chest injury criteria to predict AIS 2 injuries in contemporary crash scenarios relevant for older car passengers, the first round of testing was considered the baseline condition and served to carry out a computational parametric analysis with the THUMS finite element (FE) human body model. After the parametric study, test conditions were adapted in the second round of testing to better reflect the intended crash scenario.

Test setup and conditions

The test fixture was designed to approximate the seating position of a front seat passenger car occupant using a simplified geometry (Figure A.1, see online supplement). Additional information about the setup and instrumentation can be found in the Appendix (see online supplement).

The seat belt was adjusted before the test and given a 50-N pretension. The height and lateral position of the D-ring were adjusted to provide a similar set of conditions across the different occupants' anthropometries (its height was set at the height of the external auditory meatus of each occupant and it was positioned 100 mm outward from the right acromion of the occupant). A preinflated airbag (vented at $t = 0$ ms) attached to a rigid frame was also used to restrain the forward motion of the occupant. The airbag forward position was set so that the occupant's chest was in initial contact with the inflated bag. After all of these adjustments, 2 sets of restraint conditions were implemented as indicated in Table 1. Test subjects were exposed to a frontal impact following a trapezoidal deceleration with a plateau about 14 g that resulted in a 35 km/h delta-V (Figure A.3, see online supplement). The THOR-M dummy was exposed to similar test conditions to have paired PMHS-THOR tests that could be used to benchmark injury criteria.

Test subjects

The THOR-M dummy and 6 PMHS were exposed to matching impact conditions in the study. The THOR-M dummy used in this study corresponds to the metric version of the THOR 50th percentile male dummy, including the SD-3 shoulder assembly (Parent et al. 2013). All subsequent references to THOR in this article pertain to this specific ATD model. AIS 3+ thoracic injury risk was estimated using the maximum resultant deformation (C_{max}) and the total and differential local chest deformations (PC Score) as given by the 4 infra-red telescoping rod for the assessment of chest compression (IRTRACC) dummy sensors and was adjusted to a 65-year-old occupant (Poplin et al. 2017).

As for the PMHS, 6 male elderly surrogates were chosen for this study. Computed tomography scans were taken prior to the test to ensure that there were not previous conditions that could compromise the results of the study and posttests to assist in the injury assessment. PMHSs were also subjected to a posttest detailed autopsy. The main characteristics of the test subjects are included in Table 1. Injuries were coded according to the AIS 2005 update 2008 version (Association for the Advancement of Automotive Medicine 2008). Procurement, handling, and testing of the PMHSs was done under the approval of the Ethical Commission for Clinical Research of Aragon, which is the official body responsible for assessing all research projects involving human subjects in the region of Aragon, Spain.

Occupants' seating procedure is described in detail in the Appendix.

Table 1. Setup conditions, initial position, and anthropometry of test subjects. *XYZ* coordinates are given with respect to a coordinate system placed at the intersection of the fore/after midline of the seat and the line joining the bilateral defined position of the H-point seat.[a]

	Condition A				Condition B			
	THOR	PMHS1	PMHS2	PMHS3	THOR	PMHS4	PMHS5	PMHS6
Test	1743, 1744, 1745	1761	1763	1765	1961, 1962, 1968	1969	1970	1971
Seat belt pretension (kN)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Force limit (kN)	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0
Initial airbag pressure (kPa)	14	—	14	13	11	11	11	11
D-ring *X* position (mm)	−320	−320	−320	−320	−420	−420	−420	−420
D-ring *Y* position (mm)	260	*	*	*	303	317	290	276
D-ring *Z* position (mm)	−723	*	*	*	−740	−692	−726	−668
Airbag *X* position[b]	371	**	**	**	371	411	422	434
Airbag *Y* position[b]	1	1	1	1	6	6	6	6
Airbag *Z* position[b]	−707	−707	−707	−707	−682	−637	−642	−592
Seat friction	No	No	No	No	Yes	Yes	Yes	Yes
				Initial position				
H-point *x* position right/left (mm)	−1/2	−5/−11	0/0	−10/−5	−3/3	4/4	3/4	−4/−4
Sternum angle (°)	33.0	22.5	26.0	24.0	38.2	31.0	40	27.0
T1/T12 angle (°)	—	—	—	—	—	10.6	12	10.0
Shoulder belt angle (°)	25	28	19	22	20.6	18.0	20.6	23.5
				PMHS characteristics and anthropometry				
Age	—	74	68	94	—	74	63	73
Sex	Male	Male	Male	Male	Male	Male	Male	Male
Height (cm)	175	167	184	156	175	170	174	167
Sitting height (cm)	81.3	74.5	79.0	72.0	80.6	76.9	82.4	78.5
Weight (kg)	82	66.0	76.0	34.0	82	74	67	62
Body mass index	—	23.7	22.4	14.0	—	25.6	20.8	22.2
Cause of death	—	Hepatic infection	Hepatic infection	Prostatic cancer	—	Hepatic cancer	Lung cancer	Cardiopathy
Chest circumference fourth rib (cm)	—	95.0	102.0	71.0	—	99.0	103.0	95.0
Chest circumference eighth rib (cm)	—	100.0	101.0	58.5	—	104.2	106.0	96.0
Chest depth fourth rib (cm)	—	21.0	22.5	18.5	—	23.7	26.5	17.0
Chest depth eighth rib (cm)	—	25.5	23.0	26.0	—	25.7	27.0	20.0

