PRESSURE-BASED ABDOMINAL INJURY PREDICTION FOR THE THOR-50M

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ABSTRACT

The standard THOR-50M dummy is equipped with sensors to measure the abdomen deflection and assess the risk of abdominal injuries. Since 2016, the "ABdominal Injury and SUbmarining Prediction" (ABISUP) consortium has developed a pressure-measuring abdomen for the THOR-50M to predict abdominal injuries and submarining as a potential alternative to the current THOR-50M abdomen design. A new lower abdomen including Abdominal Pressure Twin Sensor (APTS) was designed and four identical prototypes were built and shipped to consortium member test houses. Numerous abdominal belt loadings replicating tests from the literature were carried-out to check the prototype biofidelity, sensitivity and define a pressure-based AIS3+ injury risk functions (IRFs). Two compression-based IRFs were defined using porcine test results from the literature. Compressions were defined as the ratios between the abdomen deflection and the full abdominal depth, or between the abdomen deflection and the abdominal depth in front of the spine. The abdominal depth in front of the spine was used in an attempt to minimize possible differences between species. It was estimated using simple assumptions and led to compressions exceeding 100% in a few cases. Then transfer functions between THOR abdominal compressions and pressures were applied to obtain the pressure-based IRFs. Twenty-five sled tests were performed to assess the new abdomen under various restraint conditions and to evaluate the relevance of the IRFs.

The THOR-50M new abdomen showed similar or better biofidelity than the standard abdomen without modifying the dummy kinematics. The abdomen was sensitive to loading height and no damage to the APTS was encountered during tests. Relationships between THOR-50M mean APTS pressure and abdominal compressions were modelled using a 3rd degree polynomial with 0.98 R^2. The IRF with a log-logistic distribution obtained the lowest Akaike Information Criterion. For the compression based on the full abdomen depth, the AIS3+ injury risks of 25%, 50% and 75% corresponded to APTS pressures of 133, 201 and 304 kPa, respectively. For the compression based on the abdomen in front the spine, the AIS3+ injury risks of 25%, 50% and 75% corresponded to APTS pressures of 108, 197 and 361 kPa, respectively.

The new abdomen discriminated between the restraint conditions: lower pressures (between 90 and 190 kPa) were obtained when the lap belt remained below or on the ASIS and higher pressures (170 to 450 kPa) were obtained when the lap belt loaded the abdomen. Using the IRF, a risk up to 50% could be obtained without submarining, i.e. with the lap belt still engaging the ASIS. This is not consistent with a risk expected to be low for a proper restraint. Possible adjustments are discussed in the paper to decrease APTS sensitivity when the lap belt is positioned below or on the ASIS.

INTRODUCTION

Abdominal injuries represent a significant proportion of the serious injuries sustained by car passengers in frontal crashes and become even more significant as the AIS severity increases [1]. In France, the accident data combining all crash configurations from the Rhône Registry from 2016 to 2020 reveal that 16% of seriously injured car occupants suffered from abdominal injuries [2]. In frontal crash, it is known that the rear seat occupants are generally more at risk to sustain an abdominal injuries ([3], [4]) and that the lap belt is the major source of abdominal injuries [5]. Indeed, the abdominal injuries could be due to a poor routing of the lap belt lying directly on the abdomen before the crash or to the submarining phenomenon resulting from the kinematics of the occupant during the crash which makes the lap belt slip over the pelvis bones into the abdomen. The crash test dummies should also be able to assess these interactions between the occupant and the lap belt.

Today the THOR-50M lower abdomen is instrumented with two IR-TRACCs. A THOR-50M Injury Risk Function has been developed from Kent's porcine tests [7]. It is based on the normalized abdominal deflection calculated by dividing the peak of the left and right abdominal x-axis deflections by the abdominal depth at the location of the IR-TRACCs [8]. The IRF predicts an AIS3+ abdominal injury risk of 25%, 50%, 75% for 80, 98 and 115 mm of abdominal deflection respectively. Moreover, the THOR-50M lower torso design can trap the lap belt between the lower abdomen and the upper abdomen in reclined seat back configuration [9] which does not represent realistic loading conditions. Finally, due to its geometrical characteristics and available space for the IR-TRACC compression, the maximum deflection that can be achieved when subjected to belt compression is unclear. For example, the peak abdomen deflections reported in [8] for frontal rigid barrier and oblique moving deformable barrier tests did not reach 70 mm, or a risk lower than 20%. The Euro NCAP assessment protocol for adult occupant specifies an 88 mm (36% risk) lower limit for the deflection [10].

The ABISUP consortium has developed a new lower abdomen prototype for THOR-50M, named the ABISUP abdomen, which includes Abdominal Pressure Twin Sensor. The APTS has been first introduced in child Q-dummies [11] and more recently NHTSA has also included them in the Large Omni-Directional Child (LODC) dummy [12] and in the THOR-05F [13]. Additionally, the ABISUP consortium has worked on defining a pressure-based Injury Risk Function for the ABISUP abdomen and a submarining predictor [14] to both assess abdominal injury and submarining risk.

METHOD AND DATA SOURCES

The ABISUP abdomen was designed according to the consortium agreed specifications [15], [16] and four identical prototypes were built and shipped to the US, Japan and France. An extensive test campaign was organized among the laboratories of the members. The ABISUP abdomen biofidelity and sensitivity was evaluated through impactor tests and seatbelt loadings. The pressure-based Injury Risk Functions were developed by replicating Kent's porcine belt tests and finally, their response was assessed in sled tests.

ABISUP Abdomen

The ABISUP abdomen can replace the standard THOR-50M lower abdomen without modifying the other dummy parts and its mass is equivalent to the standard lower abdomen assembly. In particular, the upper abdomen was kept in place to avoid changing the thorax response. The ABISUP abdomen was designed for the dummy slouched position but could also be used for the super slouched position. It is made of a 940g piece of foam going around the lumbar spine and down inside the pelvis bones. The geometry of the ABISUP abdomen was designed to provide a continuous surface with the pelvis flesh in the frontal and lateral aspects of the dummy. The ABISUP abdomen top surface comes into contact with the upper abdomen without interfering with the thoracic lower IR-TRACCs. The front bib between the upper and the lower abdomens used in THOR-50M was kept to prevent the belt being trapped between the two abdomens (Figure 1.c). Abdominal Pressure Twin Sensor of 50 mm diameter and 122.5 mm length was inserted in the abdomen foam into 53 mm diameter holes and fitted into low friction material socks for repeatable contact with the abdomen skin. In the dummy sagittal plane, the APTS was aligned with the dummy spine with their caps pointing downwards inside the pelvis cavity, slightly below the neutral axis of the pelvic ASIS sensors. The upper end of the APTS was aligned with the lower abdomen foam top surface and covered by two Velcro caps to prevent the APTS going out their cavity (Figure 1.a). The back of the lower abdomen was supported on its right and left side by two welded steel brackets (Figure 1.b) attached to the existing IR-TRACC rear attachment plate. The APTS was located with the aim to provide the highest pressure for a loading between the ASIS sensors and the lower thoracic ribs. An exploded view of the prototype is shown in Figure 2.

a) ABISUP abdomen assembly ***b) Rear bracket*** ***c) ABISUP abdomen fitted to THOR-50M***

Figure 1. ABISUP abdomen assembly.

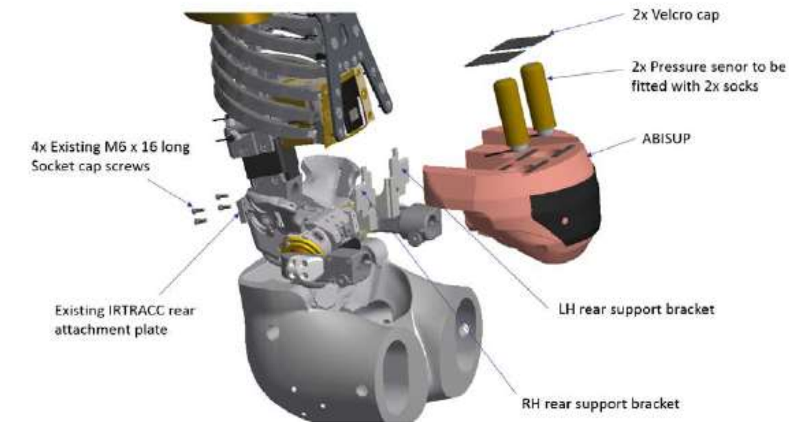
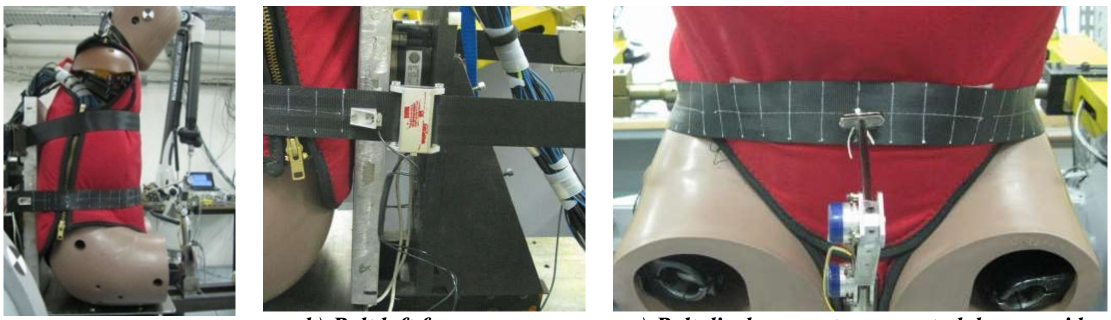


Figure 2. Exploded view of the lower abdomen ABISUP prototype and THOR-50M.

Test Setups

The biofidelity and the repeatability of the ABISUP abdomen was assessed by reproducing Post Mortem Human Surrogates (PMHS) tests of Lamielle [17], Ramachandra [18] and Foster [19]. The sensitivity of the ABISUP abdomen was evaluated by varying the seatbelt belt loading height in Foster [19] and Kent's [7] test setups. The reproducibility of the abdomen was checked under the qualification rigid bar tests of the THOR-50M [20]. The test results from the Kent setup were also used to define the relationship between the ABISUP abdomen pressure and its deflection during the development of the IRF. Sled tests were performed to check the ability of the ABISUP abdomen to discriminate between restraint conditions and evaluate the relevance of the risk predicted by the IRF. It has to be noted that for all the tests performed in Europe (at CEESAR-LAB, Université Gustave Eiffel, Forvia) the ABISUP abdomen was mounted on the same THOR Mod Kit 50th. The ASIS load cell new cover design implemented on the THOR Standard Build Level A and B was not updated but no lap belt being latched into the gap between the ASIS cover and the iliac crest bone were reported during tests. In the US and Japan, the ABISUP abdomen was mounted on a THOR-50M. Considering that the focus of this study is the response of the ABISUP abdomen and its associated IRF, it is assumed that the dummy version had little influence.

<u>Seatbelt pull tests under Lamielle's setup [17]</u> were performed at CEESAR and the setup consisted of a rigid seat and back support against which the dummy was seated upright. A standard seatbelt was initially positioned horizontally on the abdomen above the anterior superior iliac spines of the pelvis and below the ribs (Figure 3.a). The belt was routed backward through pulleys to the loading device. Both belt strands were attached to the loading system. A hydraulic piston was used to pull the belt through rotating rigid arms in order to multiply the belt displacement and speed. Two belt sensors (Figure 3.b), placed at the vicinity of the back plate on the right and left sides, were used to calculate the force applied onto the abdomen. The belt displacement was measured at the mid-point of the abdomen using a custom device with two rotary potentiometers allowing the computation of the x and z belt displacement (Figure 3.c), and at the belt side using an optical sensor or by double integration of the belt accelerations. The force applied on the abdomen was computed by adding the left and right belt forces. The abdomen deflection was calculated as the distance between the processed belt locations at each time step and at time zero. The ABISUP abdomen response was compared with the PMHS corridors defined by Lebarbé et al. [24] from the MHA test series of Lamielle.



a) Overview ***b) Belt left force sensor*** ***c) Belt displacement sensor at abdomen mid-point***

Figure 3. THOR Mod Kit 50th equipped with the ABISUP abdomen under Lamielle's test setup. Dummy on the rigid seat with the lap belt in position

<u>Seatbelt pull tests with free back under Ramachandra's setup [18]</u> were carried out at Transportation Research Center (TRC). The dummy was seated on a table with its back free to move (Figure 4). A seatbelt was wrapped around the dummy abdomen at the mid-abdomen level. The belt sides were tangent to the lateral aspects of the dummy and parallel to each other. The belt was attached on a T-bar connected to a pneumatic piston and was pulled at loading speeds of approximately 4 m/s. Two belt sensors measured the force in each strand and the belt displacement was measured in the mid-sagittal section of the belt using a string potentiometer. A string potentiometer was attached to the T-bar to measure the dummy back motion relative to the ram. The force applied to the abdomen was computed by adding the left and right belt forces. The displacement of the dummy spine was subtracted from the belt displacement. The ABISUP abdomen response was compared with the PMHS responses from Ramachandra et al. [18].

