CONTRIBUTION TO THE IMPROVEMENT OF CRASH TEST DUMMIES IN ORDER TO DECREASE ABDOMINAL INJURIES IN ROAD ACCIDENTS

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ABSTRACT

This paper describes the first steps carried out in a joint effort of Ifsttar and Toyota to contribute to the development of a new abdomen for THOR dummy.
Firstly, a review of accident data showed that abdominal injuries observed in frontal crashes were mainly caused by the steering wheel and the seat belt. However, abdomen injury rate was higher for side impacts, showing the importance of being able to predict such injuries for different impact angles. The steering wheel was mainly associated with injuries in the upper abdomen (liver and spleen injuries) whereas the seat belt was mainly associated with injuries to the lower abdomen (intestines). The former ones were well correlated with rib fractures and it was concluded that thoracic injury prediction could also give an indication of upper abdomen injury risk.
Secondly, existing abdomen designs were studied to rate technical solutions and orient future design. Notably, several technical solutions including external or internal pressure, force and deflection measurements were considered for the evaluation of abdominal injuries in the last past years.
Finally, all the conclusions were gathered in a design brief.
Before modifying the THOR abdomen, the biofidelity of different existing THOR abdomens was evaluated through impactor and static seat belt tests. None of these abdomens were able to fully meet the biofidelity corridors. These results represent the starting point for future modifications of the THOR abdomen response.

INTRODUCTION

The abdomen accounts for a smaller proportion of all vehicle crash-related injuries than head, thorax and extremities. However, the proportion of abdomen injuries increases significantly when considering serious to severe injuries. Elhagediab et al. (1998) showed that abdominal injuries represent 8% of all injuries of AIS≥3, 16.5% of all injuries AIS≥4, and 20.5% of all injuries of AIS≥5. The risk of abdominal injuries varies also with seating position and was demonstrated to be higher for rear occupants compared to front ones. Martin et al. (2010) found in frontal collisions a relative risk of AIS2+ abdominal injuries of 1.90 and 1.53 for rear occupants compared to drivers and front passengers respectively.
Therefore, to help study and improve abdominal protection, a joint project was set up by Ifsttar and Toyota to work on the development of a modified abdomen for the THOR-NT dummy. The first part of the project aimed at defining the ideal requirements for the abdomen by considering real world data and most recent knowledge on abdomen injury criteria. Biofidelity of existing dummy abdomens was also evaluated to identify required future improvements.

ACCIDENT DATA

Several analyses of abdominal injuries were performed from accident field data. The ones referred in this paper are listed in the Table 1.

Table 1.
Accident data study on abdominal injuries

Reference	Dataset	Selection criteria
Elhagediab et al. (1998)	NASS CDS 1988-1994	Frontal impacts Front occupants
Lamielle et al. (2006)	LAB Since 1970	Frontal impacts All occupants
Klinich et al. (2008)	NASS CDS CIREN 1998-2004	Frontal & Side impacts Front occupants
Martin et al. (2010)	Rhône Road Trauma Registry 1996-2006	Frontal impacts All occupants
Klinich et al. (2010)	NASS CDS CIREN 1998-2008	Frontal & Side impacts Front occupants

Influence of seat position

Martin et al. (2010) highlighted the specificities of rear occupants regarding abdomen injuries. Using Rhône road trauma registry, which covers all road casualties which occurred in the ‘‘Département du Rhône (France)’’ (1.6M inhabitants), the study showed that among car belted occupants sustaining at least one serious injury (N=1219), 16% of the 74 rear passengers had abdomen injuries, which is more frequent than for drivers (7%) and for front passengers (10%) (Figure 1).

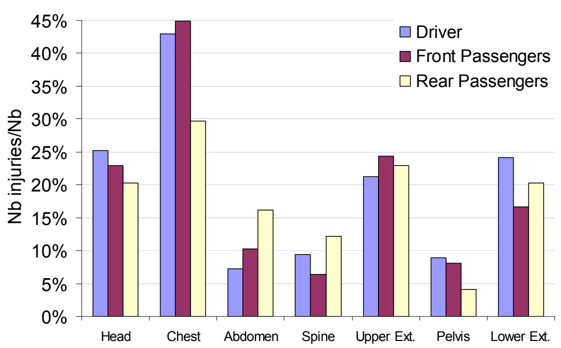

Figure 1. Car occupants with AIS 3+ injury (N=1219)(Martin et al., 2010).

Influence of impact direction and severity

Frontal impacts generally account for the highest numbers of AIS≥2 (AIS2+) and AIS≥3 (AIS3+) abdominal injuries. From NASS-CDS analysis, Klinich et al. (2010) estimated yearly 9000 front-row occupants with AIS2+ abdominal injuries due to front collisions whereas around 6000 were due to side collisions. However, the proportion of occupants with AIS2+ abdominal injuries increases substantially for near side crashes with a change in velocity (delta-V) greater than 32km/h (up to 40%), while for front impacts, 27% of occupants sustain an AIS2+ abdominal injury for delta-V between 41 and 50km/h (Klinich et al., 2008, Figure 2).