[a]*Position of the seat belt D-ring was personalized to each occupant but was not documented during the test.
**The airbag structure was positioned as close to the occupant as possible but ensuring no initial contact; position not documented during the tests.
[b]XYZ coordinates of the marker on top of the steering wheel assembly.

Parametric study with the THUMS model

A parametric study using computer simulation was carried out using the THUMS TUC Ver. 3 model (THUMS User Community 2018). The objective was to identify which features of the test setup and procedure could be improved to decrease the number of rib fractures between the 2 sets of restraint conditions. The number of fractured ribs was estimated by comparing the predicted ultimate strain with experimental data from rib cortical bone tests, adjusted by age (Forman et al. 2012).

The variables included in the parametric study were the forward position of the D-ring, forward position of the seat buckle, seat belt force-limit magnitude, airbag pressure, airbag venting trigger time, airbag height with respect to the occupant, and seat friction by adding a think sheet of foam over the seat surface (Vermafoam high-density polyether polyurethane foam impregnated with rigid conductive latex). The friction coefficient of the seat was varied between 0.3 (initial condition) and 0.6 (final condition).

Results

First round of THOR and PMHS tests

Table 2 shows the most relevant results obtained in the THOR tests using the first set of restraint conditions. Maximum resultant chest deformation was measured at the upper left IRTRACC of the ATD (33.7 ± 1.2 mm) followed by the lower left IRTRACC. This deformation resulted in a 45.5% probability of a 65-year-old sustaining AIS 3+ injuries.

Table 2. Selected results from test series, including THOR and PMHS tests.[a]

	Condition A				Condition B			
	THOR	PMHS1	PMHS2	PMHS3	THOR	PMHS4	PMHS5	PMHS6
Test	1743, 1744, 1745	1761	1763	1765	1961, 1962, 1968	1969	1970	1971
Shoulder seat belt peak force (kN)	2.6 ± 0.1	2.3	2.7	1.8	2.1 ± 0.05	2.0	1.8	1.9
Lap seat belt peak force (kN)	3.8 ± 0.1	3.7	3.8	1.7	4.2 ± 0.3	3.3	2.8	2.2
Peak airbag pressure (kPa)	28.2 ± 6.3	—	—	13.5	31.0 ± 1.0	21.9	20.2	18.5
Head CG X displacement (mm)	464.8 ± 10.8	296.7	269.7	194.7	469.3 ± 21.5	530.9	506.7	450.1
T1 X displacement (mm)	322.5 ± 11.1	213.2	202.4	141.4	325.0 ± 23.5	422.2	359.2	375.5
H-point X displacement (mm)	111.6 ± 2.8	95.4	104.8	36.6	110.4 ± 2.7	87.5	70.8	91.8
Head max ARS X (°/s)	-178.8 ± 37	658.4	293.7	281.6	-120.2 ± 31	534.9	376.8	158.9
Head max ARS Y (°/s)	$-1,307.5 \pm 23$	−1,346.8	−1,238.8	−737.1	$-1,131.0 \pm 2$	−1,759.8	−1,533.3	−1,424.9
Head max ARS Z (°/s)	325.2 ± 64	255.8	593.4	171.7	411.3 ± 99	350.9	495.7	472.4
Upper left max resultant	33.7 ± 1.2	—	—	—	27.6 ± 0.6	—	—	—
Upper right max resultant	18.9 ± 0.9	—	—	—	26.7 ± 0.4	—	—	—
Lower left max resultant	28.3 ± 1.8	—	—	—	27.1 ± 0.7	—	—	—
Lower right max resultant	10.3 ± 0.2	—	—	—	9.6 ± 1.0	—	—	—
C_{max}	33.7	—	—	—	27.6	—	—	—
$p(\text{AIS } 3+)_{Cmax}$ 65-year-old (%)	45.5	—	—	—	26.7	—	—	—
PC Score	4.64	—	—	—	3.91	—	—	—
$p(\text{AIS } 3+)_{PCscore}$ 65-year-old (%)	44.2	—	—	—	28.1	—	—	—
Rib fx	—	10	14	15	—	1	0	4
Sternum fx	—	Yes	Yes	No	—	Yes	No	No
Other injuries	—	—	C7–T1 interspinous ligament tear	—	—	—	—	—
AIS codes		450804.2 450203.3	450804.2 450203.3 640284.1	450203.3		450804.2 450201.1	—	450203.3