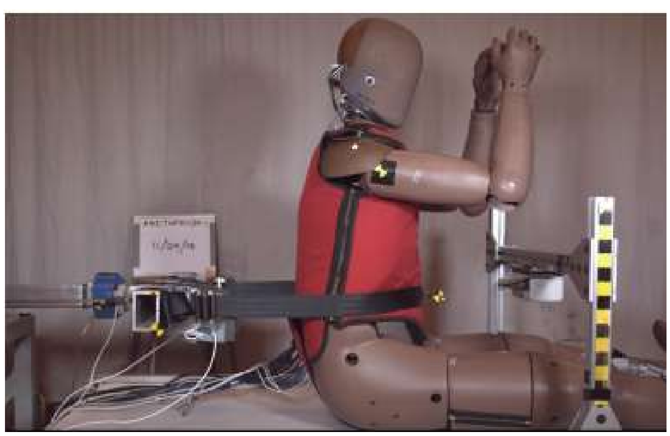
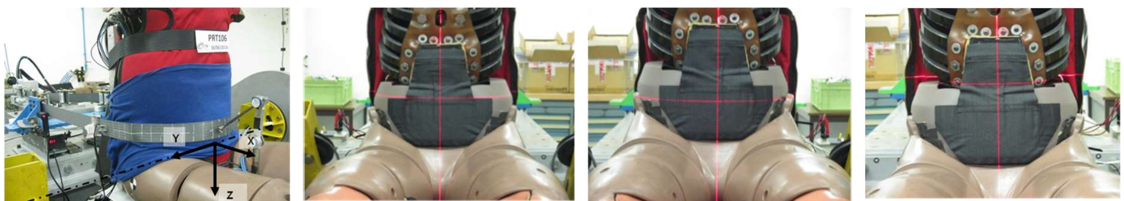


Figure 4. THOR-50M equipped with the ABISUP abdomen under Ramachandra's test setup.

Seatbelt pull tests under Foster's setup [19] were performed at CEESAR. The setup consisted of a rigid seat and back support against which the dummy was seated upright with its legs set horizontally (Figure 5.a). A seatbelt, initially positioned horizontally on the abdomen above the anterior superior iliac spines of the pelvis and below the ribs, was pulled rearwards by one or two pretensioner systems as used by Foster et al. The belt was guided in the lateral direction using two rollers. The position of the rollers was adjusted such that the distance between their most lateral points was equal to the dummy abdomen width. The pretensioners at the end of the belt were fixed onto a rigid support and their mounting axes were aligned horizontally with the centers of the rollers. The belt slack was minimized by adding a 10N pre-load on each belt strand. The dummy sitting height was adjusted to position the belt at three different heights and evaluate the sensitivity of the ABISUP abdomen to belt positioning: (1) the middle height position was where the belt lower border was aligned with the upper edge of the pelvic skin. This corresponded to the belt position in Foster's tests (Figure 5.b), (2) the lower height position was where the belt lower border touched the thigh flesh (Figure 5.c), (3) the upper height position was where the belt center line was aligned with the lower thoracic IR-TRACC attachment points (Figure 5.d). The belt displacement was measured at the mid-point of the abdomen using two rotary potentiometers allowing the computation of the x and z belt displacements. Two belt sensors, placed at the vicinity of the back plate on the right and left sides, were used to calculate the force applied onto the abdomen by summing their measurement. The abdomen deflection was calculated by subtracting the distance of the belt at each time step and the one calculated at time zero. The ABISUP abdomen response was compared with the PMHS responses from Foster et al. [19].



a) Foster's setup and instrumentation

b) Seatbelt at middle position: center line of the belt along the laser horizontal line

c) Seatbelt at lower position: center line of the belt along the laser horizontal line

d) Seatbelt at upper position: center line of the belt along the laser horizontal line

Figure 5. THOR Mod Kit 50th equipped with the ABISUP abdomen under Foster's test setup and seatbelt height variations.

Rigid bar impacts under Qualification setup [20] were performed at CEESAR. The THOR equipped with the ABISUP abdomen was seated on a flat horizontal surface on a thin Teflon sheet, its lower limbs in a horizontal position and its back free to move. The dummy was equipped with a target attached rigidly to the spine at the T12 location. The impactor face was rectangular with dimensions of 178 by 51 mm and rounded edges. The dummy sitting height was adjusted in order to align the IR-TRACC attachment points of the standard abdomen with the center of the impactor face (Figure 6.a, Figure 6). The 32 kg impactor was propelled at a target initial speed of 3.3 m/s. The impact force was calculated by multiplying the impactor mass by the impactor acceleration. The impactor displacement was measured from a target placed on its side. The abdominal deflection was calculated by subtracting the displacement of the target at T12 on the dummy from the target displacement on the impactor (Figure 6.c). The abdomen repeatability and reproducibility were evaluated by calculating the Coefficients of Variation (CV) of the APTS pressure, abdominal deflection and impactor force. CV scores were categorized according to NHTSA [6] as shown in Table 1.

a) Impactor in front of THOR Mod Kit 50th abdomen

b) ABISUP abdomen impact location

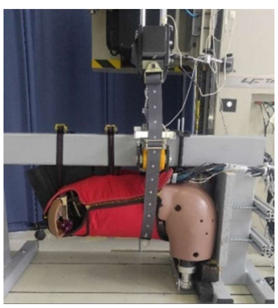
c) Targets placed on dummy and impactor

Figure 6. THOR Mod Kit 50th equipped with the ABISUP abdomen under the qualification test setup.

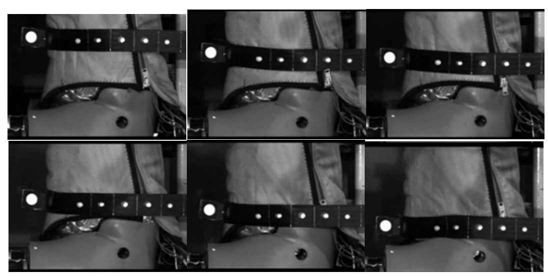
Table 1. Coefficient of Variation (CV) categories

CV (%)	Category
0-5	Excellent
> 5-8	Good
> 8-10	Marginal (Acceptable)
>10	Poor (Unacceptable)

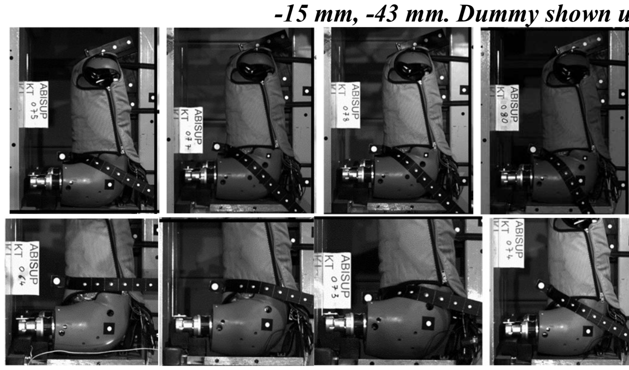
Seatbelt pull tests under Kent's setup [7] were carried out at the University Gustave Eiffel. The trunk of the THOR was fixed on a rigid structure in a seated upright position. It was attached on the rigid structure in several locations using (1) screws and a bracket to hold the pelvis posteriorly, (2) straps around its thoracic spine to pull it against the structure in two locations and (3) screws to hold the femurs in place. The dummy and the test fixture were then tilted with the dummy facing the ground and placed below a hydraulic orientable piston (Figure 7.a). Wedges were positioned behind the thoracic and lumbar spine to remove any gap with the rigid structure and all attachments were tightened. A seatbelt was wrapped around the mid abdomen. For Kent's setup, it was routed against rollers placed on each side on the dummy at the abdomen level as in Kent. Each belt strand end was attached to a transverse bar attached to the piston. The piston displacement was limited depending on the configuration to prevent any dummy damages. The belt strands and piston were parallel and oriented perpendicularly to the rigid structure. Seatbelt sensors measured the force in the belt strands and a target was placed on the seatbelt at the mid sagittal plane of the dummy to measure the belt displacement. The belt was pulled by the piston at various speeds ranging from 1 to 8 m/s.
The relationship between the abdomen deflection and the APTS pressures was defined from these tests. Additionally, the sensitivity of the abdomen was studied by varying belt position height (Figure 7.b) and orientation (Figure 7.c) at a belt pull speed of 2 m/s. These tests were performed without the rollers.



a) Dummy positioned below the piston.



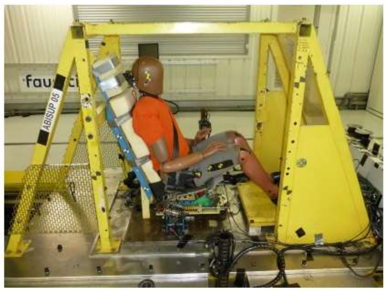
b) Seatbelt height variations. From top left to bottom right: +69 mm, +39 mm, +15 mm, Kent's seatbelt height (0 mm), -15 mm, -43 mm. Dummy shown upright for legibility.



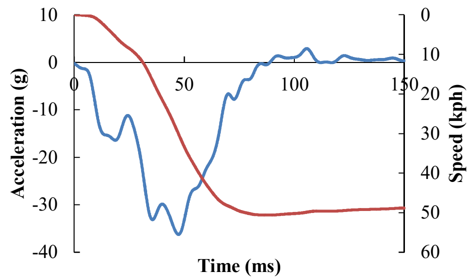
c) Seatbelt angle and position variations. Dummy shown upright for legibility.

Figure 7. THOR-50M equipped with the ABISUP abdomen in Kent's (with rollers) and sensitivity (without rollers) setups.

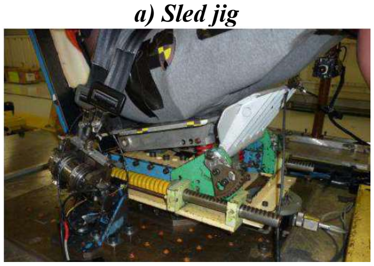
Sled tests under Uriot's setup [21] were performed at Forvia. The front and rear seat configuration tests of Uriot et al. were replicated using the semi-rigid seat and a separated rigid backrest covered by foam pads (Figure 8.a). The THOR was restrained by a separated thoracic and lap belt equipped with Uriot's load limiters at the thoracic belt retractor and both lap belt anchorages. The seat pan orientation and stiffness, and the belt anchorage locations replicated the two configurations used by Uriot. The front seat configuration replicated the geometry and the seat behavior of a front seat (Figure 8.c). The rear seat configuration (Figure 8.d) replicated the geometry of a rear bench and the seat behavior was adjusted to obtain submarining in simulations with a Hybrid III 50th dummy. The dummy feet were positioned on a rigid footrest angled by 55° with respect to the horizontal and maintained in position during the crash. The sled was submitted to Uriot's 14 m/s deceleration pulse (Figure 8.b).



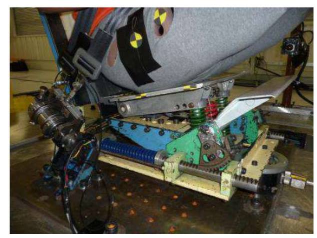
a) Sled jig



b) Uriot's pulse



c) Front seat configuration



d) Rear seat configuration

Figure 8. THOR Mod Kit 50th percentile in Uriot's sled test setup.

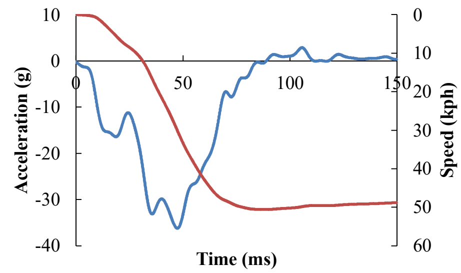
Sled tests using vehicle seats. Sled tests using vehicle seats were performed at Forvia, Virginia Tech-NHTSA and TMC. Four tests were performed at Forvia using a driver seat and a 3-point belt equipped with a 6 kN load limiter and a pretensioner in the retractor (Figure 9.a). Two tests were performed in a standard configuration for a front passenger seat (Figure 9.c) and two in a slouched configuration (Figure 9.d) where all anchorage points were moved 50 mm rearwards with respect to the seat, the dummy was positioned with its pelvis moved forward by 60 mm and the shoulder pretensioner was not activated. The sled was subjected to a 14 m/s pulse (Figure 9.b). These tests replicated Uriot et al. tests [22].

Ten sled tests were performed at Virginia Tech. using a rear seat and a 3-point belt (Figure 10.a). Five tests were performed at 36 km/h and five at 56 km/h. Figure 10.b shows the 56 km/h scaled pulse resulting in a 32 km/h pulse. Finally, a generic 36 km/h pulse (Figure 10.c) was used for the tests [23].

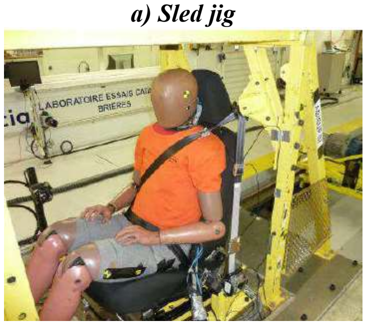
Seven tests were performed at TMC using a production driver seat with a seat-mounted 3-point belt equipped with a 4 kN load limiter and pretensioner in the shoulder retractor (Figure 11.a). A pulse corresponding to a 40 km/h crash between a family car and the Full-width Rigid Barrier (FWRB) was applied to the sled (Figure 11.b). The restraint system was varied by adding to the 3-point belt either a lap belt pretensioner or a knee bolster. Furthermore, the seatback angle was adjusted to obtain either a 21° or a 49° torso angle (Figure 11.c to f).

