WORLDSID SMALL FEMALE TWO-DIMENSIONAL CHEST DEFLECTION SENSORS AND SENSITIVITY TO OBLIQUE IMPACT

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ABSTRACT

In the EC FP6 Integrated Project APROSYS, the first WorldSID small female prototype was developed and evaluated by BASt, FTSS, INRETS, TRL and UPM-INSIA. Results were presented at the ESV 2007 conference (Been *et al.*, 2007[1]). A concern was raised that the current chest deflection measurement system, IR-Traccs, registered flat top responses and sometimes may not register the peak deflection. This was believed to be related to forward deformation of the ribs relative to the spine and associated extension of the IR-Traccs. In the mean time an update version of the dummy, called Revision1, was developed to address the issues found in the first evaluation round.

To improve oblique thorax loading sensitivity, a two-dimensional chest deflection sensor, the 2D IR-Tracc was developed. Measuring the angle between the spine box and the IR-Tracc enables the displacement of the most lateral point on the rib rib to be calculated in the XY (transverse) plane.
To evaluate the new system, FTSS conducted single rib unit tests on a drop tower under pure lateral and oblique test conditions. The compression and rotation data were analysed to find the displacement of the most lateral part of the rib, and the rib deformation in the impact area. In addition, TRL subjected a complete Revision1 prototype dummy to oblique thorax pendulum tests and LAB conducted full dummy static deployment airbag tests under various impact angles and impact severities.

The 2D IR-Tracc proved to be very useful in understanding phenomena taking place under various lateral and oblique impact conditions that could not have been understood with the current (1D) compression sensor alone. The reduced sensitivity of the conventional IR-Tracc (Dy rib) to oblique impact was confirmed in this study.
The calculated lateral displacement Y offered a simple and straightforward parameter to improve the sensitivity to oblique impacts, as compared to the current single axis deflection sensor.

INTRODUCTION

It is generally accepted that the WorldSID dummy is superior in thorax biofidelity to other side impact dummies. There is information on human response in oblique conditions (Viano[2]), but until now oblique responses were not considered, because older dummies were designed to be sensitive in the lateral axis only. During service dummies may be loaded in directions other than pure lateral. To name a few, the US National Highway Traffic Safety Administration specified a 75 degrees oblique pole test (FMVSS 214 [3]), rear seat passengers could be loaded in frontal oblique direction and seatback mounted side airbags could load the dummy from the rear of lateral, with a significant forward component. Based on its design and construction it is expected that the WorldSID oblique biofidelity and sensitivity is better than other dummies, but the comparative dummy data doesn't exist to prove this. With the existing rib deflection sensor (the IR-Tracc) of the WorldSID, the dummies displayed a reduced sensitivity of the rib deflection measurement system to oblique impact in various studies [4, 5].

Figure 1 illustrates this problem. The basic WorldSID construction is presented schematically by an oval, with the spine box in the middle. The compression measurement system is represented by a telescope. The spine box and deflection measurement system base are mounted to the rear of the rib, giving anterior-posterior asymmetry. Under pure lateral deformation (b) the spine box moves rearward and the sternum moves forward. The lateral section of the rib, where the chest deflection system is connected moves forward with respect to the base of the deflection measurement device. The forward motion of the rib lateral section introduces extension in the chest deflection measurement system. Under rear oblique load (c) the extension effect is stronger because of the larger

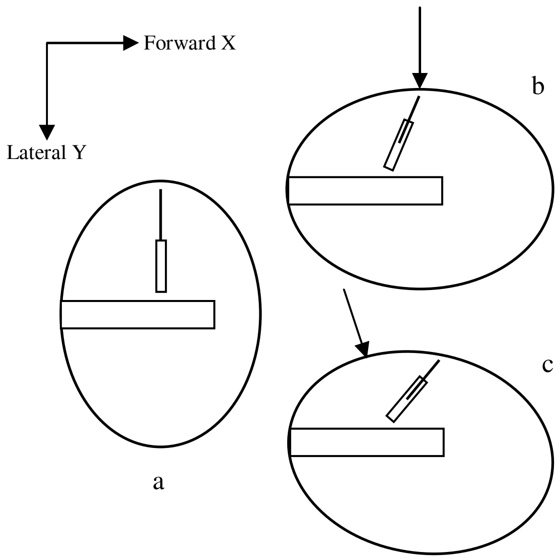

Figure 1 Schematic transverse section WorldSID chest, (a) uncompressed, (b) lateral compression, (c) rear oblique compression

forward component of rib displacement. The current chest deflection measurement device is suspected to be less sensitive to oblique load. Moreover the device does not provide information to quantify any effect of oblique load.

To address this issue and to improve oblique thorax loading sensitivity, a two-dimensional chest deflection sensor, the 2D IR-Tracc (*Infra-Red-Telescoping-Rod-for-Assessment-of-Chest-Compression*) was developed. Measuring the angle between the spine box and the IR-Tracc enables the displacement of the rib to be calculated in the transverse (X-Y) plane. The sensitivity to oblique load of the two-dimensional chest deflection measurement device was evaluated under three different test conditions. First, FTSS conducted single rib unit tests on a drop tower; then TRL subjected a complete WorldSID small female Revision1 prototype dummy equipped with 2D IR-Traccs to oblique thorax pendulum tests and finally LAB conducted full dummy static airbag deployment tests. This paper presents details of the 2D IR-Tracc and its displacement calculation method and test results under various loading conditions, impact angles and impact severities.

MATERIALS AND METHOD

2D IR-Tracc

<u>**Working principle**</u>

The 2D IR-Tracc, FTSS part IF-370, is based on the standard WorldSID small female IR-Tracc, FTSS part IF-369. The deflection sensor working principle is based on emission of Infra Red Light from a LED in the small end of the IR-Tracc and a photocell in the big end of the unit. The intensity of the infra red light on the photocell is inversely proportional to the square of the distance: the larger the distance, the smaller the light intensity. An electronic linearisation circuit is build into the unit, providing linear voltage output to the IR-Tracc compression. The separate rotation sensor works according the voltage division principle of a rotation potentiometer. The voltage output of the potentiometer central slider is linearly proportional to the input voltage and the position of the shaft.

The 2D IR-Tracc shares many components with the standard IR-Tracc. A potentiometer housing is mounted to the base of the IR-Tracc to measure its angle with respect to the interface to the spine box. To allow vertical motion of the rib, the housing of the potentiometer is pivoted about the anterior-posterior axis, see Figure 2.

Figure 2: 2D IR-Tracc

Built into the dummy the nominal length of the IR-Tracc from spine box to ball joint axis is 111.5mm; the compression range from nominal is 54mm; the extension range from nominal is 26mm. The spine box interface bracket allows over 60° of rotation of the IR-Tracc. In the first version 2D IR-Tracc, used in the drop tests and the pendulum tests, the rotation range was ±30°. As it was found that during compression the rib rotation is biased toward the front, an new interface bracket was developed. The forward range was made larger than the rearward rotation. The new interface allows forward rotation of >40° and the backward rotation of over -20°, see Figure 3 through Figure 6. The new brackets were installed in the dummy before the airbag tests.