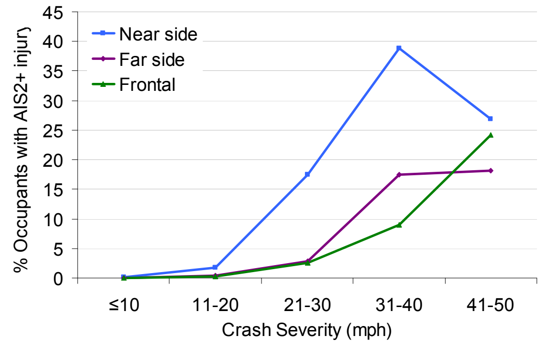

Figure 2. Risk of AIS2+ abdomen injury by delta-V and impact direction (Klinich et al., 2008).

Injury sources and types

Steering wheel was reported as the first injury source of AIS3+ abdominal injuries and represents 68% of this type of injuries. It was followed by seatbelt system (17%), interior parts (14%) and airbag (0.13%) (Elhagediab et al., 1998). More recently, Klinich et al. (2008, 2010) confirmed that airbag deployment in frontal impacts did not significantly affect the risk of abdominal injuries and was even slightly lower for belted occupants.

By looking at the injured abdominal organs with respect to car contact areas, steering wheel contacts result mainly in liver injuries (34% of all injured abdominal organs), followed by spleen injuries (14%), artery injuries (9%) and digestive organs injuries (6.5%). The seat belt was most often associated with injuries to the digestive system (almost 10%) (**Figure 3**).

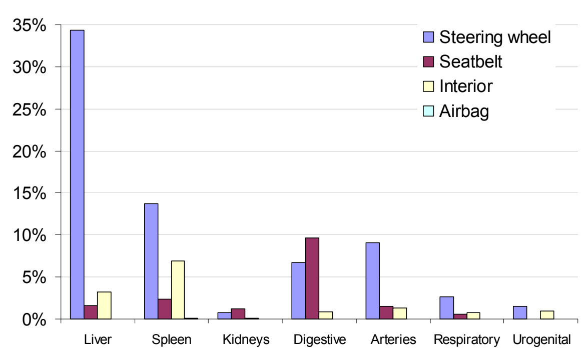

Figure 3. Contact object association with injured organs (N=38972) (Elhagediab et al., 1998).

Lamielle et al. (2006) divided abdominal organs into “solid” (e.g. liver, spleen, kidneys) and “hollow” (e.g. duodenum, jejunum, colon) categories and described different trends for each. It is important to note that solid organs are partly protected by the rib cage and are part of what is called “upper abdomen”. Hollow organs are mainly between the rib cage and the pelvis bones in the forward plane and are part of what is called “lower abdomen”.

Table 2.
Hollow and solid organ injury frequency for belted and unbelted front occupants as a function of dashboard intrusion (Lamielle et al., 2006).

Belted	≤24cm	25-45cm	>45cm
Hollow	138 (68%)	17 (34%)	6 (23%)
Solid	66 (32%)	33 (66%)	20 (77%)
Unbelted	≤24cm	25-45cm	>45cm
Hollow	17 (22%)	9 (25%)	8 (22%)
Solid	61 (78%)	27 (75%)	29 (78%)

Lamielle et al. (2006) noted that unbelted front occupants sustained solid organ injuries more often whereas belted ones suffer more from hollow organ injuries. Lamielle et al. (2006) also reported that in the case of lower intrusion (≤25cm), belted occupants suffered more from hollow organ injuries whereas unbelted ones suffer more from solid organ injuries. At higher intrusion, belted and unbelted occupants both sustain more solid organ injuries than hollow organ injuries (Table 2.).

Abdominal injuries and rib fractures

A significant link between the occurrence of abdominal injuries and rib fractures was observed by Klinich et al. (2008, 2010). The odds of sustaining a liver, spleen or kidney injury are respectively 9, 13 and 8 times higher with AIS 2+ rib fractures than without.
However, risk of sustaining abdominal organ injuries does not increase with occupant age whereas risk of rib fracture does. Klinich et al. (2010) hypothesised that “fractured ribs are not directly causing these types of abdominal injury… Rather, loading conditions likely to result in rib fracture are also likely to result in injury to these abdominal organs.” This analysis suggests that in crashes, abdominal organs are often loaded together with the rib cage and it is therefore unlikely to find abdominal injuries without rib fractures. However, rib fractures without abdominal injuries might be more frequent, especially for elderly, who are more subjected to sustain rib fractures even in low severity crashes.

Conclusions from the accident studies

Frontal impact accounts for the highest number of abdominal injuries due to the fact that frontal crashes are the most frequent type of collision (Klinich et al., 2010).
Considering rear occupants, their risk to sustain an abdominal injury is higher than for front occupants. It is therefore important to assess such risk with a valid tool.
Accident field data revealed main issues regarding abdominal injuries and should be considered in ATD design:

- Even if a higher number of abdominal injuries are seen for frontal crashes, the risk of having abdominal injuries is higher in side impacts,
- Steering wheel contact for drivers and seat belt for front and rear passengers are coded as the main sources of abdominal injuries in frontal crashes. Airbag deployment was not found to increase injury risk,
- Solid organ injury occurrence correlates with steering wheel contact and to a lesser extent with seat belt and interior part contact, whereas hollow organ injuries are mostly linked with seat belt contact,
- Solid organ injuries are predominant, compared to hollow organ ones, for high intrusion whereas hollow organ ones are predominant, compared to solid organ ones, at low intrusion for belted occupants,
- Injury risk of organs such as liver, spleen and kidneys correlates with the risk of AIS2+ rib fractures. In a first approach, it seems suitable to assess upper abdomen injury risk together with thorax. In THOR-NT, the two multi-point 3D displacement measurement systems (CRUX) located on right and left sides of lower ribs seem suitable to assess such risk.