For this paper, the analysis of the sled tests was limited to the analysis of the ABISUP abdomen pressure and the kinematics including the occurrence of submarining. These results were used to check the applicability of the developed abdominal IRFs.

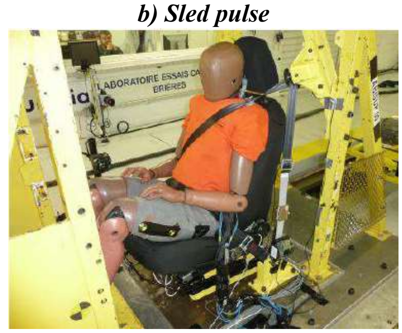
a) Sled jig



b) Sled pulse



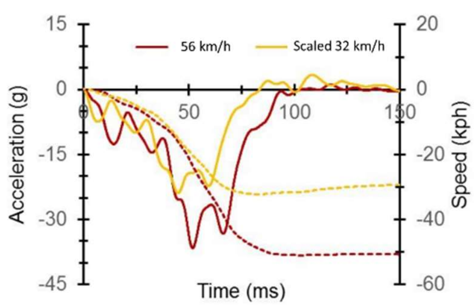
c) Standard configutaion



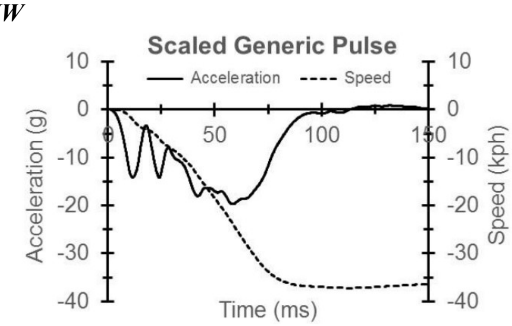
d) Slouched configuration

Figure 9. THOR Mod Kit 50th percentile in Forvia sled test setup [22].

a) BIW



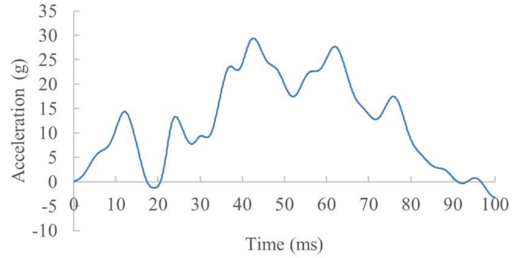
b) 56 km/h and 32 km/h scaled pulses



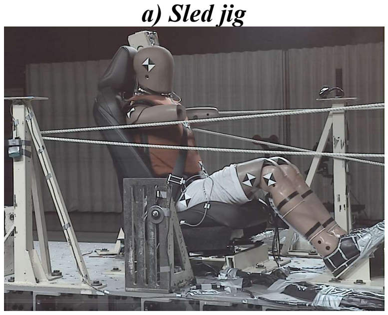
c) 36 km/h generic pulse

Figure 10. THOR-50M (left) in Virginia Tech and NHTSA Body In White (BIW) sled test setup [23].

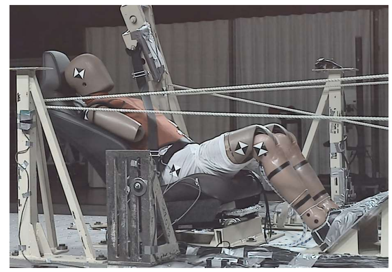
a) Sled jig



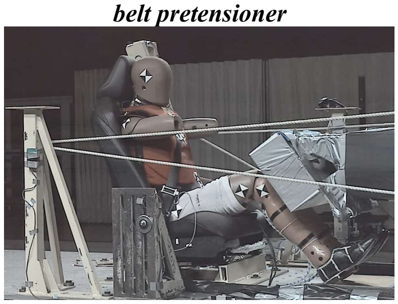
b) Sled pulse



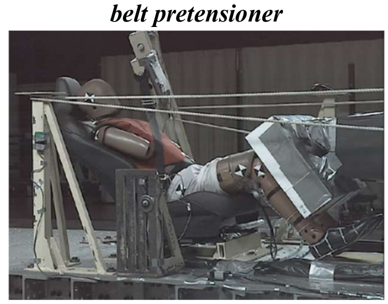
c) 21° torso angle carried out without and with lap belt pretensioner



d) 49° torso angle carried out without and with lap belt pretensioner



e) 21° torso angle and knee bolster configuration



f) 49° torso angle and knee bolster configuration

Figure 11. THOR-50M in TMC sled test setup (the dummy forearms were removed for the tests to prevent them hiding the dummy and seatbelt targets).

Summary: Test matrices

The belt and impactor tests performed on the ABISUP abdomen are summarized in Table 2. Table 3 shows the twenty-five sled tests performed on THOR dummy equipped with the ABISUP abdomen. Some of the tests were also replicated with the standard THOR.

Table 2.Seatbelt pull tests and rigid bar impacts performed on ABISUP abdomen

Reference	**Loading type**	**Number of tests**	**Comments**
Lamielle et al. [17]	4 m/s seatbelt pull test, mid abdomen 3.5 m/s seatbelt pull test, mid abdomen	2[1] 5	Biofidelity Repeatability
Ramachandra et al. [18]	4 m/s free back pull test Mid abdomen	3	Biofidelity and repeatability
Foster et al. [19]	Single pretensioner, Mid abdomen	3	Biofidelity and repeatability
	Dual pretensioner, Mid abdomen	3	Biofidelity and repeatability
	Single pretensioner, Upper abdomen	2	Sensitivity
	Single pretensioner, Lower abdomen	2	Sensitivity
Qualification [20]	32 kg, 3.4 m/s Rigid bar impact	8	Two tests per abdomen
Kent et al. [7]	Seatbelt pull test at various speed	43	Relationship between APTS pressure and belt deflection
	Seatbelt pull test at various heights on the abdomen	6	Sensitivity
	Seatbelt pull test for various belt angles	8	Sensitivity

[1] ***One test replicated with the standard*** THOR

Table 3. Sled tests performed on THOR equipped with ABISUP abdomen

Reference	Test conditions	Number of tests
Forvia sled tests (Uriot et al. [21])	50 km/h pulse, Vehicle seat, Standard sitting posture 3-point belt	2
	50 km/h pulse, Vehicle seat, Slouched sitting posture 3-point belt	2
Forvia sled tests (Uriot et al. [22])	50 km/h pulse, Semi-rigid seat, Front seat configuration Separated shoulder and lap belt	2[1]
	50 km/h pulse, Semi-rigid seat, Rear seat configuration Separated shoulder and lap belt	2[1]
Virginia Tech, NHTSA sled tests	36 km/h pulse, Rear seat, 3-point belt	5
	56 km/h pulse, Rear seat, 3-point belt	5
TMC sled tests	40 km/h FWRB pulse, Standard sitting posture 3-point belt (repeated), 3-point belt, & lap belt pretensioner, 3-point belt & knee bolster	4[2]
	40 km/h FWRB pulse, 49° torso angle sitting posture 3-point belt (repeated), 3-point belt, & lap belt pretensioner, 3-point belt & knee bolster	3[2]

[1] Two tests replicated with the standard THOR
[2] Test with the three-point belt only replicated with the standard THOR

Injury Risk Function Definition

The IRFs were developed from Kent et al. [7] porcine tests in which abdominal injuries were observed and various injury metrics including abdominal compression were tested. The tests performed on the ABISUP abdomen under similar conditions were used to define the relationship between the ABISUP compression and the mean of the maximum pressure from the right and left side of the APTS. The mean pressure was used because the setup should have been symmetrical and averaging could therefore partially correct symmetry errors. However, the peak pressure is used when applying the curve as vehicle environments are not symmetrical. Two compressions were calculated. The first one uses the same definition as Kent, i.e. the ratio between the abdominal deflection and abdominal depth. It will be called ABISUP abdomen compression. This definition does not account for possible differences in spine depth between species. The second one was calculated as the ratio between the abdominal deflection and the abdomen compressible depth in front of the dummy lumbar spine. It will be called ABISUP soft abdomen compression. The abdomen depths were measured in the dummy mid sagittal plane of the Finite Element Model (FEM) published by the University of Virginia. The compressible depth was equal to 157 mm whereas the total abdominal depth of the dummy with the ABISUP abdomen was equal to 266 mm. The depths were also checked against the physical dimension of the dummy used in the test. Kent's porcine soft abdominal compression was calculated as well considering the compressible depth in front of the porcine spine. This was done by assuming a constant ratio between the compressible abdomen depth and the total depth across specimen. Details are provided in Appendix 2. Then, assuming an equivalence between the dummy and porcine compressions, the compressions were transformed in pressures using ABISUP abdomen relationships between the compressions and the APTS maximum pressure. IRFs were created for the two compressions following partially an ISO Technical Specification [25]. Survival analysis and different distributions (Weibull, Lognormal, Log-logistic) were used to compute the risk curves with the R software. The distribution with the lowest Akaike Information Criterion (AIC) was kept and it was found to be the Log-logistic distribution. The risk of abdominal injury was given by Equation 1. Then, the risk ratio was computed for different levels of risk and a rating (between good for ratios below 0.5 and unacceptable for ratios above 1.5) was attributed. There was no check for multiple injury mechanisms or overly influential observations.

$$p(AIS \geq 3) = \frac{1}{1+exp\,\{[-\,ln(Max.pressure)+Intercept]/exp\,(log\ \_scale)\}} \qquad \textit{Equation 1}$$

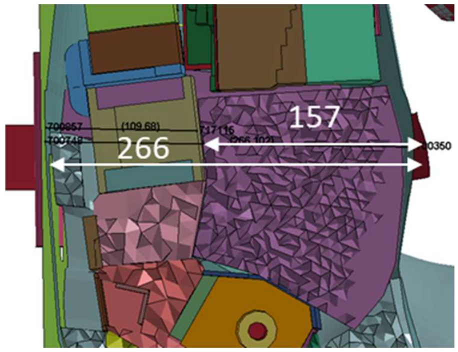


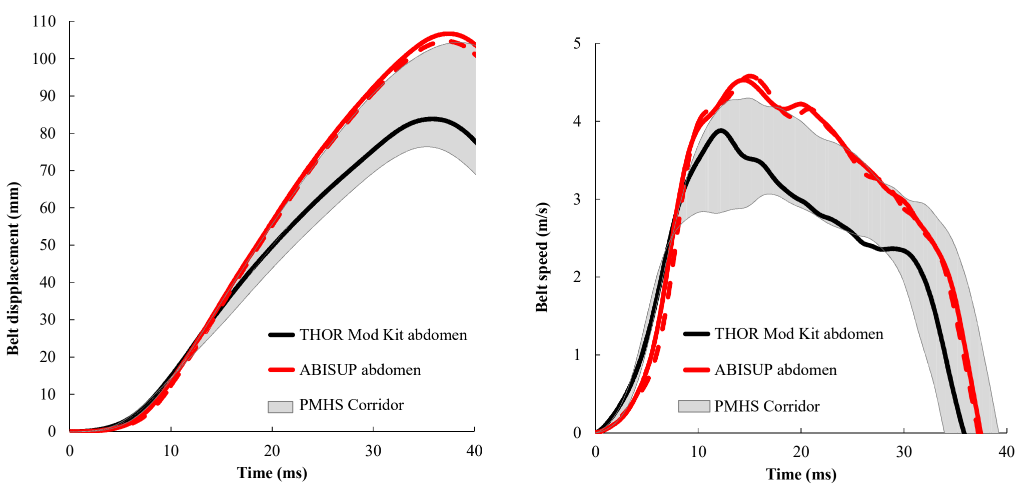
Figure 12. Compressible and total abdominal depths of the ABISUP abdomen shown on the THOR model with the ABISUP abdomen.