Figure 3: Fully extended range from nominal +26mm

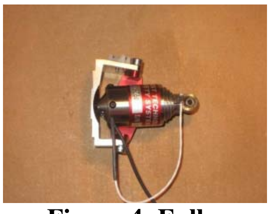

Figure 4: Fully compressed range from nominal -54mm

Figure 5: Fully forward rotation +40°

Figure 6: Fully rearward rotation -20°

Calculation method

Interpretation software was written in a spreadsheet (MS Excel) to calculate rib displacement in x- and y- direction in the dummy co-ordinate system and the resultant deformation of the rib in the x-y plane. The equations are given below and the symbols used are explained in Figure 7 (input in blue, output in red) and Table 1.

$$Xi = (L_0 - dyi) * \sin(\varphi xyi) \quad (1)$$
$$Yi = L_0 - (L_0 - dyi) * \cos(\varphi xyi) \quad (2)$$
$$Ri = \sqrt{(Xi^2 + Yi^2)} \quad (3)$$

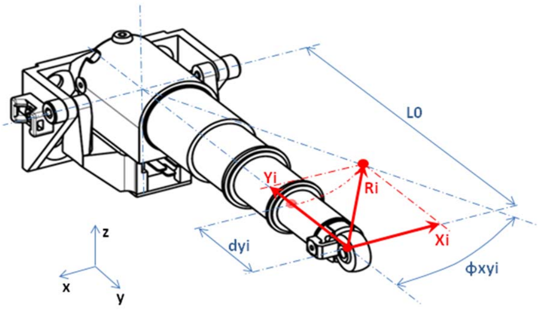

Figure 7: equations symbols

Table 1: equation symbols and description

Parameter	Description
t_0 [s]	Time zero
L_0 [mm]	Reference length at t_0.
dyi [mm]	IR-Tracc **compression dy** at time step i
ϕxyi [degrees]	IR-Tracc angle at time step i (positive angle forward)
Xi [mm]	Calculated x displacement at time step i
Yi [mm]	Calculated y displacement at time step i
Ri [mm]	Calculated Resultant displacement at time step i

Calculating the x and y co-ordinate for each time step allows to plot the rib displacement trajectory. This allows quantifying the amount of lateral (Yi) and anterior-posterior (Xi) motion of the lateral rib segment. It was expected that these parameters would be correlated with impact angle. The resultant displacement was also calculated as it seemed to be a useful output parameter to correlate with and assess impact severity, independent from impact direction. Five 2D IR-Traccs were installed in each of the two WorldSID small female revision1 prototypes. Figure 8 shows how the 2D IR-Traccs are integrated in the dummy (bottom view left thorax half, sternum at the top).

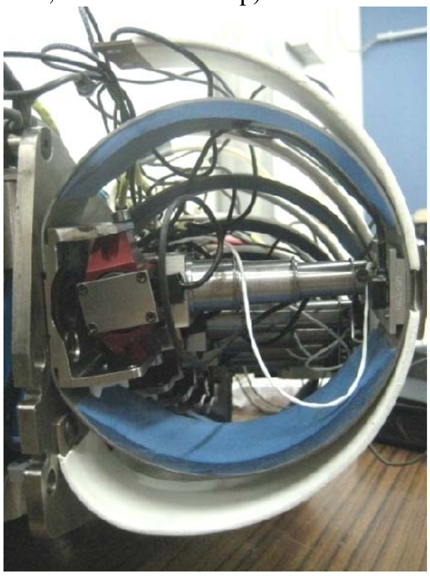

Figure 8: 2D IR-Tracc integrated in dummy

Drop tower test set up

The single rib sensitivity tests were performed on a EuroSID-1 / ES-2 drop rig. Details of the test set-up are given in Figure 9.

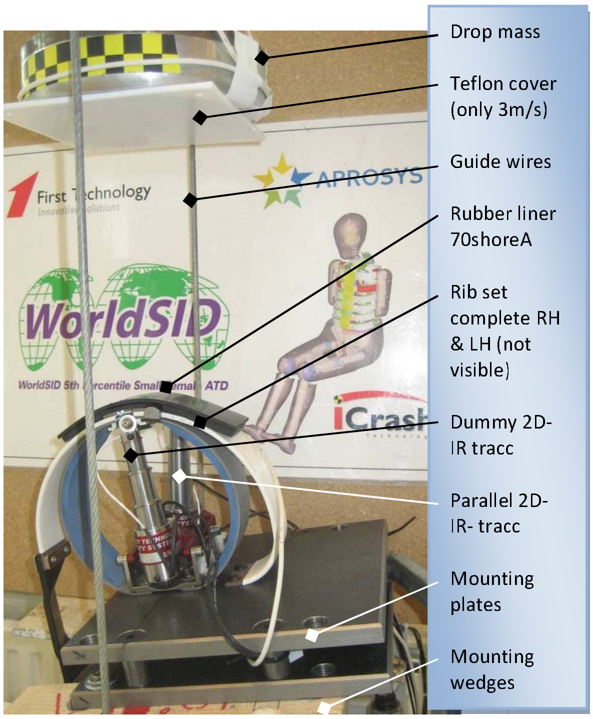

Figure 9 drop tower test set up single rib unit

Two 2D IR-Traccs were used, one is mounted in the original position in the dummy ('dummy IR-tracc'), an additional IR-Tracc is attached to the rib with a clamp in such position that the IR-Tracc centreline is in the impact plane ('parallel IR-tracc'). The single rib unit tests are done at seven impact directions: ±30°, ±20°, ±10°, and 0° pure lateral at 3m/s, positive angle is forward oblique. Also a high speed (5m/s) test condition was done at +30°, +20° and ±10°, and 0°. The 5.0m/s -30° and -20° rearward oblique tests were not conducted due to the limitation of the forward range of motion of the rotation sensor. Each test condition was repeated at least three times. In total 54 tests were performed.

Full dummy pendulum impact test set up

The oblique sensitivity tests were conducted with a set-up similar to the biofidelity pendulum test series. The WorldSID small female Revision1 dummy was seated on a platform in order to give correct vertical alignment. A wooden block was fitted to the front of the impactor, measuring 34 x 120 x 60 mm. This block was aligned so as to strike the most lateral aspect of the top thoracic rib. The dummy was supported overhead with a leash released via an electromagnet prior to contact with the pendulum. The torso was reclined until the first thoracic rib was level (anterior to posterior).

To make it easier to observe the deformation of the ribs with an overhead mounted camera, the head and arms of the dummy were removed. The test setup is shown in Figure 10.

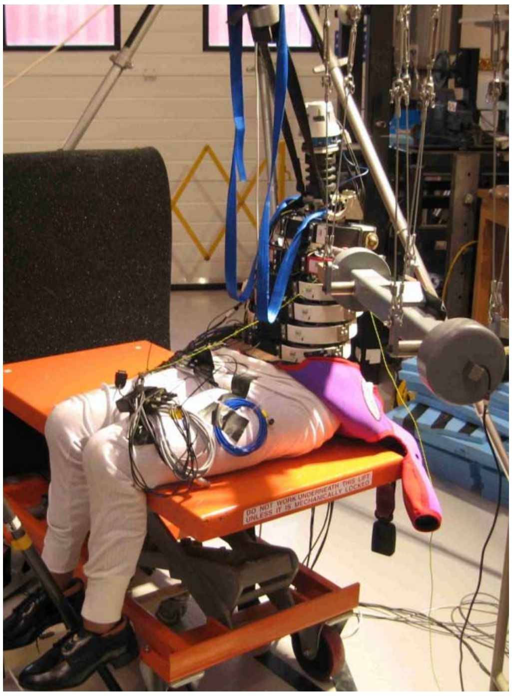

Figure 10: Full dummy oblique pendulum test

The impact velocity for the oblique sensitivity tests was 2.5m/s, the pendulum mass was 14kg. The angles of impact were +30°, ±15°, and 0°.