From these conclusions, it was decided to focus in our study on THOR-NT “lower” abdomen response and instrumentation.

EXISTING DUMMY ABDOMEN DESIGNS

Current frontal impact regulation does not consider the risk of abdominal injuries for car occupants, either children or adults. Side impact regulation includes an injury criterion for the Eurosid-2 dummy based on the maximum force applied to the abdomen block.
More recently, the need for abdomen injury estimation for children seated in a child restraint system (CRS) has been highlighted and several projects have been running for the ten last years on those topics (CREST, CHILD, CASPER in Europe, NASVA in Japan (Ono et al., 2005)). In European projects CREST, CHILD and CASPER, abdominal

sensors have been developed. A first one, designed by Ifsttar for Q-dummy series, is called Abdominal Pressure Twin Sensors (APTS) and consists of two bladders embedded in the abdomen foam. The APTS are filled with a gel-like material and equipped at one end with a pressure sensor (Johannsen et al., 2005) (Figure 4). The pressure measured by the APTS is expected to correlate well with the lap belt tension. The main advantages of these sensors were that they only require two channels and should be able to measure loads coming from different directions.

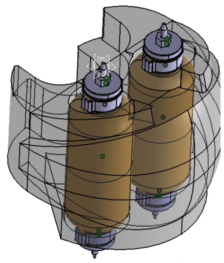

Figure 4. CAE model of Q3 abdomen equipped with Ifsttar-LBMC APTSs.

A second one was developed by Techncal University of Berlin (Johannsen et al., 2005) and used Tekscan Flexiforce® sensors in an array of 20 sensors as depicted in Figure 5. The force map gave an overview of the load distribution but the total surface force was used as injury predictor as localised force could not be linked directly with Post Mortem Human Subjects (PMHS) measurements. However, the robustness of the sensor was judged to be not sufficient by Johannsen et al. (2007).

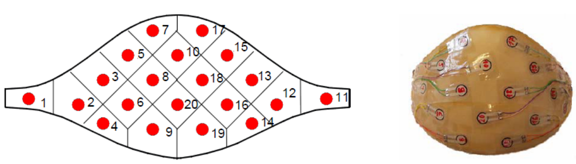

Figure 5. TUB child abdominal sensor (Johannsen et al., 2005).

A similar sensor concept was developed by the National Agency for Automotive Safety and Victims' Aid (NASVA) to be used in the Japanese CRS assessment program (Figure 6). The sensor used is an electric pressure sensor (Tekscan) which was applied to the dummy abdomen surface (Ono et al., 2005). One of the findings of the study is that measurement of abdominal compression discriminates various types of CRS.

Figure 6. Tekscan pressure map installed on the HIII 3 years old (Ono et al., 2005).

As for adult dummies, UMTRI and FTSS developed a special abdomen to simulate a 30-week pregnant woman dummy (Figure 7) and to assess possible damage to the mother's abdomen in crashes (Rupp et al., 2001). The MAMA-2B abdomen was instrumented with an anterior pressure sensor. A power-law relationship was defined to estimate the risk of adverse fetal outcome versus the anterior pressure.

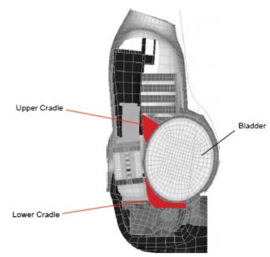

Figure 7. Side view of FEM of HIII pregnant dummy. The abdomen is represented by a urethane bladder attached by an upper and lower cradle (Rupp et al., 2001).

For the adult car occupants involved in a frontal collision, the submarining effect was identified thirty years ago (Leung et al., 1982) as the main cause of abdominal injuries. Its detection using load sensors placed on the pelvis iliac crests and the relationship between iliac crest loads and abdomen injuries were first looked at. The main drawbacks of this method were the loss of the load measurement once the lap belt slipped above the transducers and the inability to evaluate injury risk to the abdomen caused by sources other than the lap belt (shoulder belt, armrest, steering wheel…).

Similarly, JNCAP has introduced since 2009 on Hybrid III 5th percentile an "ON-OFF" rating based on the location of the lap belt during the crash: on the pelvis bones or not (Ikari et al., 2009).

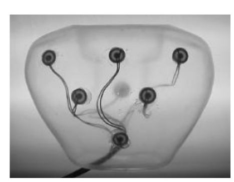

Figure 8. Front view of liquid silicone rubber abdomen insert (Rouhana et al., 2001).