RESULTS

ABISUP Abdomen Biofidelity

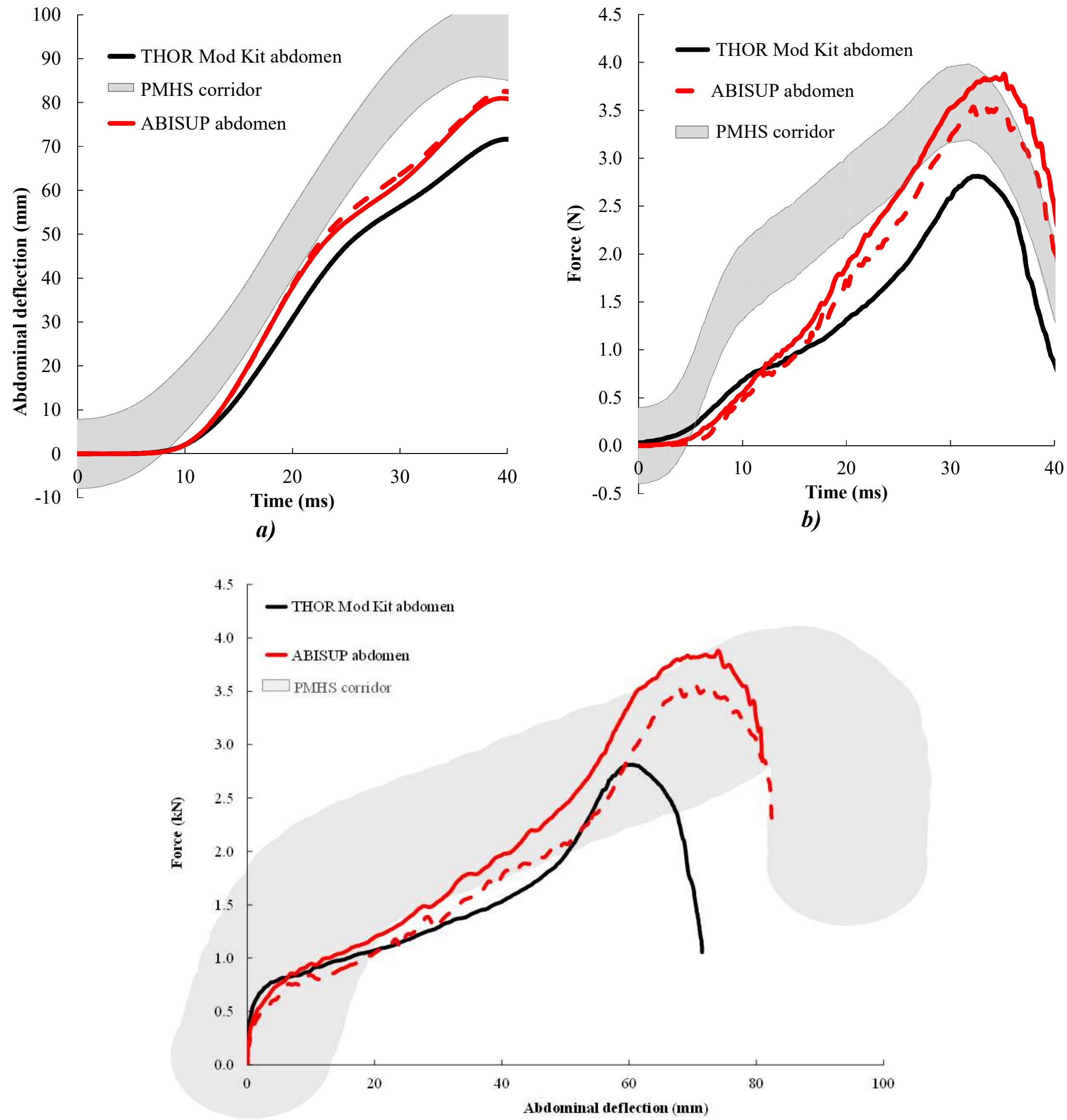
The biofidelity of the abdomen was assessed by comparing its response to the corridors defined from the PMHS responses of Lamielle et al. [17], Ramachandra et al. [18] and Foster et al. [19]. The belt displacement referred to the displacement of a point placed on one of the belt sides and the abdomen or dummy deflection corresponded to the displacement of a point placed on the belt in the dummy sagittal plane.

Comparison with Lamielle's PMHS responses. At first, the inputs used for the belt displacement and the belt speed versus time were compared between the PMHS, the standard THOR and the ABISUP abdomen. This showed that the belt displacement for the ABISUP abdomen was on the upper boundary of the PMHS corridors and that the belt speed was slightly higher than the one applied in the PMHS tests (Figure 13.a and b). This difference of input illustrated the difficulty to replicate the exact conditions of such tests as the input was affected by the surrogate characteristics. The comparison of the deflections and forces showed that the ABISUP maximum abdomen deflection was lower than the one of the PMHS and that the ABISUP force did not increase sufficiently at the beginning of the deflection (up to around 50 mm) (Figure 14.a). The ABISUP abdomen deflection and force were increased compared to the standard THOR-M50, however this might be related to the higher belt displacement and speed rather than a difference in the two abdomen behaviors. It has to be noted that the ABISUP abdomen deflection was lower than the belt displacement whereas similar values were observed for the PMHS. This may have to do with differences in the lateral deflection of the ABISUP and PMHS abdomens.



a) ***b)***

Figure 13. Belt displacement (a) and speed (b) of ABISUP abdomen test versus Lamielle's PMHS corridors.



c)

Figure 14. ABISUP abdomen response versus Lamielle's PMHS corridors: Abdomen deflection versus time (a), force versus time (b), force-abdomen deflection (c).

Comparison with Ramachandra's PMHS responses. The responses of the ABISUP abdomen and of the standard dummy were compared with the response corridors defined from the PMHS tests for the free-back test configuration. For both deflection and force, the ABISUP abdomen responded very similarly to PMHS initially, but later in the event, both dummy responses began to deviate from the PMHS, with the result being a much lower dummy peak deflection and higher dummy peak force (Figure 15). This could result from different abdomen behavior and/or differences in whole body translation compared to the PMHS as both dummy and PMHS were free to move. It can be noted that the peak PMHS deflections were close to and sometimes higher than the physical limits of the dummies resulting from their abdomen depths.

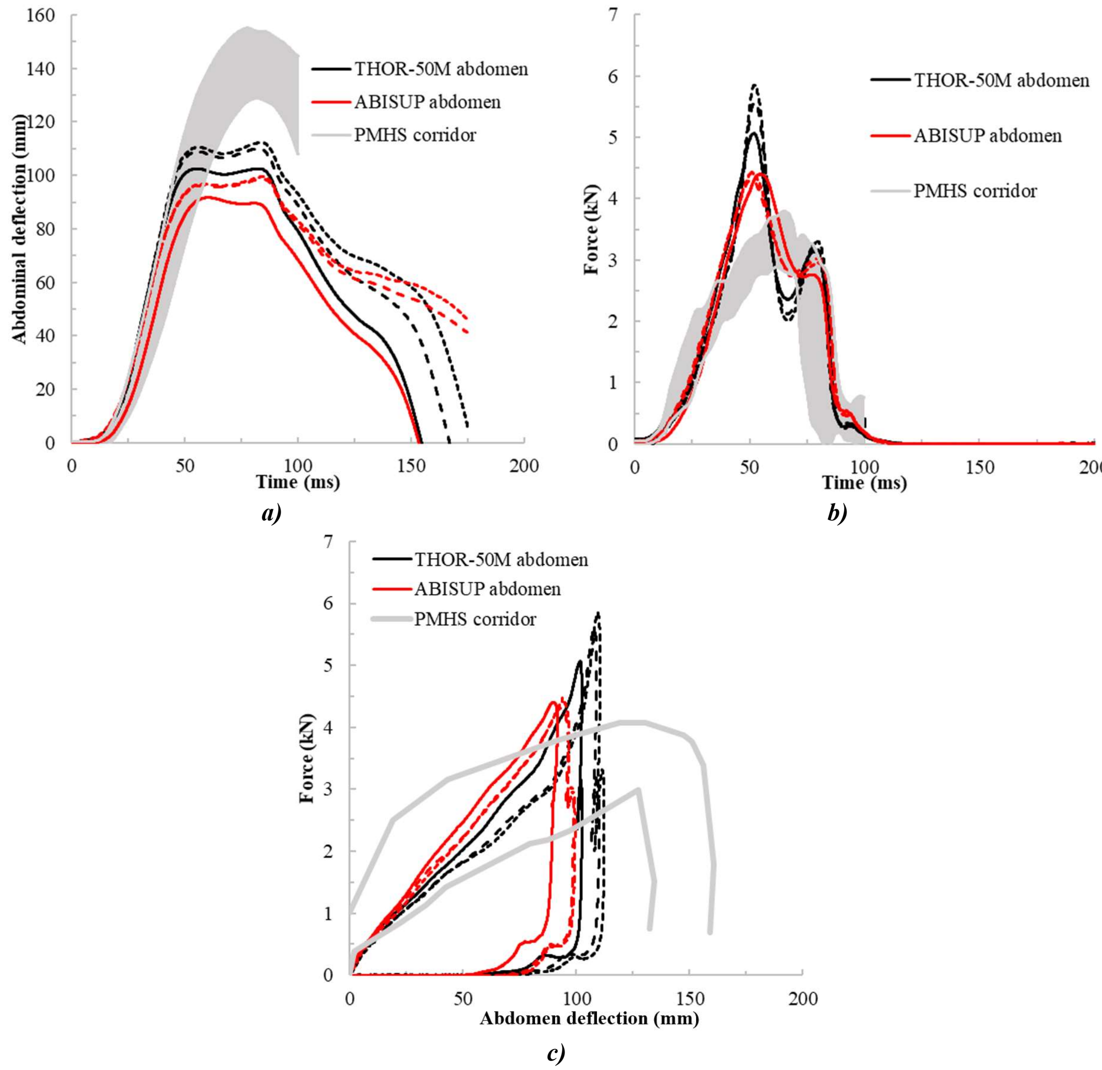


Figure 15. ABISUP abdomen response versus Ramachandra's PMHS corridors in free-back loading: abdomen deflection versus time (a), force versus time (b), force-abdomen deflection (c).

Comparison with Foster's PMHS responses. The ABISUP abdomen response was compared with the corridors defined by Foster at al. [19]. In the single pretensioner test, the ABISUP abdomen force was below the PMHS force-deflection corridor from 0 to 25 mm of deflection, but in the corridor for the remainder of the response (ref Figure 16, bottom left). In the dual pretensioner test, the ABISUP abdomen force was below the PMHS force-deflection corridor from 0 to 40 mm of deflection, but in the corridor for the remainder of the response (Figure 16). The single pretensioner tests created a belt displacement speed of 11 m/s whereas the dual pretensioner tests reached 19 m/s.

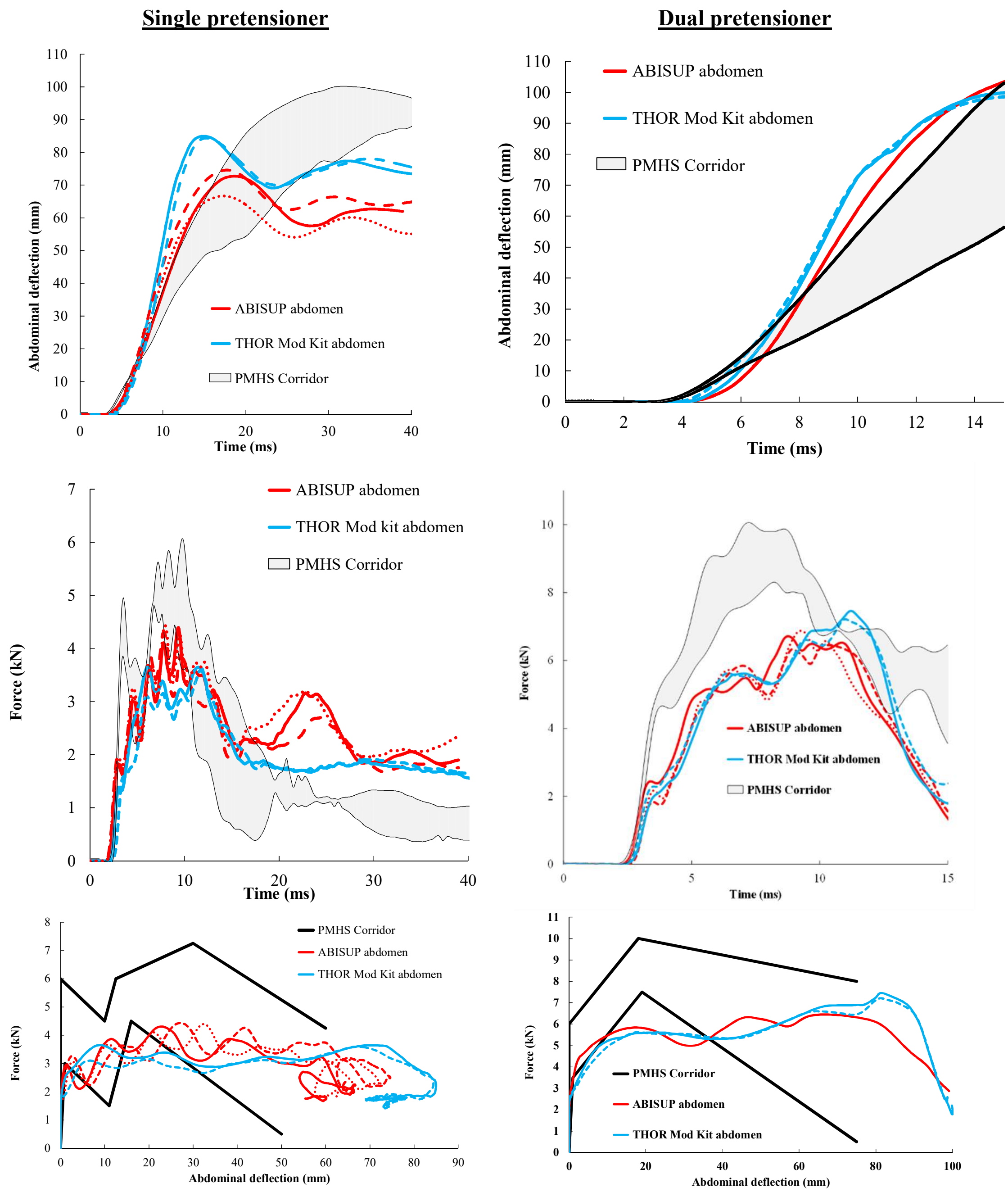


Figure 16. ABISUP abdomen response versus Foster's PMHS corridors in single pretensioner loading (left) and in dual pretensioner loading (right). From top to bottom: abdomen deflection versus time, force versus time and force-abdomen deflection.