[a]ARS = Angular Rate Sensor.

Figure 1 compares the time history of the shoulder seat belt force between the THOR and the PMHS. The interaction with the seat belt of the ATD and the PMHS was similar in terms of timing and magnitude, except for the third PMHS, who was considerably lighter than the dummy. The THOR response corridor lies in between the responses of PMHS 1 and PMHS 2. The peak lap belt force measured in the dummy tests was almost equal to the one measured in the PMHS tests (THOR, 3.8 kN vs. PMHS, 3.7 and 3.8 kN). The forward peak excursion of the THOR head center of gravity (CG) was considerably higher than those observed in the PMHS tests (464.8 vs. 283.2 mm, average of PMHS 1 and PMHS 2), but these differences in peak displacements decreased along the spine up to the lower extremities, where the displacement measured at the H-point was similar between the THOR and PMHS 1 and PMHS 2. The stature and weight of PMHS 3 resulted in very different magnitudes of seat belt forces and displacements. The autopsy revealed that the 3 PMHSs sustained more than 10 rib fractures (AIS 3; Figure 2) although the THOR prediction of AIS 3+ chest injuries was 26.6%.

Parametric study with the THUMS model

When the THUMS model was positioned and adjusted to mimic the tests of PMHSs 1 and 2, and after showing nearly matching peak values with the test-measured seat belt forces and displacements of selected anatomical landmarks (head CG, first and eighth thoracic vertebrae, greater trochanter), only a 6% risk of sustaining AIS 3+ chest injuries using the probabilistic strain-based fracture prediction method proposed by Forman et al. (2012) was predicted (Figures A.5 and A.6, see online supplement). THUMS predicted that the maximum X deformation occurred at the lower right aspect

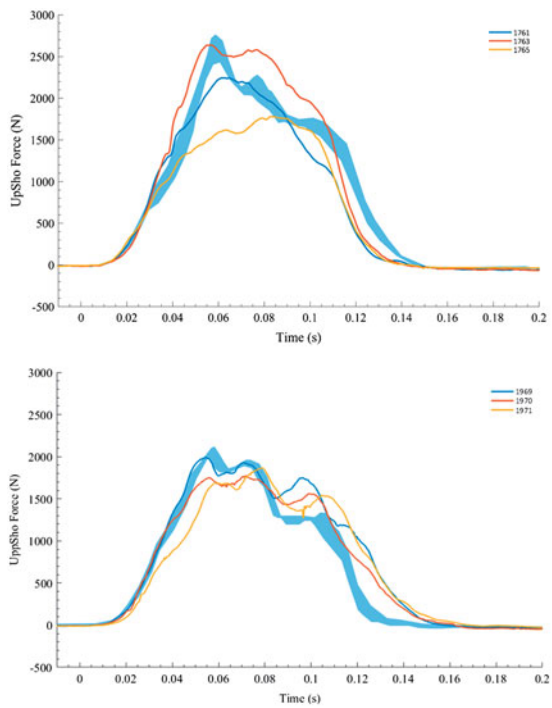

Figure 1. Time history of the upper shoulder seat belt force. Top: First series of PMHS tests (solid lines) and corridor response of corresponding THOR tests (shaded blue area). Bottom: Second series of PMHS tests (solid lines) and corridor response of corresponding THOR tests (shaded blue area).

of the rib cage, where the THOR ATD measured the lowest resultant chest deflection (39.5 vs. 10.3 mm). Despite these differences in chest deformation and based on the similar head, spine, and pelvic displacements and the time history of the seat belt forces, the model was considered to provide a reasonable approximation of the kinematics and therefore of the interaction between the occupant and the restraints observed in the physical tests.