New abdomen design was considered for the Hybrid III 50th percentile, called Re-usable Rate Sensitive Abdomen (Rouhana et al., 2001). It consists of a bladder made from liquid silicone rubber filled with silicone gel (Figure 8) allowing the record of 3D deflection at 6 different locations on the abdomen surface through six anodes and a cathode. Recent improvements have been undertaken regarding the instrumentation (Elhagediab et al, 2010).

Finally, its exists two versions of the THOR dummy abdomen and its instrumentation, for NT and FT versions; they are presented later in this paper. In addition, a prototype has been developed by GESAC and Toyota Motor Corporation, also presented in this paper.
Other developments using THOR-NT abdomen were found for railway applications (Parent et al., 2005).

DESIGN RECOMMENDATIONS

From previous literature review, main requirements for a new THOR abdomen were listed as below:

- Match UMTRI 50th percentile anthropometry
- Reproducibility, repeatability
- Remain in position
- No major modification to the dummy design
- No effect on dummy posture, global kinematics

Abdomen response:

- Biofidelity according to impactor and seat belt tests (Cavanaugh, Hardy, Foster's PMHS corridors) as these two kinds of loading were predominant from the accident field data

Abdomen instrumentation:

- Continuous measurement
- Omni-directional
- Linear sensitivity
- Detect all loads applied to the abdomen
- Discriminate submarining
- Low sensitivity to deceleration and torso flexion
- No time lagging
- Simple calibration and use
- Reliability and robustness
- Abdomen biofidelity stable along time (e.g. for fluid filled concepts)

This partly meets the recommendations from EEVC WG12 in 2006, which notably included as well the fact that if 3D abdominal measure was desirable, the current instrumentation was not adapted due to frequent damage reported after tests. EEVC also recommended to unify upper and lower abdomens. This modification was as well foreseen for the long-term by SAE THOR Committee.

EVALUATION OF BIOFIDELITY OF DIFFERENT THOR ABDOMENS

Impactor and static seat belt tests were conducted on three different abdominal inserts compatible with current THOR-NT dummy:

- the standard instrumented THOR-NT abdomen
- a uninstrumented version of the THOR-FT abdomen inserted in THOR-NT's abdominal Cordura bag
- a uninstrumented prototype developed by GESAC

Material and Method

<u>Impactor tests</u>

Figure 9. Rigid-bar impact test set-up

Impactor tests reproduced those initially developed by Cavanaugh et al. (1986) where 12 PMHS were impacted at various velocities (4.87 to 13.01m/s) with a rigid-bar weighting 32 or 64kg. This kind of testing was also reproduced by Hardy et al. (2001) on 11 PMHS (free or fixed back) and Rouhana et al. (2001) to evaluate a prototype abdominal insert for Hybrid III dummy. This test procedure is now used as the certification test for the lower abdomen of THOR dummy. Yaguchi et al. (2007) evaluated THOR abdomen biofidelity under this kind of loading. Moorhouse et al. (2007) evaluated this procedure for the certification of the THOR dummy.
In the test conducted at Ifsttar, a 32 kg guided impactor equipped with a rigid bar (300mm long, 25mm diameter) impacting face was used. The rigid bar contacted the dummy at the level of L3 (Figure 9). The spine if the free-back dummy was adjusted in a slouched position. The dummy was wearing its jacket with straight legs on a Teflon sheet and its hands upon the head. It was loosely retained to avoid any

fall following impact. Impactor was equipped a uniaxial 100g accelerometer and a light gate for direct measurement of velocity at impact. The pelvis of the THOR was equipped with 3 uniaxial accelerometers to measure its backward displacement during test. All sensors recorded data at 10kHz. Three high speed cameras (1000fps) recorded the test. Two impact velocities, 3.0±0.1m/s and 6.1±0.1m/s were tested. Targets were placed on the ATD lower spine or pelvis block (target 2 on Figure 9), the rigid-bar impactor (target 1 on Figure 9) and on dummy pelvis foam.