ABISUP Abdomen Repeatability

Repeatability in Lamielle's tests Five tests were performed giving the same input to the servo-controlled machine for the piston displacement and speed. However, as it can be observed in Figure 17 and Figure 18, the applied belt displacement and speed were not completely repeatable. Abdominal deflection, belt force and APTS pressures were compared. Maximum values and CVs are displayed in Table 4. Despite the variation of the belt displacement and speed, the abdomen CV values were close to 5%.

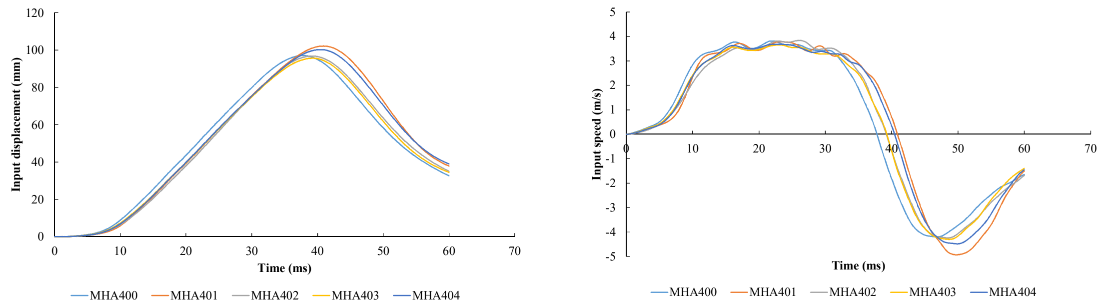


Figure 17. Belt displacement (left) and speed (right) in the five repeated tests.

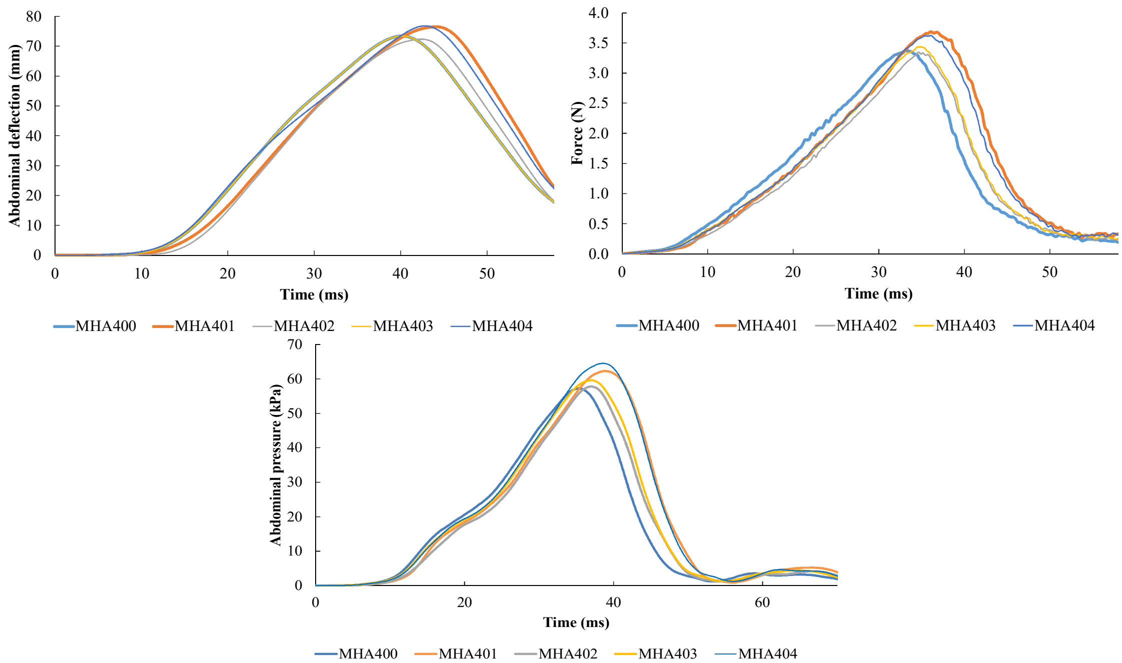


Figure 18. ABISUP abdomen deflection (top left), belt force (top right), right and left APTS average pressure (bottom)

Table 4. Maximum values in repeated Lamielle's tests

Test	Abdomen deflection (mm)	Belt force (kN)	Left APTS maximum pressure (kPa)	Right APTS Maximum pressure (kPa)
MHA400	73	3.0	59	56
MHA401	76	3.4	65	59
MHA402	72	3.0	59	57
MHA403	72	3.1	62	57
MHA404	77	3.3	69	61
Mean	**74**	**3.2**	**63**	**58**
Standard deviation	**2.3**	**0.19**	**4.2**	**1.9**
CV	**3%**	**6%**	**7%**	**3%**

Repeatability in Ramachandra's tests. Three tests were repeated. The abdominal deflection and the belt force CV values were below 5%. The APTS pressure CV values were between 3 and 4% (Table 5). In free back tests, the dummy was free to move and the APTS were therefore less sensitive to possible slightly asymmetrical loading provided by the test set-up as may be encountered in the fixed back tests under Lamielle's conditions (CV values up to 7%). These values correspond to an excellent or good rating according to [6].

Table 5. Maximum values in repeated Ramachandra's tests

Test	Abdomen deflection (mm)	Belt force (kN)	Left APTS maximum pressure (kPa)	Right APTS maximum pressure (kPa)
Fixed back	67	2.5	41	44
Fixed back	70	2.7	47	52
Fixed back	71	2.6	45	47
Fixed back	72	2.5	45	48
Mean	**70**	**2.4**	**45**	**48**
Standard deviation	**1.9**	**0.09**	**2.6**	**3.4**
CV	**3%**	**4%**	**6%**	**7%**
Free back	92	4.4	91	91
Free back	100	4.5	97	95
Free back	99	4.3	98	96
Mean	**97**	**4.4**	**95**	**94**
Standard deviation	**4.3**	**0.08**	**3.8**	**2.9**
CV	**4%**	**2%**	**4%**	**3%**

Repeatability in Foster's tests. Tests were repeated three times for the single and for the dual pretensioner test configurations. The abdomen response was well repeatable with CV values below 5% except in the first single pretensioner test in which a lower abdomen deflection and therefore APTS pressure were recorded (Table 6). The reason was not identified.

Table 6. Maximum values in repeated Foster's tests

Test	Abdomen deflection (mm)	Belt force (kN)	Left APTS Maximum pressure (kPa)	Right APTS Maximum pressure (kPa)
Single pretensioner	67	4.4	101	108
Single pretensioner	75	4.5	137	144
Single pretensioner	73	4.5	132	129
Mean	**71**	**4.5**	**123**	**127**
Standard deviation	**4.1**	**0.06**	**19.6**	**17.9**
CV	**6%**	**1%**	**16%**	**14%**
Dual pretensioner	NA	7.3	207	203
Dual pretensioner	109	6.7	201	199
Dual pretensioner	NA	7.1	202	186
Mean	**NA**	**7.0**	**203.5**	**195.8**
Standard deviation	**NA**	**0.3**	**3.3**	**8.7**
CV	**NA**	**4%**	**2%**	**4%**

ABISUP Abdomen Reproducibility

Four identical prototypes were built (two for the US, one for Japan and one for Europe) and finally all shipped back to CEESAR to be subjected to the qualification test and compared. All prototypes were identical except that one of the US prototypes had a thicker skin implemented after damages were observed on previous prototypes (Table 7, Figure 19).

Figure 20 shows the force-deflection curves of the four prototypes. The damages of two abdomens prior to the qualification tests did not seem to affect their responses compared to the undamaged ones. The reinforced skin also did not seem to influence the mechanical behavior of the abdomen.

The results were normalized using the target impact speed of 3.30 m/s and assuming that all parameters were proportional to the impact speed. The speed varied between 3.24 and 3.54 m/s and the normalization helped to reduce the result variance. The normalized peaks of the qualification tests are summarized in Table 8. The difference between the left and right APTS pressure could not be explained. In average, pressure peaks were almost 10% higher on the right side. The pressure on the right side was also higher than on the left side in seven of the eight tests. This is surprising as the left and right APTS were identical and it was not known at manufacturing on which side they would be installed. This would point towards a difference related to the foam or the test setup.

The four prototypes exhibited a similar response with CV values between 2 and 7% corresponding to an excellent or good rating. The reinforced skin did not modify the response of the abdomen while improving the durability.

Table 7. ABISUP abdomen prototype description

Abdomen (serial number)	APTS.		Number of final certification tests	Region of round robin tests	Comments
	Right side	Left side			
EI 3455	W170DC	W170DA	2	Europe	Damaged*
EI 3466	P182T5	P182T4	2	US	-
EI 3467	P182R9	P182R8	2	Japan	Damaged*
EI 3513	W170DC	W170DA	2	US	Thicker reinforced skin

* Damages to the outer skin and the foam beneath it occurred before the certification due to other tests. The abdomens were repaired with tape.

Figure 19. ABISUP abdomens before the qualification test.

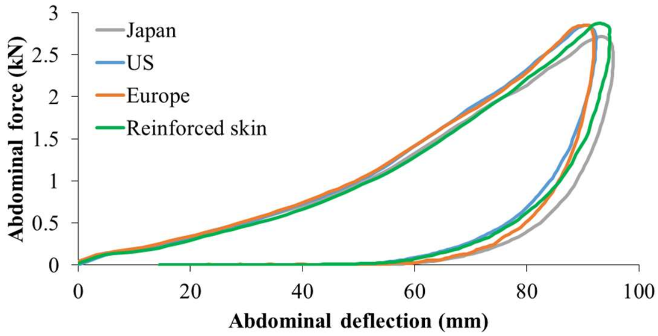


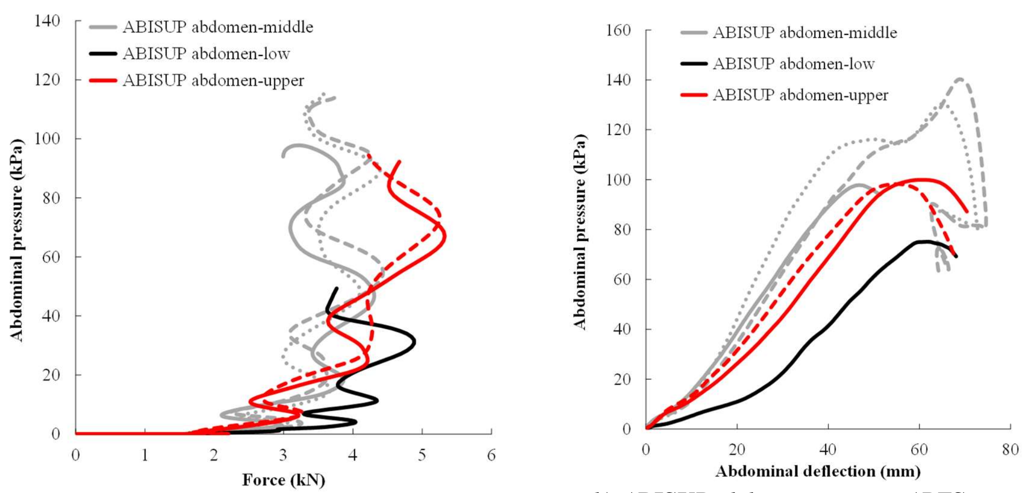
Figure 20. Force-abdomen deflection curves of the four prototypes.

Table 8. Normalized peak values

Abdomen prototype	Impact speed (m/s) (not normalized)	Maximum pressure (kPa)		Abdominal deflection (mm)	Impact force (N)
		Left	Right		
EI 3467 (Japan)	3.42	66.8	70.6	99	2714
	3.34	64.5	72.8	95	2717
EI 3455 (US)	3.44	76.8	71.8	94	2810
	3.46	73.4	75.5	92	2853
EI 3455 (Europe)	3.51	69.9	76.3	97	2750
	3.54	69.3	84.9	92	2855
EI 3513 (US, skin reinforced)	3.32	68.1	83.8	97	2854
	3.24	67.9	81.3	97	2878
Mean value	**4.41**	**70**	**77.1**	**95.5**	**2804**
Standard deviation	**0.10**	**4**	**5.6**	**2.6**	**67**
CV (%)	**3**	**5.6**	**7.2**	**2.7**	**2.4**

ABISUP Abdomen Sensitivity

The ABISUP abdomen sensitivity to loading height was evaluated under Foster's test configuration. The average APTS pressure versus belt force and versus abdomen deflection are shown in Figure 21. The highest APTS pressure was recorded for the middle height seatbelt position, when the lap belt laid between the pelvis skin and the lower thoracic ribs. The lowest pressure was measured when the belt was in the low position, in contact with the pelvis (Figure 21.b). From Figure 21.a it can be observed that both pressure and deflection increases were delayed compared to the belt force increase which might be due to an inertial effect (e.g. created by the jacket rib stiffeners), and possibly to some viscous effect of the abdomen under the high initial belt speed delivered by the pretensioner (11 m/s).



a) ABISUP abdomen average APTS pressure versus belt force

b) ABISUP abdomen average APTS pressure versus abdomen deflection

Figure 21. ABISUP abdomen responses versus belt height (middle, lower, upper) under Foster's test setup.