Static airbag deployment test set up

The testing device is shown in Figure 11. The WorldSID small female Revision1 dummy was positioned left side onto the unfolded airbag, in an upright sitting position. The pelvis was fixed to a metallic structure which only rotates about the dummy x axis immediately below the pelvis of the dummy. Prior to the test, nylon straps kept the thorax in a balanced position. At time to fire, the lifting strap was released using a controlled electromagnetic system. The pyrotechnic generator ignition inflated the airbag membrane which applied thoracic loads. The airbag-thorax distance was varied in order to modify the force magnitude. Forces applied to the thorax were measured by means of load cells mounted behind the airbag mounting plate. The dummy was instrumented with rib deflection sensors and thoracic accelerometers.

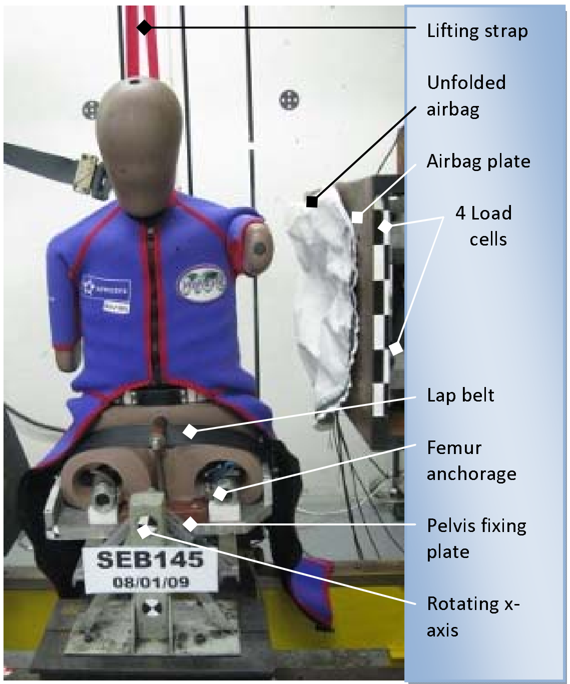

Figure 11: Static deployment airbag test set up

The WorldSID small female Revision1dummy was tested at two distances between the thorax and the airbag module (178mm and 108mm) and two angles (pure lateral and 30°forward).

RESULTS

Drop tower tests

Figure 12 - Figure 16 show the rib trajectories of the dummy 2D IR-Tracc (yellow) and the additional parallel 2D IR-Tracc (red), with a pictures of the test set-up in the background. The graph's orientations are aligned with the spine box co-ordinate system and show the actual motion trajectories of the rib relative to the background picture. The plots are arranged on the page, such that corresponding angles are plotted next to each other, placed on the left are forward oblique, and on the right are rearward oblique.

Figure 12: + 30 degrees forward impact

Figure 13: +10 degrees forward impact

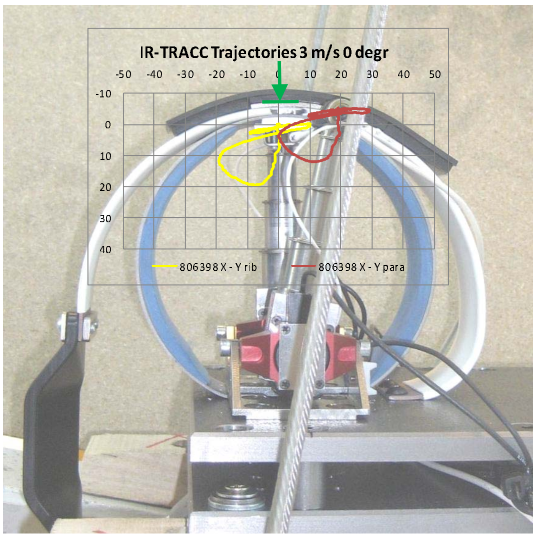

Figure 14: 0 degrees lateral impact (Note: Picture shows not actual set-up. For illustration a photo of -10 degrees set-up was rotated.)

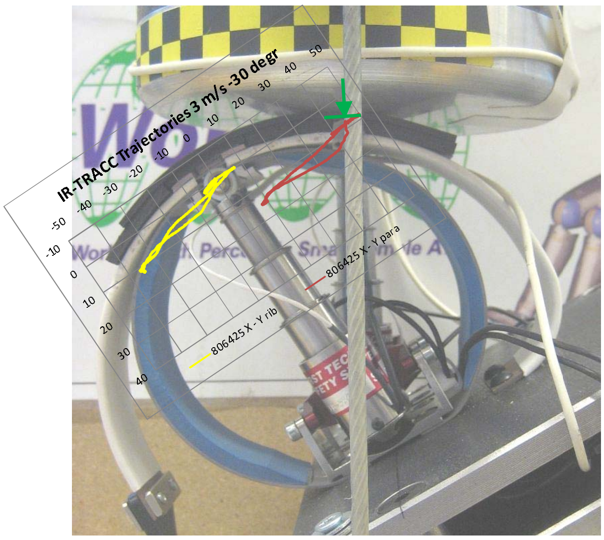

Figure 15: -30 degrees rearward impact

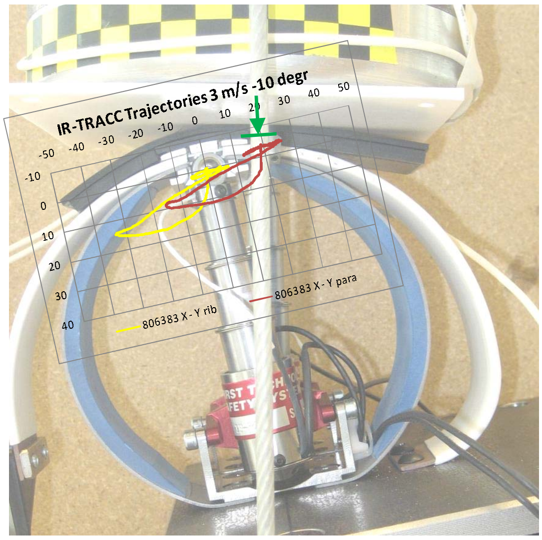

Figure 16: -10 degrees rearward impact

Note the considerable differences in response to rearward and forward oblique tests, by comparing adjacent images. The graphics show that trajectories of the rib measured with 'parallel' (red) and with 'dummy' (yellow) IR-Traccs are very similar. Also note that in all test conditions the rib deformation starts inline with the impact direction. The plots show 3.0m/s results.

Note that in the drop tower tests forward displacement has a negative sign, whereas in the pendulum and airbag tests forward displacement is positive.

Figure 17 and Figure 18 show the rib trajectories in all impact directions, at 3.0m/s and 5.0m/s impact velocity. Figure 17 also shows displacement parameters X (anterior-posterior), Y (lateral) and R (resultant X-Y). A schematic overhead view of a human is shown for orientation purpose.