Seatbelt loading tests

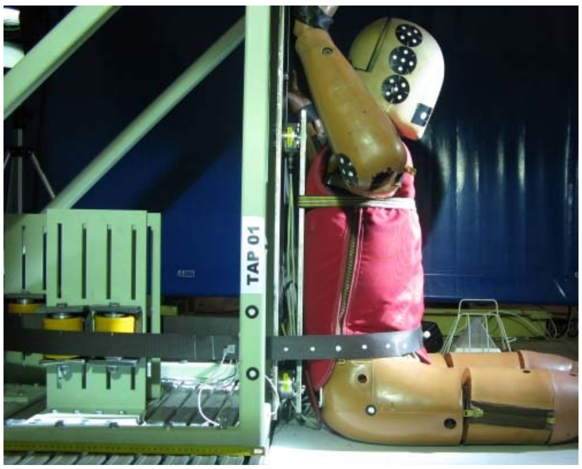

Figure 10. Side view of the pretensioner test set-up

Several studies in the last decade focused on abdominal seatbelt loading. In PMHS tests, the belt was wrapped around the abdomen and pulled backwards in a symmetrical way. Most of time, these loads tried to maximize seatbelt/abdomen interaction. Hardy et al (2001) used a ram to pull the belt placed on PMHS abdomens. A peak velocity of 3m/s and a sine curve shape were applied. 26 to 37% abdominal compression was recorded. Rouhana et al. (2001) used the same device to evaluate its silicone abdomen prototype for Hybrid III dummy. Trosseille et al. (2002) applied abdominal seatbelt loading on PMHS through one or two pretensioners. Velocity peaks of 8 to 12 m/s and compression between 25 to 32% were recorded. Steffan et al. (2002) loaded PMHS abdomen at 6m/s with a pretensioner system linked to a seatbelt cinching mechanism. Peak load between 2.9 and 7.1kN and pull-in distances from 104 to 200mm were observed. Foster et al. (2006a) performed PMHS abdomen seatbelt loadings through the help of single or dual systems of pretensioners. Velocity peaks of 4 to 13m/s and compression between 25 and 55% were recorded. Lamielle et al. (2008) used either a ram or pretensioners and obtained velocity peaks from 4 to 5m/s (compression from 28 to 40%) and 5 to 6 m/s (compression 27 to 31%) respectively.

Seatbelt loading tests conducted in this study reproduced conditions from Foster et al. (2006a). Same pretensioners as in Foster's study were used, ensuring the reproducibility of input for the tests and allowing later comparison of the results. For this test, a specific structure was manufactured and attached to a working plan. The THOR dummy wore only its jacket and was seated on a Teflon sheet with its back resting on the structure. Legs were straight and arms were attached above elbows. Straps maintained the dummy against the backseat (Figure 10). The seat belt was wrapped around the lower abdomen at mid-abdomen height, attached on itself and guided in the back of the dummy to the retractor/pretensioner by a series of pulleys. The seatbelt was equipped on each side with a 16kN force cell and a 500g accelerometer. The seatback of the dummy was equipped with 4 250daN load cells. A laser (900mm range, 100µm resolution) measured the backward displacement of the seatbelt and a light-gate returned a live (rough) estimation of the seatbelt retraction velocity. All sensors recorded at 20kHz. Three high-speed cameras (1000 and 2000fps) recorded the test.
Two kinds of pretensioner were used, corresponding to Foster's "B" and "C" systems. Targets were positioned on the ATD, every 50mm on seatbelt and on fixed reference points for the video motion analysis. An additional spherical target on the most prominent point of the umbilic was used for the measurement of the penetration.

THOR-NT abdomen

The THOR-NT lower abdomen is attached to the lumbar spine of the THOR dummy. It is composed of two foam layers enclosed in a Cordura nylon bag. Two DGSPs (Double Gimballed String Potentiometer) go through both foam layers from back of the insert to front cover of the bag. These devices record variation of angle in two dimensions as well as compression through two telescopic columns to derive deflection in 3D on the two points of DGSP attachments. Deflection of the abdomen is the mean of the two DGSPs records. Its total weight is 2.62kg.

Modified THOR-FT abdomen

The THOR-FT is an alternative version of THOR-NT. Based on former THOR-α, this dummy was developed in the frame of FID project. Its abdominal insert consists in a single foam block with a vinyl skin layer equipped with 2 IR-TRACCs (InfraRed

Telescoping Rod for Assessment of Chest Compression) measuring deflection and angle variation through an optical measurement. Similarly to DGSP, 3D motion of the IR-TRACC attachment points is derived. A uninstrumented, modified version of the abdomen was manufactured on demand by FTSS for the needs of this study, without sensors nor associated holes.

A specific setup was designed to attach the modified abdomen in its usual position. The virgin foam block was inserted in THOR-NT's Cordura bag (Part #T1LAF100) and fixed to the lumbar spine by using THOR-NT's spinal mounting elements and a simplified version of Internal Mounting Welded Assembly (Part #T1LAW081) in the back of the Cordura bag. The total mass was 2.30kg. The effect of the bag fabric layer in addition to the insert was considered as non-significant under dynamic loadings on the biomechanical response of the abdomen.

GESAC prototype abdomen

The GESAC abdominal insert is a 3.62kg prototype developed at the end of the 2000s by GESAC in partnership with Toyota Motor Corporation. It consists of a urethane core (shore hardness 35A) enclosed in a 20mm-thick skinned urethane shell in which three Cerobase™ weights are also moulded. GESAC abdomen is attached to the lumbar spine by using the same attach points as the THOR-NT insert. The abdomen is designed to include a pair of curvature sensors in its outer shell enabling the reconstruction of its deformation under impact and calculation of the abdominal compression. However, no instrumentation was available for these tests.

Post-Treatment

In rigid-bar loading tests, time "zero" corresponded to the first contact between impactor and abdomen. Penetration was obtained through video analysis by subtracting the backward movement of ATD's pelvis to impactor deflection. Force was obtained by the product of the deceleration of the impactor and the mass of the impactor - 32kg. All sensors data were filtered using CFC180. Data were then compared to biofidelity corridors or targets defined by Hardy et al. (2001) for each considered velocity, 3.0 and 6.1m/s.