Under Kent's test setup, the rollers guiding the belt were removed, the two strands were made parallel and compression tests were conducted for several seatbelt heights. The pressure versus the abdomen deflection relationships were found to be relatively insensitive to the belt location, with the exception of a drop visible for the +69 mm belt position (on the thorax). The sensitivity to belt force was the highest for the belt position at Kent's test height (Base configuration) and 15 mm caudal from that position (Figure 22 left). At these heights, the belt was mainly in contact with the abdomen with little interaction with the pelvis and no interaction with the thorax. For the other heights, the pelvis or thorax carried some of the loads, which explained the reduced pressure sensitivity as these loads were not applied to the abdomen. The pressure sensitivity to deflection was much less marked with only significant drops visible for the most cranial positions of the belt (+39 and +69 positions, Figure 22 center) and limited differences otherwise even when the pelvis was involved.

The tests were then expanded to use various belt angles. The highest pressure sensitivity versus the belt force was obtained for the belt positioned at the mid abdomen and various angles between 15° and -30° (Figure 23 left). As in the belt height tests, this was consistent with the limited involvement of thoracic and pelvic structures. The highest pressure sensitivity to the abdomen deflection was obtained for the mid abdomen negative belt angles (which may occur during submarining) followed by the base and small positive angles with the belt in the mid abdomen (Figure 23 center). The pressure drop was relatively limited for 30° despite the belt involving the pelvis. This was interpreted as resulting from the sizeable proportion of the abdomen in front of the pelvis.

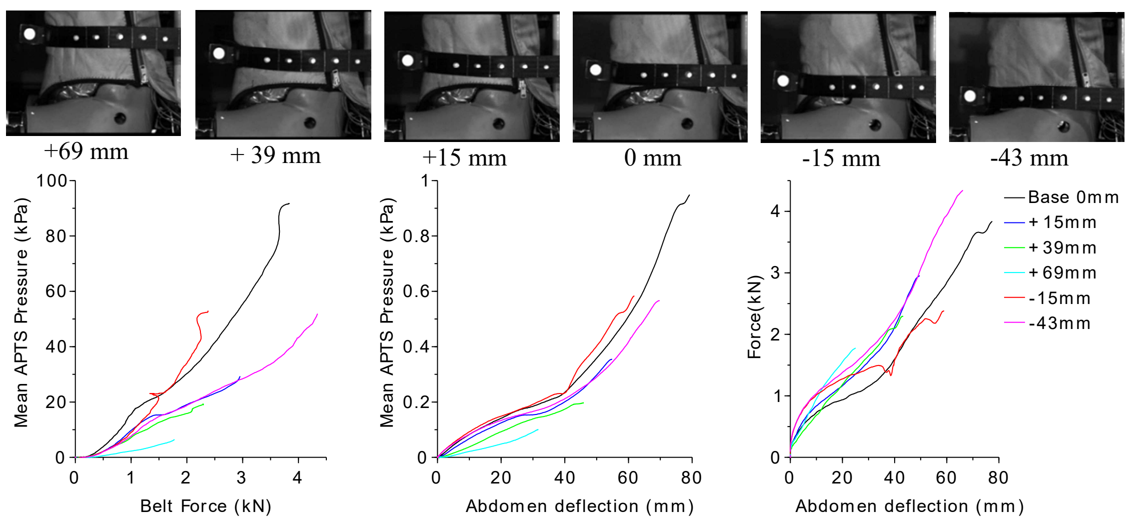


Figure 22. ABISUP abdomen responses versus belt height. The legend indicates the shift from the baseline position (0mm) with positive distances being cranial. The deflection is always measured at the belt in the dummy mid sagittal plane.

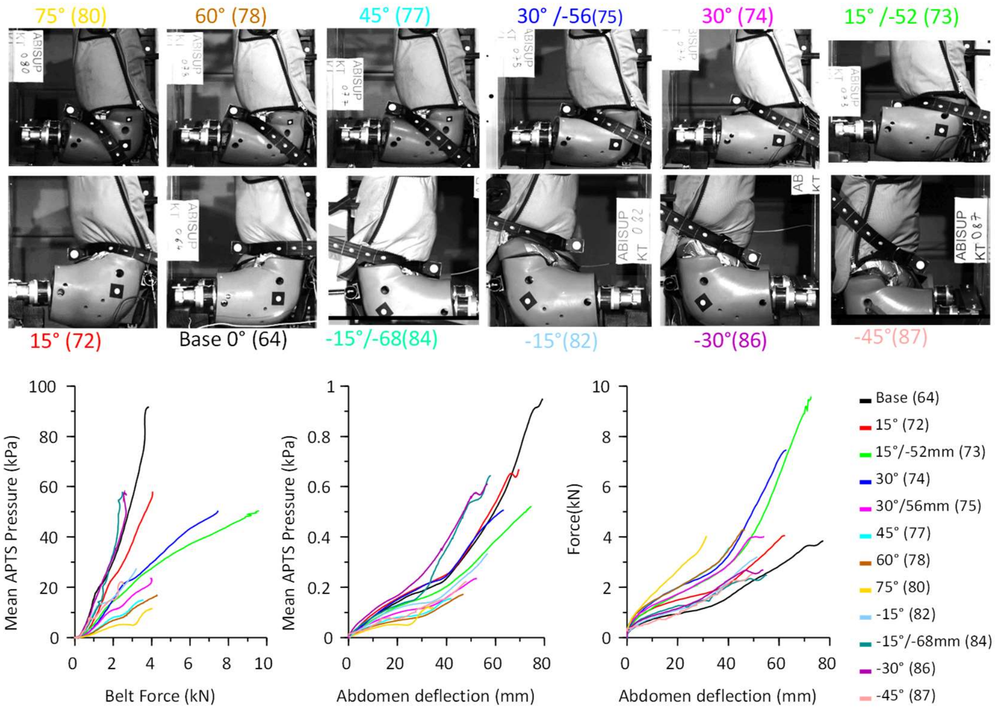


Figure 23. ABISUP abdomen responses versus belt angle. The legend indicates the angle (0° being horizontal, positive values with the belt engaging the pelvis) and, when different from 0mm (baseline) the shift of the mid-sagittal point from the baseline in the cranio-caudal direction with positive distances being cranial. The deflection is always measured at the belt but only the antero-posterior component is kept.

ABISUP Abdomen Injury Risk Function

From the 43 tests performed according to Kent's setup, the relationships between the average pressure of right and left APTS and the abdomen compressions were defined by fitting a second order polynomial curve through the experimental data points (Figure 24, Equations 2 & 3). The data points are provided in Appendix 1. The maximum belt displacement achieved was 118 mm, or about 44% abdomen compression and about 75% soft abdomen compression. It was not attempted to achieve higher compressions as the total belt force was already over 13 kN in that case (measured after the rollers).

Assuming an equivalence of the compressions, Kent's abdomen compressions were then converted to dummy pressure using the equations 2 and 3. Then, Kent's abdomen deflection data was changed to soft abdomen compression considering the compressible depth of other porcine specimen of similar size. It was assumed that the ratio of soft and total abdominal depth would be the same for all specimens. This led to compressions higher than 100% in four cases out of 45 (see details in Appendix 2). The pressure was calculated from the abdomen and soft abdomen compressions using the equations 2 and 3. When the soft abdomen compressions derived from Kent's porcine tests was over 75% (i.e. the maximum reached in the dummy tests), the pressure was calculated by extrapolation.

The AIS3+ IRFs obtained using the survival analysis and a Log-logistic distribution (distribution with the best AIC score) are shown in Figure 25, together with its confidence interval and risk ratio calculated according to ISO [25]. At 50% risk, the risk ratios of the IRFs were 0.61 and 0.85 for the abdomen compression and soft abdomen compression, respectively. Both are rated as "fair" according to ISO [25]. For the abdomen compression, an average of the maximum pressure of the right and left APTS of 133, 201 and 304 kPa corresponded to a 25%, 50% and 75% risk of AIS3+ abdominal injuries, respectively (Table 9). For the soft abdomen compression, an average of the maximum pressure of the right and left APTS of 108, 197 and 361 kPa corresponded to a 25%, 50% and 75% risk of AIS3+ abdominal injuries, respectively (Table 9).

The risks corresponding to the pressures measured in the component tests (seatbelt pull and rigid bar tests) are shown in Figure 26. They were all below 55% risk.

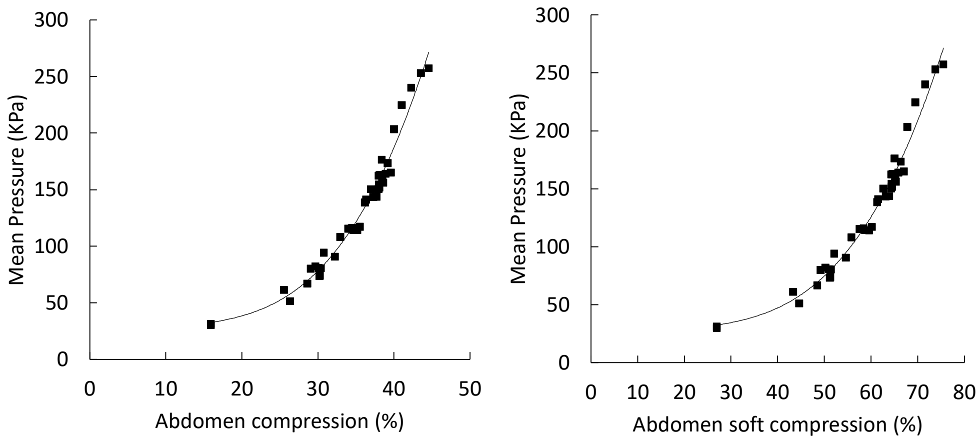


Figure 24. Average pressure of right and left APTS sides versus the abdomen compression: left versus abdomen compression, right versus abdomen soft compression.

For x=Abdominal Compression (C_{max}):

$$\text{Pressure} = 6.9440E\text{-}3\ x^3 - 2.7868E\text{-}01\ x^2 + 4.7133\ x\ ;\ R^2 = 0.978 \qquad \textit{Equation 2}$$

For x=Soft abdominal Compression (Soft_C_{max}):

$$\text{Pressure} = 1.4278E\text{-}3\ x^3 - 9.7084E\text{-}02\ x^2 + 2.7819\ x\ ;\ R^2 = 0.978 \qquad \textit{Equation 3}$$

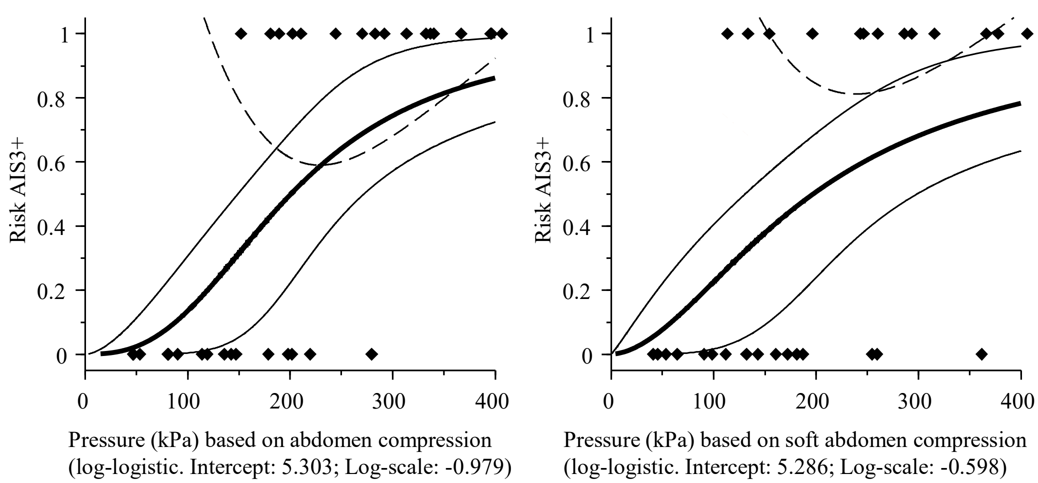


Figure 25. AIS3+ IRF versus APTS pressure (kPa) calculated from abdominal compression (left) or soft abdominal compression (right) (IRF in bold, 95% confidence interval in light, risk ratio in dashed line, injury status as diamonds).

Table 9. Pressure and associated AIS3+ risk calculated from abdominal compression (C_{max}) or soft abdominal compression (Soft_C_{max}) equivalence

	25%	**50%**	**75%**
Pressure (kPa) calculated from $\boldsymbol{C_{max}}$	133	201	304
Pressure (kPa)calculated from ***Soft_*** $\boldsymbol{C_{max}}$	108	197	361

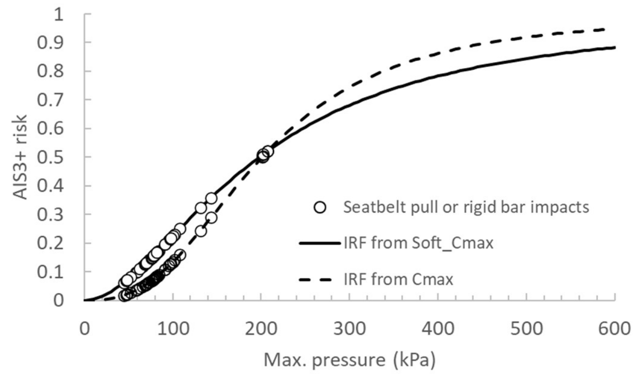


Figure 26. AIS3+ injury risk predicted in component tests.