The combination of lowering the force limit and moving the D-ring rearward resulted in a 30% predicted reduction of having 2+ fractured ribs. The effect of modifying the airbag pressure or the venting trigger time was unclear in the simulations, although it contributed slightly to reducing the predicted injury risk. Increasing the friction of the seat surface alone reduced the forward displacement of the pelvis by 14%. All of these factors together resulted in a 0% prediction of 2+ fractured ribs. Consequently, this setup was chosen to be used in the second series of THOR and PMHS tests. Compared to the initial set of testing conditions, the final setup modified the following parameters:

- Seat belt system: Lowered the force limit to 2 kN; moved the position of the D-ring rearward 100 mm.
- Airbag system: Lowered the height of the airbag by 25 mm; filled the airbag at 11 kPa.
- Seat: Increased the friction of the surface of the seat.

Second round of THOR and PMHS test

The THOR C_{max} value was reduced to 27.6, which corresponded to an estimated 26.7% AIS 3+ chest injury risk (a similar reduction was observed using the PC Score criterion; see Table 2). The deflection of the THOR thorax was spread over the 2 left and upper right IRTRACC sensors, and the lower right one provided the minimum resultant deflection as in the previous test round. Lowering the load limit of the seat belt and the airbag pressure did not influence the peak forward displacement of the CG of the ATD head (469.3 ± 21.5 mm) compared to the one obtained in the first round (464.8 ± 10.8 mm). Similar observations were made for the upper spine and H-point locations. The lap belt seat force increased by 400 N, despite the greater friction coefficient of the seat surface. The time history plot of the shoulder belt force shown in Figure 1 illustrates that the THOR ATD response closely reflected the measurements observed in the PMHS tests in terms of peak values and also showing the 2 plateau stages between 50 and 70 ms and 90 and 110 ms. On the contrary, the prediction of the upper shoulder seat belt force given by the THOR dummy failed to reflect the phasing of the responses measured in the PMHS test in the first restraint condition. This can be attributed to a more detailed positioning of the subject that included the scaling relationships shown above that improved the matching loading conditions between PMHS and ATD.

In addition to the inherent intersubject variability, these changes in restraint parameters and geometry affected the injury outcome of the 3 PMHS tests. In this case, the reduction in airbag pressure and load limit caused an increased head forward excursion (average excursion: 495.9 mm) that was greater than that observed in the THOR dummy although the PMHSs were shorter. The displacement of T1 followed the same trend, but the H-point forward excursion remained within the values observed using the initial restraint conditions (average excursion: 83.4 mm), likely indicating that the increased friction of the seat surface was more effective than in the case of the THOR dummy. The additional restraint provided by the seat surface caused the lap seat belt forces to be around 600 N (in average) lower than those observed in the first round of PMHS tests, contrary to what had occurred with the ATD. As for the rotation of the head, the new set of restraint conditions resulted in an increased flexion rotational speed of the head compared to the initial tests. The major difference, however, was found in the injury outcome of the 3 subjects because PMHS 4 sustained only one rib fracture, no injury was found in the case of PMHS 5, and PMHS 6 received 4 rib fractures. All of these results are included in Table 2.

Discussion

Development of chest injury risk functions for the THOR M ATD

One of the primary goals of the European Union–funded SENIORS project was to develop injury risk functions and testing methods that could be used to improve the protection of elderly road users. Contemporary research has proposed several thoracic injury criteria to be used with THOR, taking advantage of the multipoint deflection characteristics