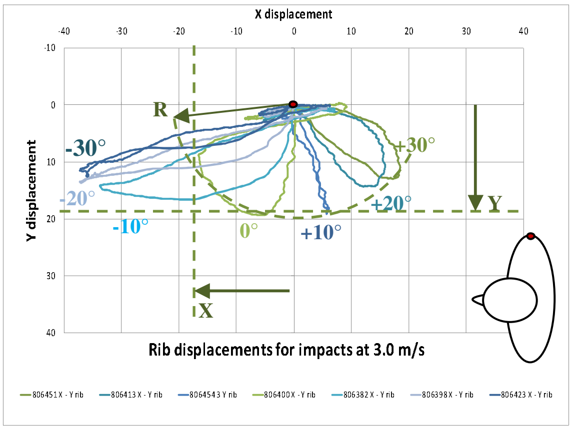

Figure 17: Rib trajectories all impact directions at 3.0m/s and human body overhead view

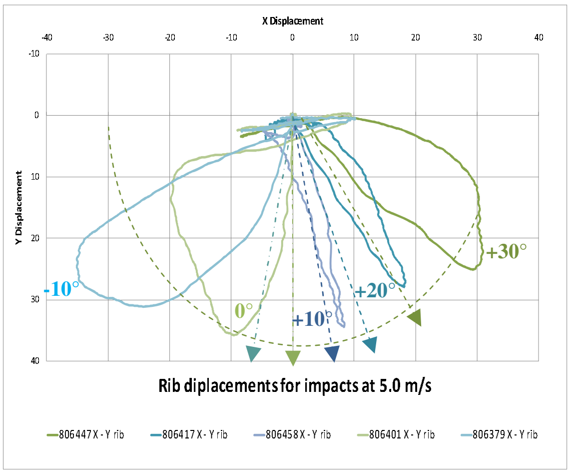

Figure 18: Rib trajectories all impact directions at 5.0m/s

Both figures clearly show there is large forward deformation even under pure lateral tests. In all rearward oblique tests, the forward motion exceeds the lateral deformation. Figure 17 also shows that the resultant displacement R remains relatively constant for pure lateral and forward oblique tests, but R is much larger for rearward oblique. The R parameter alone is therefore not a good indictor of impact severity or injury risk. All test results are summarised in Table 2, in a numerical format, giving averages of three tests and the coefficient of variation, which is the standard deviation divided by the average. In the table F_{imp} is the impactor force (N), Dy is the compression of the IR-Tracc alone, X, Y, and R are calculated parameters as explained in the 'Calculation Method' section (in mm). The coefficient of variation is well below 3% for most test conditions and parameters. Note that the parameters Dy, X and Y from dummy IR-Tracc and parallel IR-Tracc cannot be directly compared, as the results are given in the co-ordinate system aligned with the instrument. The resultant displacements (R) from the dummy IR-Tracc and parallel are independent from impact direction and can be compared directly. The R parameters are generally very similar. This makes sense, as these segments are coupled by the rib section between them. Some further observations: The impactor forces F_{imp} are more or less constant and appear to be not very dependent on impact direction, however the highest impact forces appear under 20° forward loading and the lowest under rearward oblique impact.

Table 2: Average peak results 3 tests each condition

			Dummy IR-Tracc				Parallel IR-Tracc			
		F_{imp}	Dy	X	Y	R	Dy	X	Y	R
3m/s	+30°	827	11.1	19.0	12.9	22.6	19.1	13.2	19.8	22.8
	+20°	846	13.6	15.4	14.5	20.0	19.2	11.3	19.5	20.9
	+10°	802	19.0	5.8	19.2	19.8	20.1	-3.0	20.1	20.2
	0°	795	19.0	-17.9	18.9	20.8	16.8	-13.3	16.8	18.1
	-10°	719	14.3	-33.3	16.4	36.2	16.7	-31.3	20.1	36.8
	-20°	702	9.0	-37.2	13.4	39.5	16.6	-30.8	22.8	38.2
	-30°	709	5.7	-36.7	12.2	38.3	18.3	-28.8	23.9	37.3
	CV	1.24	1.75	1.55	1.73	2.03		1.95	0.80	2.40
5m/s	+30°	1293	19.0	29.9	24.9	38.1	32.8	22.0	34.8	38.4
	+20°	1398	25.0	18.4	27.7	33.0	35.2	7.6	35.5	36.1
	+10°	1299	34.0	8.2	34.6	35.6	36.2	-5.9	36.2	36.2
	0°	1231	35.2	-18.5	35.9	36.9	32.4	-16.0	32.5	32.7
	-10°	1248	26.4	-36.0	31.1	44.7	31.4	-31.5	34.5	44.3
	CV	1.1	1.6	4.2	1.2	1.3			3.6	3.5

Full dummy pendulum impact test

Observations from the overhead camera view are shown in Figure 19 through Figure 22, starting with +30° and +15° forward impact followed by lateral and -15° rearward oblique tests. Rearward motion of the IR-Tracc is observed in the 30° forward oblique test; approximately pure lateral compression is visible in the 15° forward oblique test, which was also observed in the single rib unit drop tests at 10° forward oblique. In this test the end of the rotation range was reached at around 31° rotation, as can be observed in Figure 23 as a discontinuity.