ABISUP Abdomen Response in Sled Tests
The occurrence of submarining of the THOR equipped with the ABISUP abdomen was checked in the sled tests. The peak values of the APTS pressure, the ASIS forces/moments and lower thoracic IR-TRACC deflections are shown in Appendix 3. Figure 27 shows the maximum APTS pressure versus the submarining occurrence (visually identified from movies) and the risk of abdominal AIS3+ injuries versus the maximum APTS pressure.

Considering the IRF defined from the relationships between the pressure and the soft abdominal compression, in the case of submarining, a risk between 42 to 82% was estimated whereas a risk between 16 and 52% was estimated without submarining. The ABISUP abdomen and the IRF could discriminate restraint system conditions: a 28% risk was estimated for the reclined torso test in which the lap belt was positioned directly on the dummy abdomen and the dummy lower torso was restrained by a knee bolster; a risk between 77 and 79% was estimated for the reclined torso without a knee bolster. Similar risks would be obtained using the IRF defined from the relationships between the pressure and the abdominal compression. Post-test pictures and estimated risks are shown in Table 10.

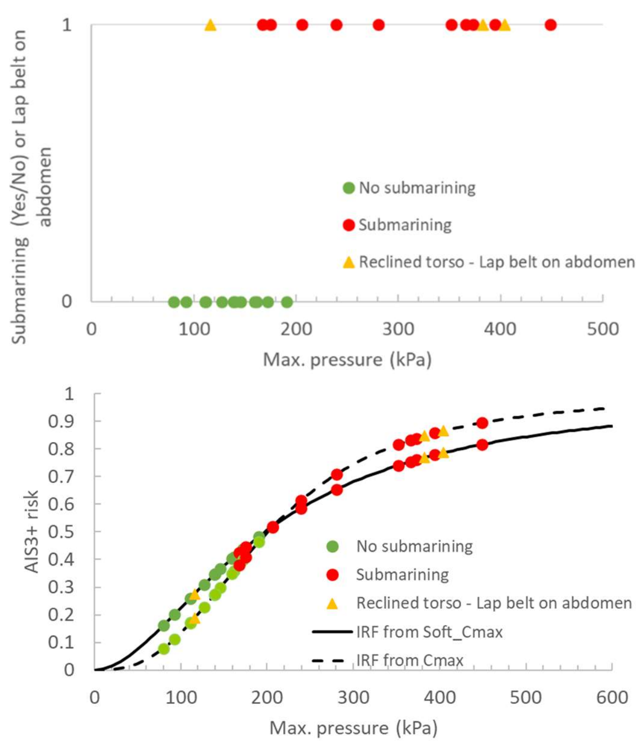


Figure 27. Submarining occurrence and risk of AIS3+ abdominal injury risk versus APTS pressure.

Table 10. Post-test pictures and estimated abdominal injury risk

<table>
<tr>
<td>
***50 km/h, slouched sitting posture,
Submarining
AIS3+ abdominal injury risk= 76 to 78%***</td>
<td colspan="2">
***50 km/h, separated belt, rear seat,
Submarining
AIS3+ abdominal injury risk= 45 to 52%***[1]</td>
</tr>
<tr>
<td>
***40 km/h, reclined torso, knee bolster
Lap belt on abdomen
AIS3+ abdominal injury risk=28%***</td>
<td colspan="2">
***40 km/h, reclined torso
Lap belt on abdomen
AIS3+ abdominal injury risk= 77 to 79%***[1]</td>
</tr>
<tr>
<td>
***40 km/h, standard position
No submarining
AIS3+ abdominal injury risk=16 to 44%***[1]</td>
<td>
***50 km/h, standard position
No submarining
AIS3+ abdominal injury
risk=35 to 37%***</td>
<td>
***50 km/h, front seat,
standard position
No submarining***
**AIS3+ abdominal injury
risk=26%**[1]</td>
</tr>
</table>

[1] These tests were repeated with the standard THOR equipped with IR-TRACC.

As listed in Table 3, the standard THOR was also used in a few tests. The right IR-TRACC was damaged in the TMC sled test with the 49° torso angle sitting posture. This may be consistent with observations in [23] who noted that it was unknown if the IR-TRACCS "could tolerate submarining events at high speed". Results and injury risk predicted using NHTSA IRF [8] are shown in Figure 28. Very low risks (below approximatively 15%) were predicted whatever the sled conditions and the occurrence or not of submarining. Maximum deflection values were between 46 and 70 mm. These values are much lower than 98 mm which corresponds to a 50% risk and to the 88 mm Euro NCAP limit.

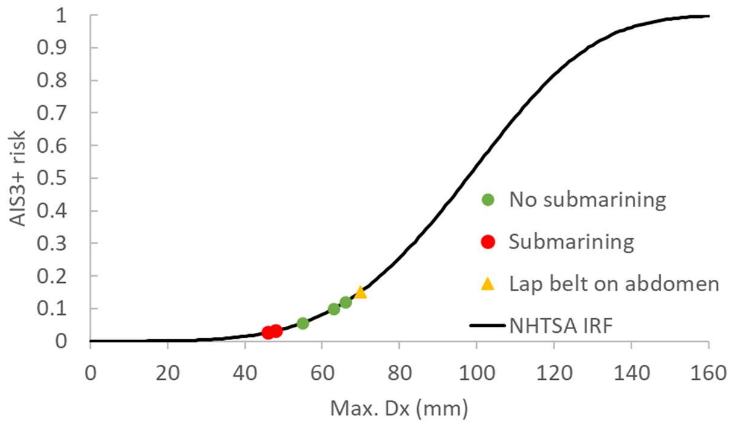


Figure 28. Risk of AIS3+ abdominal injury versus abdominal deflection (x-axis) for the standard THOR-50M: risk function and results from the sled tests.

DISCUSSION AND LIMITATIONS

The ABISUP abdomen geometry was designed to enlarge the existing THOR lower abdomen volume and prevent discontinuities between the lower abdomen and the pelvis or the lower thorax. This would help to prevent belt entrapment between the two body regions. The abdomen internal plate present in the standard dummy was also removed as it did not represent any anatomical structures and limited the compression.

The abdomen biofidelity was assessed under various seatbelt pull test conditions. In three different seatbelt pull conditions, the ABISUP abdomen demonstrated varying degrees of biofidelity in terms of both deflection and force. The peak deflection of the ABISUP abdomen tended to be lower than PMHS with the exception of the dual pretensioner case, but the peak force response consistency with PMHS corridors varied by test condition.
The abdomen durability including the APTS was very good and further improved by the reinforcement of the abdomen skin. The repeatability and the reproducibility of the abdomen was good, however some significant variations between the left and right APTS pressures were observed and could not be explained. Further investigation to understand if this may be caused by the foam, the APTS or the loading would be required. Based on the asymmetry observed in the final certification tests, investigating the foam and the loading setup could be of particular interest.

The sensitivity of the abdomen and its measurement were good as it could discriminate restraint systems with the highest APTS pressures measured when the lap belt was directly on the abdomen compared to when the lap belt was partly or in contact with the pelvis or the lower thoracic ribs.

The IRF could only be defined from the porcine tests of Kent as attempts to create IRF from PMHS tests gave only poor quality IRFs due to inconsistent results between the studies in terms of observed injuries versus abdominal compression. The defined IRFs did not account for the ABISUP abdomen biofidelity since it predicts abdominal injury risk versus the APTS pressure calculated from the compression measured on the porcine specimen and not the compression of the ABISUP abdomen itself. In other words, it was assumed that the same abdominal compression would have been obtained with the ABISUP abdomen than for the porcine specimen under the same loading.

The risks predicted in the case of submarining and non-submarining were overlapping. Some degree of overlap could be possible as the presence of the belt on the abdomen did not necessarily mean that the loading was high. In particular, submarining could occur late in the deceleration with limited belt forces. In many other cases, the predicted risk was high and it could reach up to close to 90% for submarining or lap belt on abdomen conditions. Conversely, it was found that the risk without submarining could be too high (up to 48%, Figure 27) compared to the low occurrence of abdominal injuries for properly restrained occupants. However, one limitation of this study is that the predicted risks were not assessed against injury statistics accounting for actual restraint conditions.

While the exact reason for the mismatch between expected and predicted risk in case of proper restraint is unknown, different reasons could be investigated. The IRFs were defined from seatbelt pull tests in which the injuries were created by the compression of the mid abdomen by the belt with side rollers guiding the belt. In sled tests, the force interaction on the abdomen was more complex as (1) there was no side rollers preventing the lateral compression, (2) there were inertial effects and force of the upper torso on the abdomen, (3) the loading was not necessarily applied to the mid abdomen.

For the first point, the pressure compression curve and the original experimental data from Kent were generated using antero-posterior compression while some of the lateral compression, which could contribute to the pressure, was prevented by the use of rollers. As a result, the ratio between compression and pressure or the relationship between compression and injury could differ from more realistic loading cases. This could be investigated using a simulation-based approach.

For the second point, it was also previously reported that the APTS maximum pressure was coincident with the maximum chest excursion in sled tests [26], however the pressure increase due to the dummy torso flexion was not considered in the IRFs. From [26], it was estimated that the pressure increase due to the torso forward movement was between 28 and 92 kPa depending on the magnitude of torso flexion. Due to the lack of biomechanical data, it is unknown if torso flexion should contribute to the injury risk as some coupling between the thorax and the abdomen is present through the diaphragm. If needed, the APTS location could be adjusted (e.g. moved rearward) to reduce the pressure sensitivity.

For the third point, the sensitivity of the APTS to loading location was found to remain relatively stable on the abdomen including in some cases for which the path of the belt involved some of the pelvis or was below the ASIS. Some of these cases may be considered as acceptable restraints but significant abdomen compression still occurred in the dummy. It must be remembered that in the current THOR-50M design, a large portion of the soft abdomen was located anteriorly to the ASIS (approximately 86 mm at the level of ASIS measured in the mid sagittal plane on the FE model, Figure 29 bottom). As a result, to prevent the APTS from being too close to the spine, they were positioned partially anterior to the ASIS in the current design. Also, approximately a third of the APTS is caudal of the ASIS. To reflect the fact that loading was not expected to be injurious below the ASIS, a reduced pressure sensitivity in that region may be achieved using a different design (e.g. shorter APTS, APTS reinforced at the bottom or with a longer cap) or a different location (e.g. more lateral, cranial and posterior, perhaps with a smaller diameter and length). Preliminary investigations were conducted by simulation.

Some of the abdomen geometric characteristics (largely in front of the ASIS) may also be relevant for some of the responses observed with the IR-TRACC in the standard dummy: the ASIS are only approximately 30 mm in front of the flared overload cones protecting the IR-TRACCs, and the distance between the flared overload cones and the IR-TRACC attachments on the surface of the abdomen is only approximately 105 mm (Figure 29 bottom, measurements made on the FE model). This suggests that (1) in some cases, the first 75 mm of deflection may result from a loading that is in front of the ASIS, and (2) the maximum deflection may be limited to a value around 105 mm (contact with the flared overload cones). Based on the NHTSA IRF [8], a 50% AIS3+ risk would correspond to 98 mm, while 75 mm and 105 mm would correspond to 20% and 61% risks, respectively. In preliminary FE simulations, deflections over 95 mm (46% risk) could not be achieved in part due to the interaction between the belt and the backing plate (illustrated in Figure 30). Higher deflections (up to 98.5mm, or 51% risk) were observed in 32 kg / 6.1 m/s impactor tests [27]. Similar values (99.3 mm, or 53% risk) were reached in this study in Foster dual pretensioner tests. This would suggest that risks of at least up to 53% could be obtained in tests, but that risks below 20 % could result from loading anterior to the ASIS. However, despite this range, risks below 15% were obtained independently of the restraint conditions in the sleds with IR-TRACC performed as part of ABISUP (Figure 28), and the submarining condition was associated with the lowest risk, followed by the non-submarining and belt on abdomen. It is unclear if the high lap belt angles that could occur during the submarining could be recorded by the IR-TRACC.

Overall, despite the limitations listed about the ABISUP abdomen and its associated IRFs, the ABISUP abdomen could better discriminate the restraint systems and predict more realistic abdominal injury risks than the standard THOR.