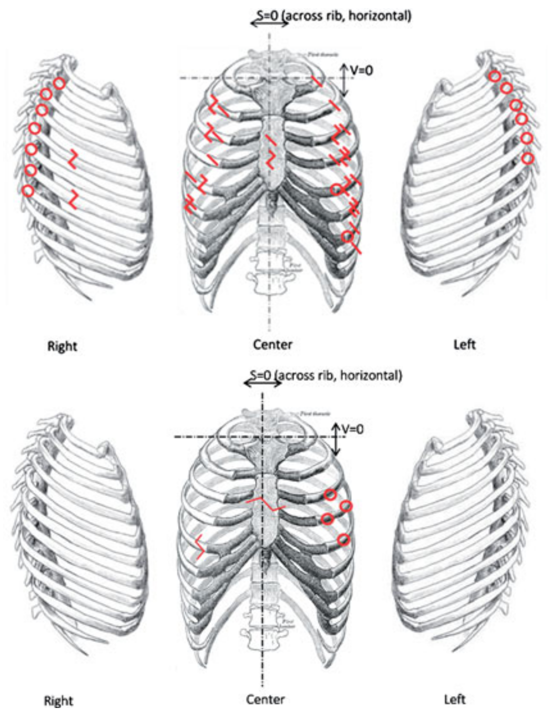

Figure 2. Approximate location of the rib and sternal fractures observed in the posttest PMHS examination. First PMHS series, top (PMHS 1: angled line; PMHS 2: straight line; PMHS 3: circle). Second PMHS series, bottom (PMHS 4: angled line; PMHS 5: straight line; PMHS 6: circle).

of this ATD (Davidsson et al. 2014; Hynd et al. 2013; Poplin et al. 2017). To develop a robust injury risk function, the Poplin et al. (2017) study combined diverse test conditions to overcome the difficulties associated with initial positioning, restraint type, and impact conditions (Kent et al. 2003; Petitjean et al. 2003). Poplin and coauthors (2017) proposed to use the so-called C_{max} and PC Score as the most appropriate injury metrics for the THOR ATD, given that both were qualitatively equivalent. The present study is completely independent from the tests used in the development of the proposed injury risk functions and therefore can serve to benchmark them. Both injury risk functions can be adjusted by age and were used in this article to quantify the injury risk of a 65-year-old occupant, which was considered an acceptable boundary between middle age and older age categories based on previous publications (Forman et al. 2015). Two of the PMHS tests resulted in numerous rib fractures (PMHS 1 and PMHS 2), which corresponds to an AIS 3 injury, and the 3 PMHS in the second series received only AIS 1, no injuries, and AIS 3 injuries (as a result of 4 rib fractures). The C_{max} values obtained in the THOR tests were 33.7 (first test series) and 27.6 (second test series), resulting in 45.5 and 26.7% age-adjusted injury risk, respectively, and the corresponding PC Score values were 4.64 and 3.91 (44.2 and 28.1% age-adjusted injury risk, respectively), which seem to underestimate and overestimate the results observed in the 2 series of PMHS tests. However, both injury metrics were capable to capture the injury severity reduction later observed in the PMHS tests. Thus, the THOR ATD and the C_{max} and PC Score criteria were sensitive to these restraint changes despite existing differences in the prediction of the displacements and angular rate of the head (Table 2). This finding is particularly relevant because the load cases involved in the tests included here are substantially different from the restraint conditions involved in the development of the injury criteria.

Interestingly, both injury criteria resulted in very similar estimations of AIS 3+ injury, a phenomenon that had been already identified in Poplin et al. (2017). This agreement between C_{max} and the PC Score was also identified in other THOR tests performed within the SENIORS European Union–funded project that suggested that higher order components could be introduced in a new formulation of the PC Score index so that the risk function could benefit from the recording of multiple chest deformation measuring points, which was at the core of the development of the THOR dummy (Eggers et al. 2018). It should be kept in mind that adding new components to the existing formulation requires increasing the test sample size to maintain a reliable model fit (Vittinghoff et al. 2012).

Test surrogates

Both the physical THOR dummy and the FE THUMS human body model failed to capture correctly the exact kinematics, dynamics, and injury outcome observed in the PMHS tests. These differences can be at least partially explained by the difficulties encountered in defining a matching initial position between the 3 different types of surrogates. This is particularly true between the ATD and the human surrogates. The challenge of defining a common initial position exists also within the PMHS group given the differences in anthropometry across subjects. A method that would allow documenting the initial position of internal bony landmarks and scaling the restraint geometry accordingly would be the preferred option. However, this method would require knowing the seating posture of the PMHS in advance or measuring it during the preparation of the test, which may constitute a cumbersome task to be added to the usually long procedures associated with PMHS testing.