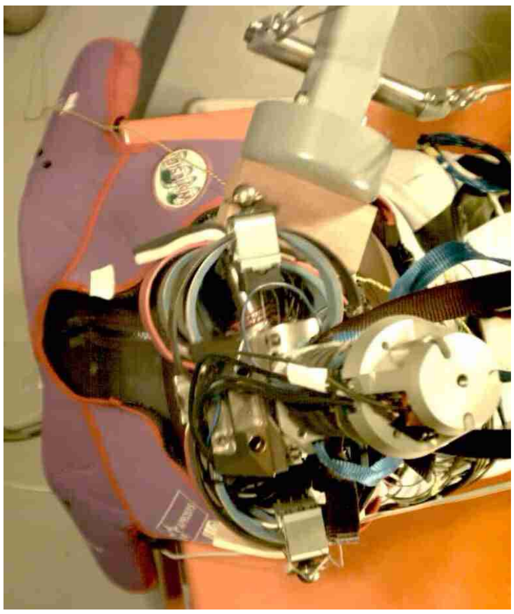

Figure 19: Overhead image + 30 degrees ~26 ms

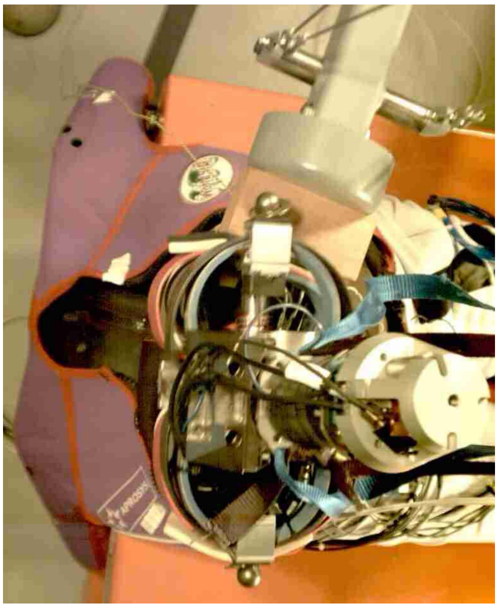

Figure 20: Overhead image +15 degrees ~26 ms

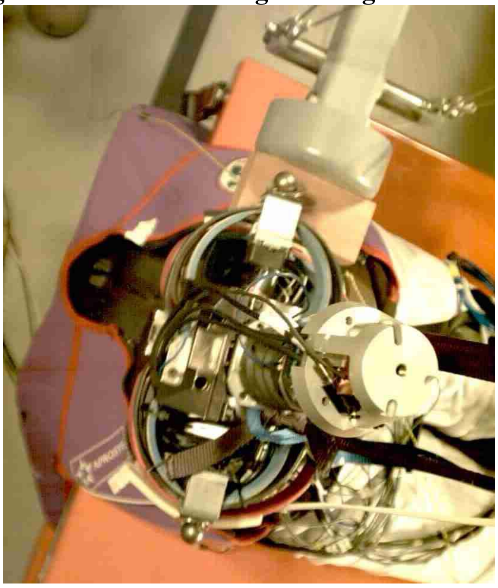

Figure 21: Overhead image lateral test ~26 ms

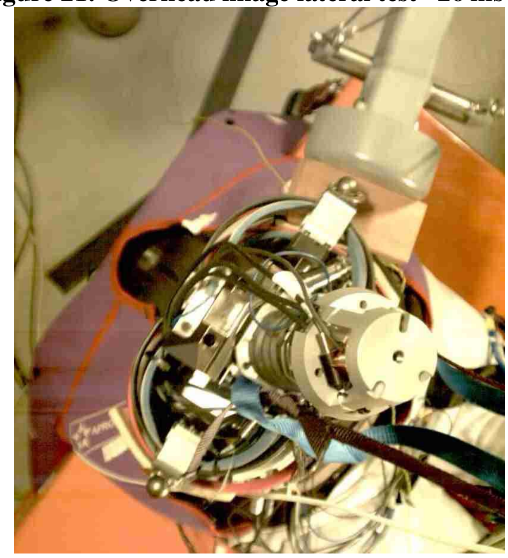

Figure 22: Overhead image - 15 degrees ~26 ms

The purple dotted line is an estimated reconstruction of the response without rotation bottoming out. As a result of this test, the 2D IR-Tracc mounting brackets were updated to shift the range of motion from ±30° to +40° – -20°.

Figure 24 shows the IR-Tracc compression. The output of the IR-Tracc is much lower for the +30° and -15° impact angle tests than the lateral and +15° forward oblique tests. Figure 25 shows the calculated Y lateral displacement. The -15° test (purple) clearly shows the bottoming out of the rotation, with its deviating waveform. Clearly the calculated Y is less dependent from the impact angle, however at +30 the output is still lower than pure lateral test.

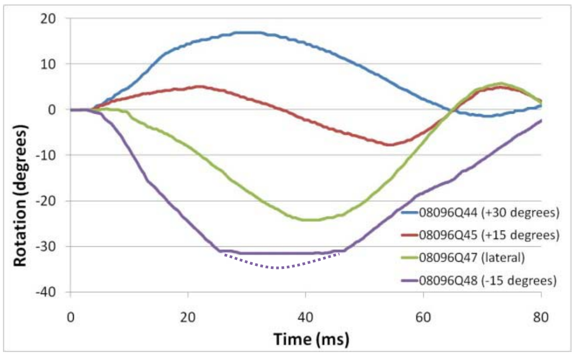

Figure 23: 2D IR-Tracc rotation oblique sensitivity tests

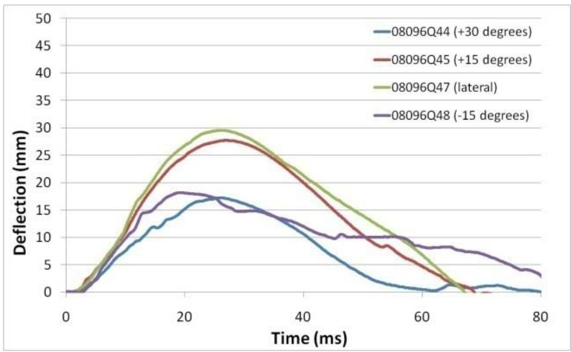

Figure 24: Dy IR-Tracc compression oblique sensitivity tests

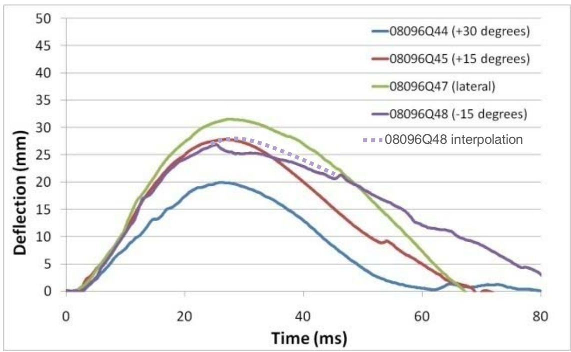

Figure 25: Calculated Rib Y displacement oblique sensitivity tests

The pendulum acceleration responses from the four oblique sensitivity tests are shown in Figure 26. It is evident from this figure that the + 30 degree and the -15 degree impacts had a slightly lower peak pendulum acceleration than the +15 degree and lateral impacts. This probably reflects the alignment of the pendulum being closer to the dummy centre of gravity in the +15 degree and lateral impacts. The responses from the 15 degrees forward of lateral and pure lateral tests are similar, with a difference of only 0.5 % between the peak values.

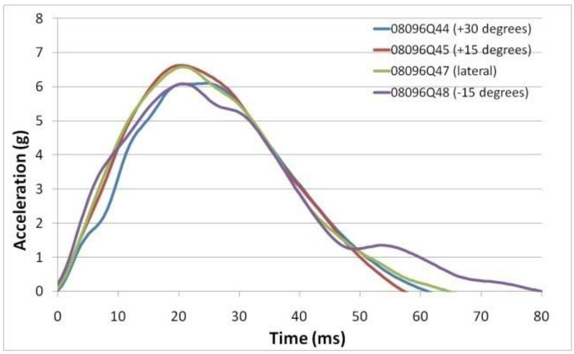

Figure 26: pendulum acceleration responses

The results of the pendulum test are presented in numerical format in Table 3. The table includes a comparison of the oblique test peak results with the peak result from the lateral test.

Table 3: Peak parameters pendulum tests

Direction	F_{imp}	Dy	2D IR-Tracc calculated			Ratio oblique/lateral		
			X	Y	R	$Dy/Dy_{0°}$	$Y/Y_{0°}$	$R/R_{0°}$
+30°	838	17.2	20.5	20.0	28.1	0.58	0.64	0.74
+15°	909	27.8	-10.5	27.9	28.1	0.94	0.89	0.74
0°	904	29.5	-27.4	31.5	38.1	1	1	1
-15°	835	18.1	-39.4	26.9	45	0.61	0.85	1.18

Static airbag deployment test

The peak results of the static airbag tests are given in Table 4. In this table the average of two tests is given. For the ribs results are given for IR-Tracc compression Dy, 2D IR-Tracc rotation, X displacement, Y displacement and R resultant displacement. The bold figures highlight the highest of three thorax ribs and two abdomen ribs. The table shows that peak thoracic rib deflections occur either at thorax rib 2 or 3, and peak abdominal rib deflections always occur at the first abdominal rib. Figure 38 is illustrative for the reason behind this, as the airbag deploys in a spherical shape, putting more load on the centrally placed ribs. The parameters Dy and Y do not always agree on which of the thorax ribs is in highest deflection, however the difference between the thorax 2 and thorax 3 are generally low for both parameters. The results clearly show that the 30° forward tests gives much lower rib lateral deflections that the lateral tests. The output of the rotation sensor does provide insight of the loading direction of the dummy, with forward rib displacement under lateral and rearward rib displacement under forward load.

The largest rib rotations and X displacements occur at thoracic rib 2 in the lateral tests and at thoracic ribs in the oblique conditions.