For pretensioner tests, time "zero" corresponded to the firing of the retractor/pretensioner mechanism. Video analysis data were CFC1000 filtered and penetration was obtained through target tracking by

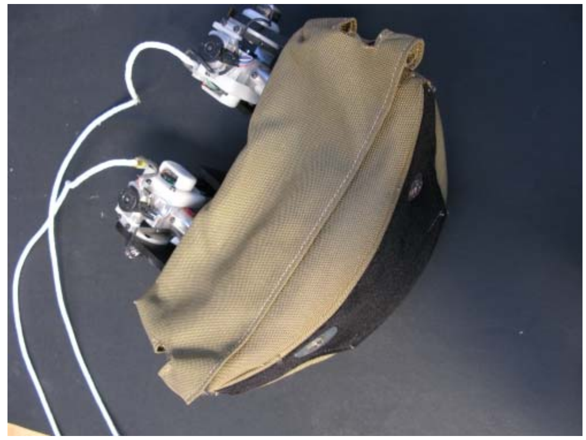

Figure 11. Top view of the THOR-NT lower abdomen insert prior to assembly on the dummy

Figure 12. Modified THOR-FT abdominal insert prior to assembly on the dummy

Figure 13. General view of the GESAC abdominal insert prior to assembly on the dummy

subtracting the backward movement of ATD's pelvis (even if limited) from the seatbelt displacement at the umbilic, followed by a CFC1000 filtering. All sensors data were filtered using CFC600. Data obtained with Foster's "B" system were compared to the biofidelity corridor developed by Foster for this particular configuration. Data obtained with Foster's "C" system were compared to PMHS scaled responses obtained by Foster. No scaling was performed in this study as Foster chose Eppinger's method (Eppinger, 1976) for scaling with a reference mass of 78.2kg, which is very similar to THOR-NT mass.

RESULTS

Rigid-bar impacts

Test matrix for impactor tests is presented in Table 3. Figure 14 presents the response of the three inserts at 3.0m/s overlaid with the biofidelity trend curve defined by Hardy et al. (2001). THOR-NT abdomen exhibits an exponential shape, close to biofidelity trend curve up to 40mm penetration. It then diverges until final penetration of 100mm for a 3kN force. THOR-FT follows a very similar loading path for a final force of 2.5kN but an equivalent penetration. GESAC abdomen presents a mostly linear slope of approximately 60kN/m (six times the slope defined in Hardy's study).

Figure 15 presents the response of the three inserts at 6.1m/s compared with the biofidelity corridor defined by Hardy et al. (2001). Corridors available in Rouhana et al. (2001) and Cavanaugh et al. (1986) are very similar. THOR-NT and THOR-FT inserts remain within corridor for approximately 80mm. A peak appears for THOR-FT around 80mm penetration, followed by a gap at 100mm. This phenomenon was observed on both tests performed at this velocity on this abdomen. Video analysis associates it with a contact between the rigid-bar impactor and the skin above pelvis iliac crests. The GESAC abdomen presented a much stiffer response, with an average slope of 100kN/m - approximately three times higher than the upper boundary of the considered biofidelity corridor.

The loading parts of THOR-NT and FT abdomen force-penetration curve are comparable. Response of THOR-FT abdomen could be improved by avoiding the contact between pelvis skin and the rigid bar (no peak at 80mm penetration), but the effect of removing the IR-TRACCs cannot be seen from our tests. The GESAC insert is stiffer than the upper limit of biofidelity corridors (Figure 14 and Figure 15).

Table 3.
Test matrix for rigid-bar impact tests on dummy abdomen

Test	THOR NT	GESAC	THOR FT	Velocity (m/s)
01	X			3.03
03	X			2.75
04	X			6.16
05	X			6.15
06	X			3.02
09		X		3.00
10		X		3.01
11		X		6.10
12		X		6.12
13		X		6.11
14		X		3.02
16			X	3.04
17			X	3.01
18			X	6.20
19			X	6.16

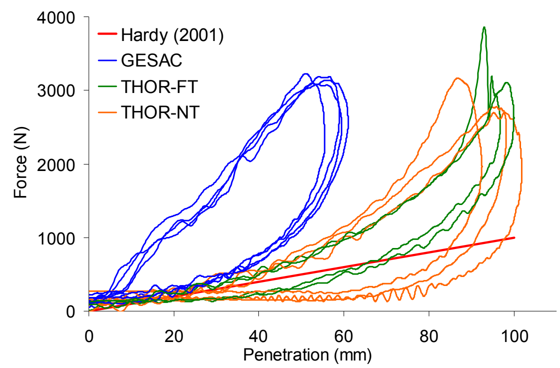

Figure 14. Force-penetration curves of the three inserts at 3.0m/s compared to Hardy et al. (2001)

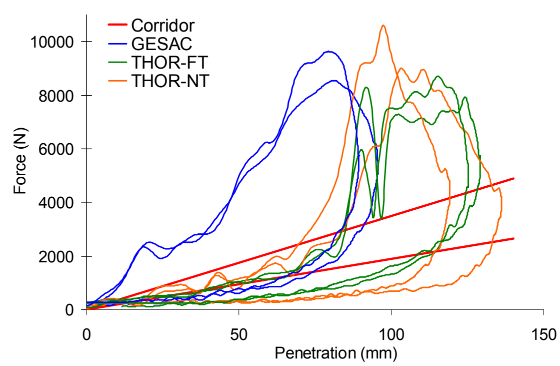

Figure 15. Force-penetration curves of the three inserts at 6.1m/s compared to biofidelity corridors by Hardy et al. (2001)

Seatbelt loading tests

Test matrix for seatbelt loading tests is presented in Table 4.