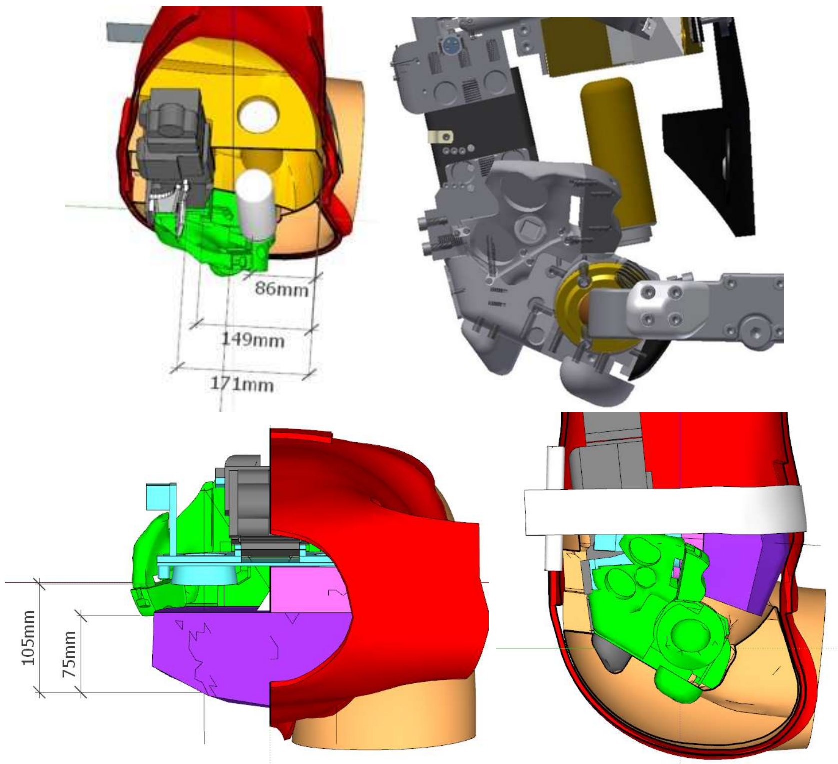


Figure 29. ABISUP abdomen APTS location versus THOR-50M compressible abdominal depth (top) and THOR-50M ASIS (bottom).

Figure 30. Illustration of the possible interaction between the belt (green) and the abdomen internal plate (blue) in a simulation of the standard abdomen with the FE model. The IR-TRACCs are materialized by the line at the center of the backing plate flared overload cones and the abdomen and jacket are not shown. For a belt pull, the belt motion and IR-TRACC compression can be limited by the internal plate (laterally) and the flared overload cones (anteriorly).

CONCLUSIONS

A new abdomen prototype was developed by the ABISUP consortium that could be integrated into the THOR-50M without modification of other dummy parts. The ABISUP abdomen integrated APTS instead of the two IR-TRACCs which could be easily damaged in sled tests and require more complex post-processing. Moreover, the APTS had the advantage of being sensitive to different loading directions. The ABISUP abdomen could discriminate well the different restraint systems used in sled tests and predicted AIS3+ injury risk between 42 to 82% in the case of submarining. In the future, design adjustments might be relevant to decrease the APTS sensitivity to belt loading at the ASIS level.

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Appendix 1: ABISUP abdomen maximum values in Kent's setup (with rollers)

Test ID	Speed (m/s)	Deflection (mm)	Compression (%)	Soft Compression (%)	Mean Pressure (kPa)
ABISUP_KT_001	3.9	42.3	15.9	26.9	30.1
ABISUP_KT_002	4.1	42.3	15.9	26.9	31.3
ABISUP_KT_003	4.7	67.9	25.5	43.3	61.3
ABISUP_KT_004	4.9	77.3	29.0	49.2	80.1
ABISUP_KT_005	5.2	80.1	30.1	51.0	80.8
ABISUP_KT_006	5.2	80.8	30.4	51.5	80.6
ABISUP_KT_007	2.2	70.0	26.3	44.6	51.4
ABISUP_KT_008	2.9	76.1	28.6	48.5	66.9
ABISUP_KT_009	2.6	92.2	34.7	58.7	114.4
ABISUP_KT_010	2.5	93.6	35.2	59.6	114.1
ABISUP_KT_011	2.6	85.7	32.2	54.6	90.7
ABISUP_KT_012	2.5	80.5	30.3	51.3	74.1
ABISUP_KT_013	2.6	80.4	30.2	51.2	73.5
ABISUP_KT_014	7.5	87.6	32.9	55.8	108.2
ABISUP_KT_015	7.4	81.8	30.8	52.1	94.1
ABISUP_KT_016	6.6	78.9	29.7	50.3	82.2
ABISUP_KT_017	5.1	90.4	34.0	57.6	115.4
ABISUP_KT_018	5.0	91.7	34.5	58.4	116.1
ABISUP_KT_019	6.7	96.2	36.2	61.3	138.7
ABISUP_KT_020	6.5	98.4	37.0	62.6	150.4
ABISUP_KT_021	6.4	101.0	38.0	64.3	162.4
ABISUP_KT_022	6.7	101.4	38.1	64.6	162.6
ABISUP_KT_023	6.8	101.6	38.2	64.7	163.0
ABISUP_KT_024	5.0	94.5	35.5	60.2	117.2
ABISUP_KT_025	5.0	100.4	37.7	63.9	143.7
ABISUP_KT_026	5.0	99.2	37.3	63.2	143.5
ABISUP_KT_027	5.1	101.1	38.0	64.4	154.4
ABISUP_KT_028	5.2	101.3	38.1	64.5	151.7
ABISUP_KT_029	5.0	101.1	38.0	64.4	151.9
ABISUP_KT_030	5.1	101.0	38.0	64.3	150.5
ABISUP_KT_031	5.0	102.6	38.6	65.3	156.2
ABISUP_KT_032	5.0	102.3	38.5	65.2	157.4
ABISUP_KT_033	2.6	104.2	39.2	66.4	173.5
ABISUP_KT_034	2.5	103.4	38.9	65.9	164.0
ABISUP_KT_035	1.4	105.3	39.6	67.1	165.1
ABISUP_KT_036	7.9	91.4	34.4	58.2	115.4
ABISUP_KT_037	8.0	96.6	36.3	61.5	141.1
ABISUP_KT_038	7.9	102.1	38.4	65.0	176.4
ABISUP_KT_039	5.1	106.5	40.0	67.8	203.5
ABISUP_KT_040	5.0	109.1	41.0	69.5	224.7
ABISUP_KT_041	5.0	112.4	42.2	71.6	240.1
ABISUP_KT_042	5.1	115.8	43.5	73.8	253.1
ABISUP_KT_043	5.0	118.6	44.6	75.5	257.4

Appendix 2: Kent's data summary and transformation

Specimen	Location	AIS soft tissues	Defl (mm)	Abdo depth (mm) [1]	Compr (%)	Estimated soft depth (mm)[2]	Soft Compr (%)[3]
PAC1.1	lower	2	67	149	45.0	82	82.0
PAC1.2	lower	4	72	135	53.3	74	97.2
PAC1.3	lower	3	58	122	47.5	67	86.7
PAC1.4	lower	3	68	140	48.6	77	88.5
PAC1.5	upper	4	74	148	50.0	96	77.2
PAC1.6	upper	4	96	149	64.4	96	99.5
PAC1.7	lower	3	53	132	40.2	72	73.2
PAC1.8	upper	4	56	149	37.6	96	58.1
PAC1.9	lower	0	48	129	37.2	71	67.8
PAC1.10	lower	2	89	146	61.0	80	111.1
PAC1.11	lower	0	47	137	34.3	75	62.5
PAC1.12	lower	2	41	113	36.3	62	66.1
PAC1.13	upper	2	47	135	34.8	87	53.8
PAC1.15	lower	2	54	132	40.9	72	74.6
PAC1.16	lower	3	59	127	46.5	70	84.7
PAC1.17	lower	0	41	174	23.6	95	43.0
PAC1.18	upper	0	37	146	25.3	95	39.1
PAC1.20	lower	3	61	134	45.5	74	83.0
PAC1.21	lower	3	61	141	43.3	77	78.9
PAC1.22	lower	3	52	127	40.9	70	74.6
PAC1.23	lower	2	59	145	40.7	80	74.2
PAC1.24	upper	2	75	190	39.5	123	61.0
PAC1.25	lower	4	64	129	49.6	71	90.4
PAC1.26	upper	3	61	137	44.5	89	68.8
PAC1.27	lower	1	41	135	30.4	74	55.4
PAC1.28	upper	2	65	155	41.9	100	64.8
PAC1.29	lower	3	73	140	52.1	77	95.0
PAC1.30	upper	0	37	158	23.4	102	36.2
PAC1.31	upper	3	58	140	41.4	91	64.0
PAC1.32	lower	0	56	152	36.8	83	67.2
PAC1.33	upper	3	61	154	39.6	100	61.2
PAC1.34	upper	3	68	143	47.6	93	73.4
PAC1.35	lower	3	60	133	45.1	73	82.2
PAC1.36	upper	0	46	151	30.5	98	47.1
PAC1.37	lower	0	45	142	31.7	78	57.8
PAC1.38	upper	3	64	135	47.4	87	73.2
PAC1.39	upper	3	71	143	49.7	93	76.7
PAC1.40	lower	3	56	108	51.9	59	94.5
PAC1.41	lower	3	60	127	47.2	70	86.1
PAC1.42	lower	3	65	131	49.6	72	90.4
PAC1.43	lower	2	79	154	51.3	84	93.5
PAC1.44	lower	3	92	152	60.5	83	110.3
PAC1.45	upper	4	103	151	68.2	98	105.4
PAC1.46	upper	3	89	138	64.5	89	99.6
PAC1.47	lower	3	70	124	56.5	68	102.9

[1] Calculated by dividing the deflection by the abdominal depth.

[2] Estimation of the soft abdomen depth in front of the spine. The ratio (soft depth)/(abdomen depth) was assumed to be the same as in supine CT-scans of two porcine specimens of similar size as in Kent's study. The scans were collected for an unrelated study and used retrospectively at Univ. Eiffel. The mean ratio was 79/144 and 101/156 at the lower and upper locations, respectively.

[2] Calculated by dividing the deflection by the estimated soft depth.

Appendix 3: Sled test results

Reference	Test conditions	Submarining No/Yes @time (ms)	Left APTS (kPa)	Right APTS (kPa)	Left ASIS Fx (kN)	Right ASIS Fx (kN)	Left ASIS My Min/Max (Nm)	Right ASIS My Min/Max (Nm)	Left lower thoracic IR-TRACC (mm)	Right lower thoracic IR-TRACC (mm)
Forvia sled tests (Uriot et al. [21])	50 km/h pulse, Vehicle seat Standard sitting posture 3-point belt	No	129.4	146.1	6.1	4.8	-73.2/1.7	-64.3/0.4	8.6	39.3
		No	111.3	138.9	4.6	4.7	-54.3/2.3	-70.3/0.1	13	43.5
	50 km/h pulse, Vehicle seat Slouched sitting posture 3-point belt	Yes @57 ms	345.2	394.4	6.2	5.5	-5.8/42.3	-4.2/22.8	19.1	42.5
		Yes @56 ms	339.7	373.2	6.4	5.4	-1.4/36.7	-5.2/24	20.4	35.4
Forvia sled tests (Uriot et al. [22])	50 km/h pulse, Semi-rigid seat Front seat configuration Separated shoulder and lap belt	No	103.7	111.3	3	2.7	-33.7/0.1	-32/0.4	16.5	52.1
		No	98.1	111.0	3.2	2.8	-33.1/0.4	-29.6/0.5	18.4	50.5
	50 km/h pulse, Semi-rigid seat Rear seat configuration Separated shoulder and lap belt	Yes @72 ms	126.0	175.2	4.2	3.4	-12.2/15.6	-10.3/21.6	21.8	48.8
		Yes @75 ms	105.6	206.0	4	3.6	-17.8/15	-4/16.4	22.6	43.1
Virginia Tech, NHTSA sled tests	36 km/h pulse Rear seat, 3-point belt	No	117.7	190.6	2.3	2.2	-1.9/16.7	-2.4/12.9	18.2	33.7
		Yes @74 ms	239.0	189.4	2.8	3.5	-0.9/24.6	-0.8/38.8	28.7	33.9
		No	80.4	92.5	2.8	2.6	-1.8/10	-3.4/28.8	18.8	28.4
		Yes @74.9 ms	89.8	280.3	3.3	2.5	-9.3/12.6	-1.1/27.4	29.0	37.6
		Yes @76.4 ms	99.8	167.2	3.1	3.3	-1.0/16.7	-2.2/28.6	30.3	29.5
	56 km/h pulse Rear seat, 3-point belt	No	113.8	161.5	2.5	2.7	-1.8/12.4	-3.7/19.7	18.3	32.9
		Yes @61.1 ms	351.9	294.1	4.3	3.95	-1.3/43.1	-2.1/46.5	27.6	37.5
		No	127.1	126.0	3.9	4.2	-3.9/27.9	-1.1/27.7	19.3	54.5
		Yes @65.8 ms	366.1	326.1	4.5	2.2	-1.3/52.7	-1.7/26.0	38.3	46.3
		Yes @73.8 ms	427.6	448.7	4.6	3.5	-0.9/56.5	-1.6/30.6	31.7	38.6
TMC sled tests	40 km/h FWRB pulse 3-point belt Standard sitting posture	No	149.2	159.2	4.7	3.8	-3.2/10.9	-10.1/4.03	14.2	24.6
		No	149.3	171.9	4.6	3.7	-6.2/10.4	-13.9/2.9	15.1	27.6
		No	129.8	139.8	4.0	3.4	-3.3/31.9	-3.5/17.4	14.8	23.3
		No	79.9	76.2	0.3	0.49	-2.6/1.5	-4.3/2.1	10.3	22.7
	40 km/h FWRB pulse 3-point belt 49° torso angle sitting posture	Lap belt on abdomen	382.6	339.2	1.1	0.46	-19.4/0.78	-5.6/0.82	15.8	29.5
			404.5	357.9	1.5	0.76	-21.3/1.6	-8.5/1.1	14.4	33.1
			116.3	81.8	0.5	1.0	-3.6/4.1	-6.82.03	17.2	17.1