It should also be noted that the chest deformation response varied between surrogates. Whereas THUMS predicted that the maximum X strain occurred at the lower right area of the rib cage, the THOR ATD measured the maximum chest deflection at the upper left chest. Because there is not an accepted definition of exactly which points in the THUMS rib cage and spine correspond to those of attachment of the IRTRACC sensors in the ATD, calculation of chest deformation in THUMS in a way similar to that available for THOR was not carried out. This is clearly a limitation of the ATD because the measurement capabilities are limited to just 4 specific points on 4 ribs without providing information about what happens in the remaining areas of the rib cage. However, rib strain prediction with human body models is still an open research question that requires further investigation, which is outside the scope of this article. Other published studies have pointed out that, despite differences in the specific magnitudes predicted by THUMS and THOR, both surrogates provided similar conclusions in the overall assessment of restraint systems (Pipkorn et al. 2016).

Despite these limitations, it is remarkable that both the THOR dummy and the THUMS model were capable of capturing the differences between restraint conditions 1 and 2 and predicted injury severity reductions that were later corroborated by the PMHS tests (even if other factors not present in the THOR and THUMS tests, such as intersubject variability, may have also influenced the PMHS injury outcome).

Subject-related risk factors for rib fractures

A substantial body of recent literature has discussed the role of intersubject variability in the likelihood of sustaining rib fractures. Differences in anthropometry and in local rib geometry, bone quality, pretest health conditions, etc., are known to play a major role in the likelihood of sustaining injuries in a crash. Rib cortical bone properties in the literature have shown not only large intersubject variability but also substantial intraspecimen variability (Kemper et al. 2005). The cross-sectional area and geometry have been identified to play a major role in the mechanical behavior of ribs exposed to bending and compression tests (Kemper et al. 2007; Murach et al. 2018) that is more relevant than material properties.

A number of studies have explored how to incorporate all of these sources of variability within deterministic human FE models and the question remains open. Some studies have shown that the more personalized the human FE model (anthropometry and position) is to the experimental subject test, the more accurate the results are (Piqueras-Lorente et al. 2018). Antona-Makoshi et al. (2015) found agreement in the prediction of the number of fracture ribs given by a FE human model and PMHS tests carried out in matching conditions when the model accounted for the changes in rib cortical thickness, material properties, and strain (among others) associated with age. Contrary to the previously mentioned studies, Schoell et al. (2015) found that changes in the material properties of the thorax of the Global Human Body Models Consortium FE human body model have little to no effect in frontal and lateral impacts. It should be noted that the THUMS model used in this study was never modified to more accurately predict fractures of an elderly occupant, which can explain the mismatch between the injuries found in the tests and the predictions given by THUMS.

Predeath health conditions may have played a role also in the bone injury tolerance differences between the test subjects. Given the relationship of certain cancer types with bone loss (U.S. Department of Health and Human Services 2004), the donor protocol in place at the Impact Laboratory required that cancer was not metastasized to the bone. However, it should be noted that 3 PMHSs suffered from cancer and it is likely that they had been exposed to cancer treatment that could also have affected the mechanical response of the tissue. Therefore, although all of these factors could have affected the response of the test subjects, they could not be controlled in the set of experiments discussed in this article.

Influence of restraint conditions and initial position

The calculation of C_{max} and the PC Score allowed establishing some differences in how the chest was loaded in the 2 studied restraint conditions. Both criteria indicated a reduction of the overall chest deformation of the THOR dummy switching from condition 1 to condition 2. Though the C_{max} criterion only uses the maximum chest deformation regardless of its location (which, interestingly, was the upper left thorax in both cases but followed closely by the upper right and lower left chest regions in the second test series), the PC Score allows identifying a substantial reduction (17.8 ± 1.2 vs. 5.4 ± 1.3) in the coefficient up_{dif} that corresponds to the maximum difference in upper chest left and right in-phase resultant deflection time histories. Though there was also a reduction in the magnitude of the low_{dif}, it was not as important as the one found in the upper chest. In summary, the change in restraint conditions resulted in a more symmetric loading of the dummy chest that led to a reduction in the likelihood of AIS 3+ injury. In parallel, the risk reduction predicted in the THOR dummy tests was also supported by the parametric study with the THUMS human body model. It should be noted that in the physical tests with the THOR dummy and in the computational study run with THUMS, the initial positions of the surrogates did not change between the 2 restraint conditions and therefore the reduction observed in the prediction of injury risk can be attributed only to the changes related to the restraint parameters.