Figure 16 presents the results obtained with the three inserts using C-system ('lower velocity') pretensioner. Both PMHS curves, extracted from Foster's study, present a significant initial peak which is not visible in the tests performed on THOR. Both NT and FT inserts show a similar initial slope followed by a plateau below 1kN and a mean maximal penetration of 30mm. Tests on GESAC abdomen displayed a very different response, with a quasi-linear behaviour and a reduced penetration.

Figure 17 presents the results obtained with the three inserts using B-system ('higher velocity') pretensioner compared to associated biofidelity corridor defined in Foster's study. Both NT and FT abdomens display once again a similar response including an initial rise up to approximately 1kN followed by a linear and constant increase. However, the instrumented NT abdomen reached a slightly higher penetration than the uninstrumented FT insert with 110mm against 95mm. Response of both inserts mostly remains out of the corridor. GESAC abdomen presents an initial higher slope, and reaches a maximal penetration of 50mm and a maximal load of 5kN. If the initial expected peak is still missing, its response is mostly within corridor boundaries.

Table 4.
Test matrix for seatbelt loading tests on dummy abdomen

Nr	THOR NT	GESAC	THOR FT	Foster's system	Retraction Velocity (m/s)
02	X			B	12.3
03	X			B	14.5
04	X			C	5.0
05	X			C	5.0
06		X		C	4.75
07		X		C	4.0
08		X		B	8.0
09		X		B	7.2
10			X	C	5.7
11			X	C	5.1
12			X	B	8.7
13			X	B	9.0

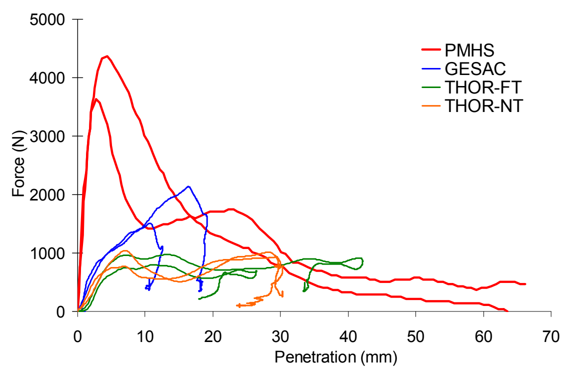

Figure 16. Force-penetration curves of the three inserts with C-system compared to PMHS curves (Foster, 2006b)

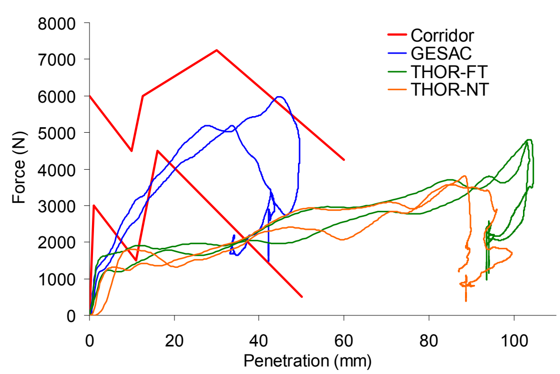

Figure 17. Force-penetration curves of the three inserts with B-system compared to PMHS corridor (Foster et al., 2006a)

DISCUSSION

The present study underscores the limited biofidelity of THOR abdominal response.
For rigid-bar impacts, the manikin response was the most biofidelic under the 6.1m/s loading, which was used as a design guideline for both THOR-NT and THOR-FT inserts. However, their observed limited biofidelity performances above 80mm compression, were also reported during the development of THOR-FT (FID, 2003) and by Yaguchi et al. (2007) for THOR-NT. The same author remarked as well that the abdomen of this ATD was softer than the standard Hybrid III abdominal insert (Yaguchi et al., 2008). Tested under the same conditions, Rouhana's HIII silicone abdomen, exhibited a more human-like response (Rouhana et al., 2001).

No ATD were evaluated to our knowledge under 3m/s, 32kg rigid-bar impacts. The limited amount of PMHS data for this configuration tested by Hardy et al. (2001) should lead to a careful analysis of associated ATD biofidelity results.

It is difficult to compare results of existing studies involving 6.1m/s rigid-bar impacts. This paper focuses on biofidelity using the penetration calculated from external measurement; and two of the three evaluated inserts were not instrumented. Onda et al. (2006) compared the response of internal measurement (DGSP or IR-TRACCs) of NT and FT inserts to the certification requirements. Moorhouse et al. (2007) demonstrated that external and internal measurements were significantly different and could cause a 20 to 30mm difference in terms of penetration. Hence, any comparison between studies focusing on certification procedure and biofidelity requirements should be done with caution as first ones consider dummy internal measurements and the second ones consider external measurements. Figure 20 presents certification and biofidelity corridors.
Similar responses of NT and FT concepts were observed in this study, confirming results by Onda et al. (2006). The same design targets of both inserts is a reasonable explanation for this observation.