Table 4: Test results airbag average of two tests

Condition		178mm, 0deg	108mm, 0deg	108mm, 30deg	178mm, 30deg
	F	3624	6232	5704	3757
Shoulder	Dy	16.9	21.0	9.6	5.6
Thorax 1	Dy	6.4	14.8	3.7	3.2
	Rot	9.3	19.8	**-17.4**	**-11.0**
	X	13.3	25.1	**-26.7**	**-16.8**
	Y	7.3	19.2	5.4	3.7
	R	14.8	31.4	26.9	16.9
Thorax 2	Dy	10.3	**18.8**	5.5	4.8
	Rot	**12.3**	**20.4**	-14.1	-9.1
	X	**17.2**	**25.1**	-20.6	-13.9
	Y	**11.6**	**22.9**	**6.2**	5.1
	R	19.9	33.2	20.8	14.0
Thorax 3	Dy	**10.6**	17.3	**5.7**	**5.2**
	Rot	10.9	18.9	-10.8	-7.4
	X	15.2	23.7	-16.3	-11.2
	Y	11.5	21.0	6.1	**5.5**
	R	18.2	31.0	16.5	11.4
Abdomen 1	Dy	**9.1**	**15.0**	**5.3**	**4.9**
	Rot	9.2	16.3	-7.0	-5.5
	X	12.9	21.1	-10.9	-8.5
	Y	**9.9**	**17.7**	**5.6**	**5.1**
	R	15.4	27.0	10.9	8.5
Abdomen 2	Dy	2.8	6.0	3.5	2.3
	Rot	4.9	11.5	-6.5	-0.4
	X	7.8	16.1	-10.1	-0.6
	Y	3.0	7.5	3.5	2.3
	R	8.1	17.7	10.1	7.7

Figure 27 shows the trajectories for pure lateral and 30 degree tests. It can be observed that the deflections are more due to the rotation than the compression of the IR-Tracc, confirming the necessity to measure both parameters.
The lateral displacement is almost absent in the 30° oblique test, and also in the pure lateral test, forward motion is larger than the lateral compression.

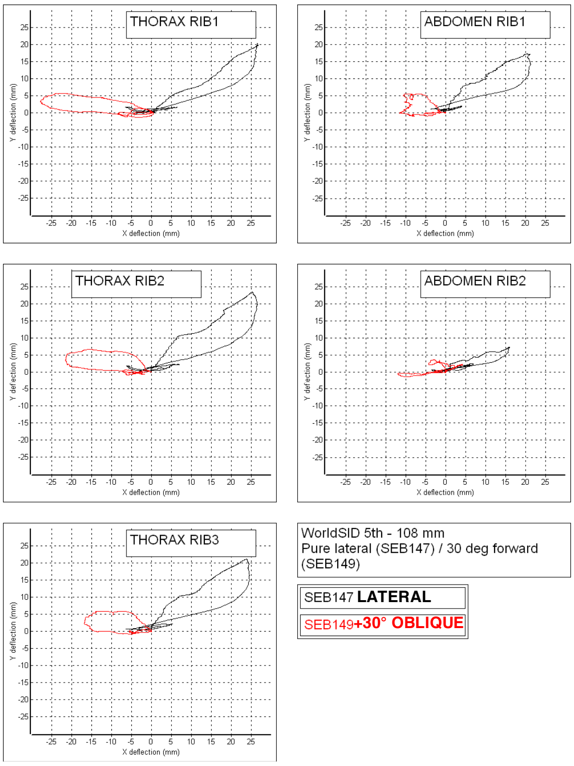

Figure 27: Rib trajectories for pure lateral and 30 deg forward tests at 108 mm

ANALYSIS, DISCUSSION AND SYNTHESIS

Drop tower tests

In Figure 28 the peak impact forces versus impact direction are shown both in absolute values as well as in percentages of peak lateral impact forces. For this analysis the average peak impact forces are calculated for each impact direction and impact speed.

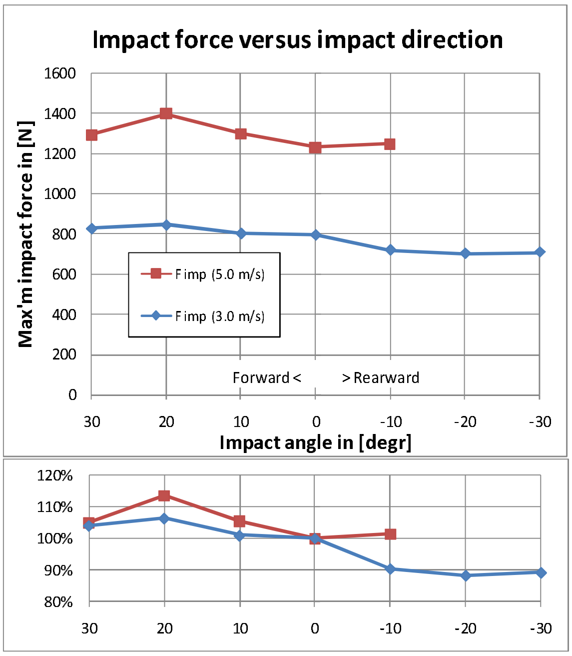

Figure 28: Impact force versus impact direction absolute and in percentages of pure lateral

It can be concluded that the impact force generated by the rib is not largely dependent on the impact direction and remains rather constant. For impacts at an impact speed of 3.0 m/s the deviations are between +6.3% and -11.8% and for impacts at an impact speed of 5.0 m/s the deviations are between +13.5% and 0%. At +20 degrees forward impact direction the ribs compressions are 6-14% lower than pure lateral and beyond 20 degrees rearward impact the ribs displacements are higher by 10%.

In Figure 29 the peak lateral displacements (Y rib) versus impact direction are shown both in absolute values as well as in percentages of the peak displacements at pure lateral impacts. For reference the compression of the IR-Tracc (Dy) is also given. The average rib displacements at lateral and +10 degrees impact angles are more or less constant at 19mm for 3m/s and around 35-36mm for 5m/s. The plots in Figure 29 show reduced Y rib compression under both rearward and forward impact, around 20% reduction of the average peak displacement at -10° and +20° impact angles increasing to 30% reduced average rib displacement at +30° and -20° to -30° impact directions.

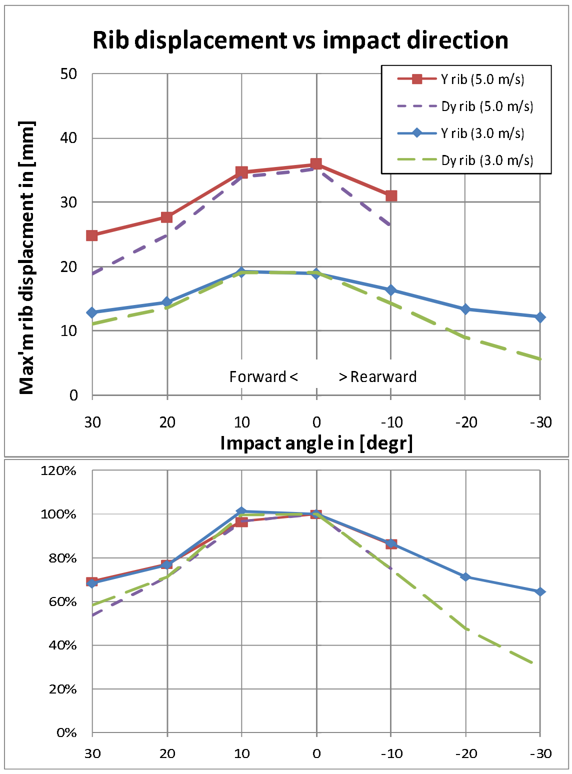

Figure 29: Rib displacement versus impact direction absolute and in percentages of pure lateral

Figure 29 reveals another important difference if we compare the output of the 'plain' IR-Tracc alone (green and purple dotted lines) with the lateral displacement Y rib calculated from the 2D IR-Tracc. The reduced sensitivity of 'plain' IR-Tracc is clearly illustrated: at 30 degrees forward impact the IR-Tracc compression, Dy, is 54-58% of the pure lateral output and at 30 degrees rearward impact the output is reduced to 29% of the pure lateral output. Although reduced, the calculated parameter Y rib is much more sensitive under oblique impact direction: at 30 degrees forward impact the Y rib is 68% of the pure lateral Y rib and at 30 degrees rearward impact the Y rib is reduced to 63% of the pure lateral Y rib. It can be concluded that Y rib obtained from the 2D IR-Tracc provides a much better insight in the rib deformation under both lateral and oblique impacts, than the deformation recorded with the IR-Tracc alone (Dy). More over the parameter Y rib discriminates between the high severity and the low severity test conditions.