Recognizing the importance of the subject-related risk factors (rib cortical thickness, rib material properties and geometry, bone quality), the injury outcome observed in the PMHS tests also supported the trend observed in the simulations with the THUMS model and in the sled tests with the THOR dummy. The increased torso angle in the second series of PMHS tests resulted in a greater excursion of the head and in more favorable overall kinematics of the occupant (Adomeit and Heger 1975; Kent et al. 2011; Lopez-Valdes et al. 2014). Examination of the high-speed video showed that in the initial set of conditions, the trunk and head of the PMHS moved forward almost as a rigid body, whereas in the second case the pelvis is restrained by the seat belt and the additional friction of the seat, causing the torso to pitch forward in much more favorable restraint interaction with the thorax structures (see the selected video frames included in Figure A.9, online supplement).

Two rounds of THOR and PMHS frontal sled tests in matching restraint conditions including a force-limited seat belt and a preinflated airbag were performed at 35 km/h. The goal was to develop a test condition relevant for up to AIS 2 chest injuries in elderly occupants involved in crashes at moderate speeds and to benchmark existing THOR chest injury criteria. Though the initial test conditions resulted in Maximum AIS 3 chest injuries for the 3 PMHSs, changes in the restraints (including lowering the seat belt load limiter, increasing the friction of the seat, decreasing the airbag initial pressure) and providing an increased torso angle contributed to reducing the severity of injuries. These changes were substantiated by a parametric study carried out with THUMS. The reduction in severity of chest injuries was pointed out in the tests and simulations were run with the 3 types of surrogates (THUMS, THOR, and PMHS). Existing THOR chest injury criteria (C_{max} and PC Score) were sensitive to the restraint and position changes and offered comparable estimations of the injury risk in both conditions.

Limitations

Though the positioning of the PMHS in the first round of tests was performed according to normal procedures in PMHS tests, the differences observed between the outcome in the THOR and PMHS tests caused the positioning procedure to be reviewed. The new protocol included a more quantitative approach to positioning, finding corresponding landmarks and scaling relationships between the surrogates. Unfortunately, several of the positioning parameters used in round 2 were not registered in round 1 because they were not considered necessary for the tests. For instance, this is the case of the sternum angle measurement that was complemented in the second test series with the measurement of the so-called T1–T12 angle (which consisted of a measurement of the slope with respect the horizontal of a straight line connecting the spinous process of the 2 vertebrae). This change in the measurement of torso angle was made after discussing the positioning procedures with researchers experienced in performing matching PMHS and THOR sled tests (G. Shaw, personal communication, March 16, 2017). The need to establish reliable seating procedures based on external landmarks that could be identified in the ATD surrogates was present throughout the whole project and has not been completely solved.

PMHS 3 is an outlier in this study in terms of age and anthropometry, and so are the results observed from this test. We considered that it was worth reporting the results observed for this subject because, if corrected by age, its anthropometry is not far from the predicted anthropometry of a 94-year-old (average height: 159 cm; average weight: 59.7 kg; Perissinotto et al. 2002). Interestingly, this subject sustained 15 rib fractures and most of them occurred in the posterior aspect of the rib cage, bilaterally and close to the costovertebral junction. This chest injury pattern is uncommon and was totally different from what was observed in the other 2 PMHS tests in this series. This test subject presented a very stiffened spine due to the formation of osteophytes, which produced a prominent kyphosis of the thoracic spine. Whether this characteristic is related to the exhibited injury pattern is unknown. A recent study by Shurtz et al (2018) exposed 2 small elderly females to a simulated side impact. The 83-year-old subject tested in this study had an anthropometry similar to that of PMHS 3 (44 kg, 155 cm) and also exhibited a similar pattern of rib cage fractures (AIS 3), with many fractures near the costovertebral joint. Unfortunately, the authors did not provide any further explanation for the injury mechanism associated with the posterior rib fractures.

The use of chest bands to quantify PMHS thorax deflection is common practice in this type of test; however, the equipment was not available for this study. Adding chest deflection measurement capabilities would have been useful in characterizing the PMHS thoracic response. Nevertheless, the quantification of PMHS deformation is not part of the development of the thoracic injury criteria because the measurement of chest deflection is based only on the THOR IRTRACC data (Poplin et al. 2017). This is why the matching PMHS and THOR tests were planned, though not all of the PMHS information could be recorded.

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