Submitted to pretensioner seatbelt loading, both THOR-NT and THOR-FT behaviour differ greatly from biofidelity corridors. The tested GESAC prototype response was observed to be not biofidelic at low speed (Figure 18), but proved to have a more human-like response under high-velocity seatbelt loading, despite its absence of initial force peak (Figure 19). However, in absence of other published work on this abdomen, these conclusions are only based on the present study.
Responses under B-system and C-system seatbelt loading conditions for THOR-α and Rouhana's silicone abdomen (Foster, 2006b) were compared to the results of the present study in Figure 18 and Figure 19. THOR-NT and uninstrumented THOR-FT abdomens do not match biofidelity targets. They both present a good repeatability (Figure 17) but are particularly soft at low penetrations. They notably differ in response from THOR-α despite the fact that THOR-NT has a similar abdominal conception. No satisfactory explanation was found for this difference. In the meanwhile, THOR-α response is quite close to GESAC prototype under high-speed loadings and is very different at low speed.
Another aspect to be mentioned is the lack of human-like initial peak in the force response of abdomens submitted to seatbelt loading, with the exception of Rouhana's Hybrid III silicone concept. The post-treatment of the data in this study showed the high influence of force and penetration time alignment on the shape of the curve and its initial peak: a special care has to be given when creating such curves.

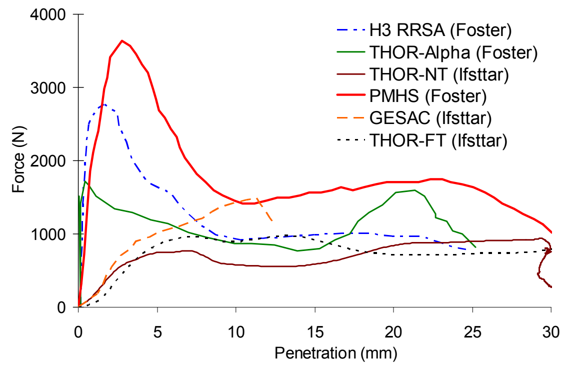

Figure 18. Compared response of various ATDs under Foster's C-system seatbelt loading (Foster, 2006b)

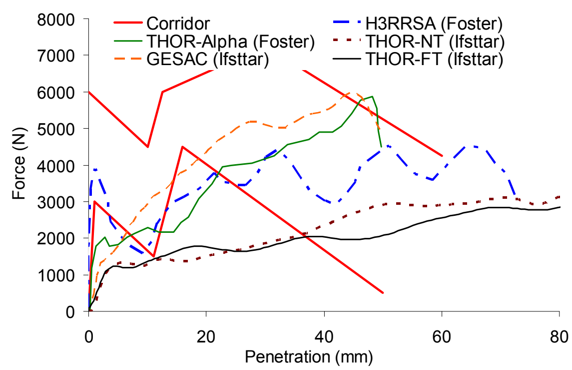

Figure 19. Compared response of various ATDs under Foster's B-system seatbelt loading (Foster et al., 2006a)

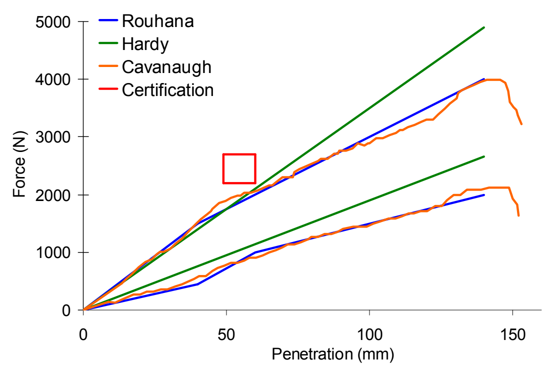

Figure 20. Certification requirements of THOR-NT's lower abdomen and biofidelity corridors available in literature for 6.1m/s, 32kg, rigid-bar impact on the abdomen

Currently, no currently existing THOR abdominal insert provides a human-like load-penetration response under both rigid bar and seat belt loadings.

CONCLUSION

The review of accident studies showed the need to further develop dummies to better evaluate the risk of sustaining abdominal injuries, especially for rear seat occupants.
The regulatory frontal impact dummy HIII does not have this capacity. During the last decade, THOR dummy was developed with instrumented lower and upper abdomens but with no associated tolerance limit. In addition, its response was mainly tuned under 6.1m/s rigid-bar impacts.
Human abdomen response was characterised by different authors under rigid bar or steering wheel impacts and seat belt loadings and was shown as rate-sensitive, different from THOR dummy abdomens tested in the current study. Silicone abdomen developed by Rouhana et al. (2001) for Hybrid III was found to have an improved biofidelity, but as for THOR dummy, improvements are needed to obtain a more human-like abdominal response so that it can better predict abdominal injuries in car crashes. Various instrumentation and design solutions were considered on different dummies. However, the challenge would also be the definition of a suitable injury criterion.

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