Figure 30 shows a comparison between Y para (compression aligned with impact direction) and Y rib, lateral compression in spine box co-ordinate system. Please note that these parameters are not in the same co-ordinate system. The figure shows that the deviation between the parameters becomes larger with larger deviation of the angle between the instrumentation, which is to be expected. The compression in impact direction remains more or less constant, between +30 and -10 degrees impact angle for both 3m/s and 5m/s impacts. The compression increases with rearward of lateral tests.

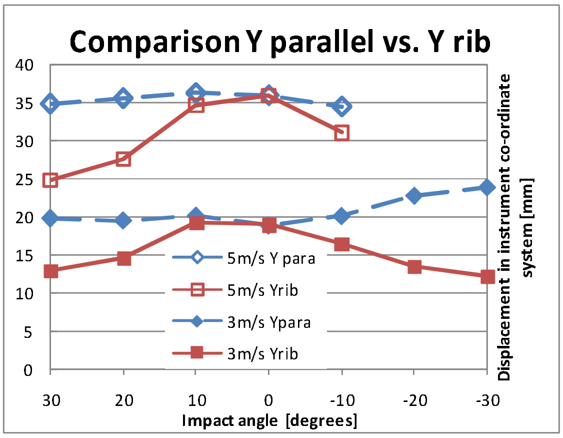

Figure 30: Comparison displacement Y para and Y rib in instrument co-ordinate system

Figure 31 shows the correlation between the calculated peak resultant displacement versus the impact angle in absolute values as well as percentage of the pure lateral impact value. The resultant displacements are relatively flat in the pure lateral and forward oblique tests. This means that the resultant displacement is not dependant on impact angle. However, under rearward oblique impacts, the resultant displacements of the 3m/s tests are as high as the lateral and forward oblique results of the 5m/s test. This parameter alone is not able to discriminate between a high severity lateral test and a rearward oblique impact of lower severity. Figure 31 also shows a comparison between the resultant displacements as measured by the parallel IR-Tracc and the dummy IR-Tracc. The results are clearly close together the dummy IR-Tracc, is reflecting the rib displacement in impact direction, independent form the impact direction.

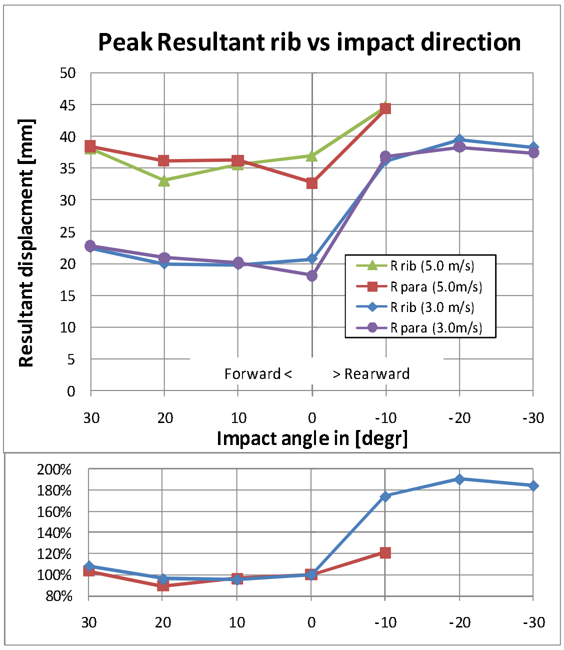

Figure 31: Peak resultant rib displacement versus impact angle drop tests

Larger forward than rearward motion of the rib can be explained from the construction of the ribs in the WorldSID dummy. The rib units are assembled from inner and outer ribs. The inner ribs are a cylindrical hoop attached symmetrically with respect the lateral axis to the spine box. The outer ribs are asymmetrically attached only to the rear of the spine box, similar to the human thorax construction. An asymmetric behaviour of the dummy and the human chest is to be expected.

Pendulum tests

The pendulum tests show similar results to the single rib unit drop tests (Figure 32). Rib displacements are similar for lateral and small angles frontal, with reduced output with increasing oblique test angles. Also in the pendulum test the Y displacement is less sensitive to impact angle than the Dy compression of the IR-Tracc alone. The R resultant displacement is higher under rearward oblique than forward oblique tests. The force response is hardly dependent from impact angle (Figure 26). Interestingly, at +15° impact all parameters are very close to one another around 28mm. This indicates that there is very little rotation in this test. Indeed around the time of peak displacement of the +15° test, the rotation angle is close to 0° (Figure 23 & Figure 24). This observation is illustrative of the valuable insight the

2D IR-Tracc offers in the behaviour of the rib deformation.

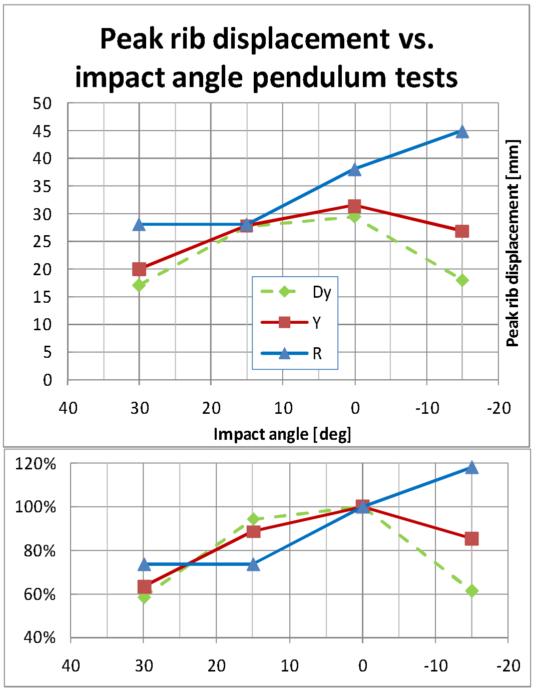

Figure 32: Pendulum tests rib displacements vs. impact angle

Airbag deployment tests

Figure 33 to Figure 37 show the effect of angle respectively on the plate force, the IR-Tracc compression Dy, the X deflection the Y deflection and the Resultant deflection. The compression Dy and the Y deflection demonstrate a large sensitivity on the loading angle, with reduced output under oblique load, while the resultant deflection is less affected. The X deflection parameter is also very sensitive for oblique load and clearly indicates the direction of load. Regardless of the sign, the peak X displacements are rather similar in amplitude in the pure lateral and 30° forward tests. This implies that the smallest forward and backward displacements (thus pure lateral displacement) could be expected around 15° forward impact. This is in line with the pendulum test result, see Figure 32.

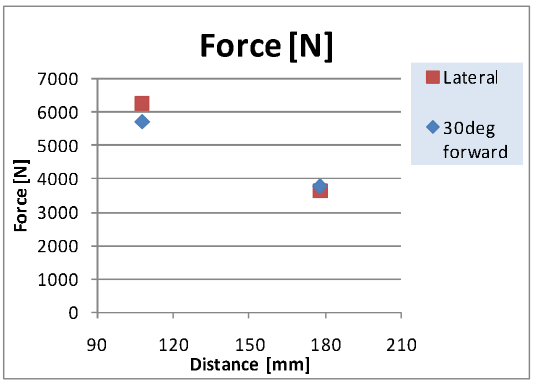

Figure 33: Plate force vs. airbag distance

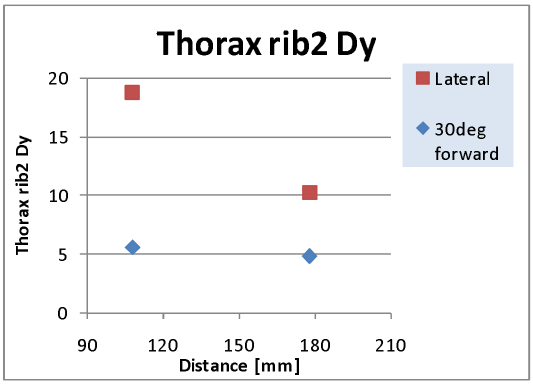

Figure 34: Thorax rib 2 IR-Tracc compression vs. airbag distance

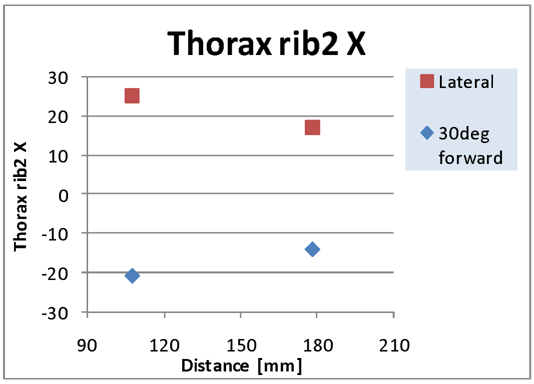

Figure 35: Thorax rib 2 X-displacement 2D IR-Tracc vs. airbag distance

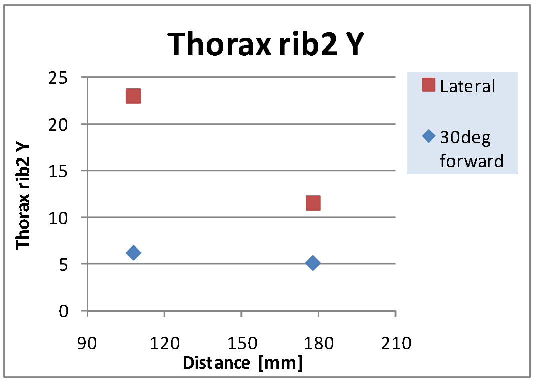

Figure 36: Thorax rib 2 Y-displacement 2D IR-Tracc vs. airbag distance

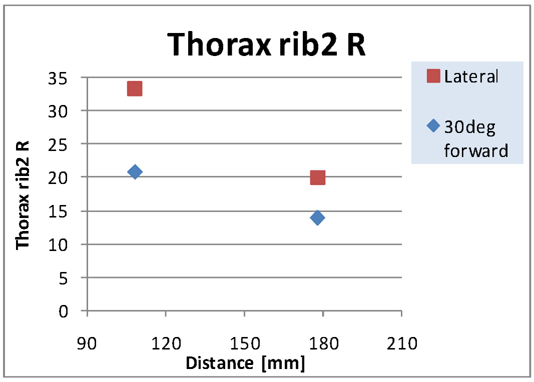

Figure 37: Thorax rib 2 Resultant displacement 2D IR-Tracc vs. airbag distance

Table 5 gives a summary of the test results in numerical format for the three thorax ribs. In this table the results are presented in the ratio of the oblique and the lateral parameter. A ratio of more than 1 indicates the parameter is higher in the oblique condition and below 1 indicates that the oblique parameter is lower. The lower severity test results are shown in the left column and the higher severity in the right column. For Dy and Y parameters, the oblique results are lower than the lateral results. For the force and thorax rib1 X- and resultant displacement the ratio is higher than 1, indicating the oblique results are higher. Further it is clear that generally the ratios of parameters are much lower in the high severity test, with ratios around 0.25-0.30. An exception is the X parameter, which changes its sign, but the absolute values are closer to 1.

Table 5: Ratio of parameters 30° and parameters lateral

		ratio +30° oblique/ lateral	
		178mm	108mm
	F	1.04	0.92
Thorax 1	Dy	0.50	0.25
	X	-1.26	-1.07
	Y	0.50	0.28
	R	1.14	0.86
Thorax 2	Dy	0.46	0.29
	X	-0.81	-0.82
	Y	0.44	0.27
	R	0.70	0.63
Thorax 3	Dy	0.49	0.33
	X	-0.73	-0.69
	Y	0.47	0.29
	R	0.63	0.53

To study further the reasons for the large difference between the outputs of two test condition, the high speed videos of the tests were analysed. Sequences of high speed videos of the lateral test (Figure 38) and oblique test (Figure 39) clearly show the different behaviour of the dummy in these test conditions. In the pure lateral test, the dummy's response is pure sideways motion; and in the 30° oblique the dummy's chest is rotating backward. Peak displacements were around 35ms in pure lateral and, much earlier, around 20ms in forward oblique tests. The chest rotation could explain a lower deflection in the oblique test; however, the rotation began after the deflection started to decrease, i.e. in the unloading phase.

A plausible explanation could be the following. In the lateral test the vector of force is directed towards the centre of gravity of the dummy. The inertia of the dummy provides a counter reactive force within the dummy against which the ribs (which are acting like springs/dampers) are deforming. In the forward oblique test however, the

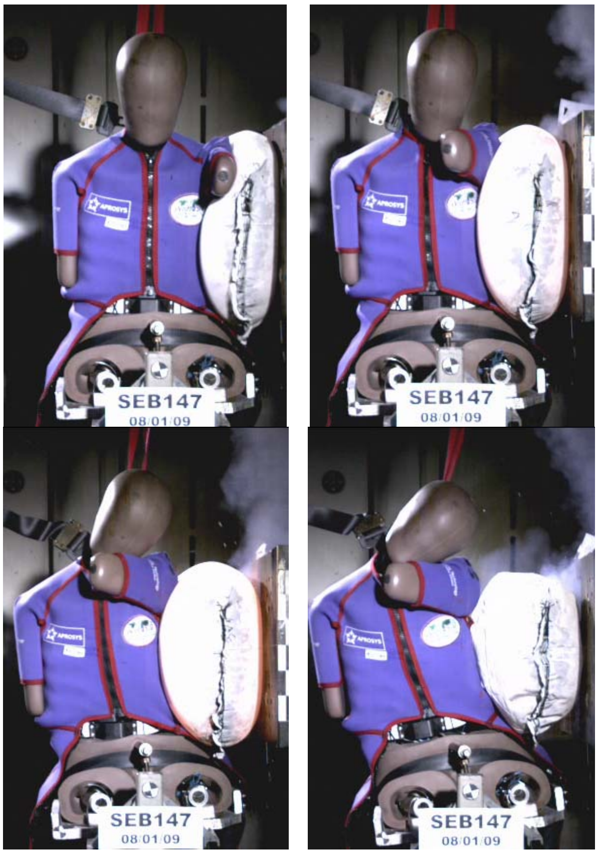

Figure 38: Sequence of high speed video stills 20, 30, 40 & 50ms lateral tests

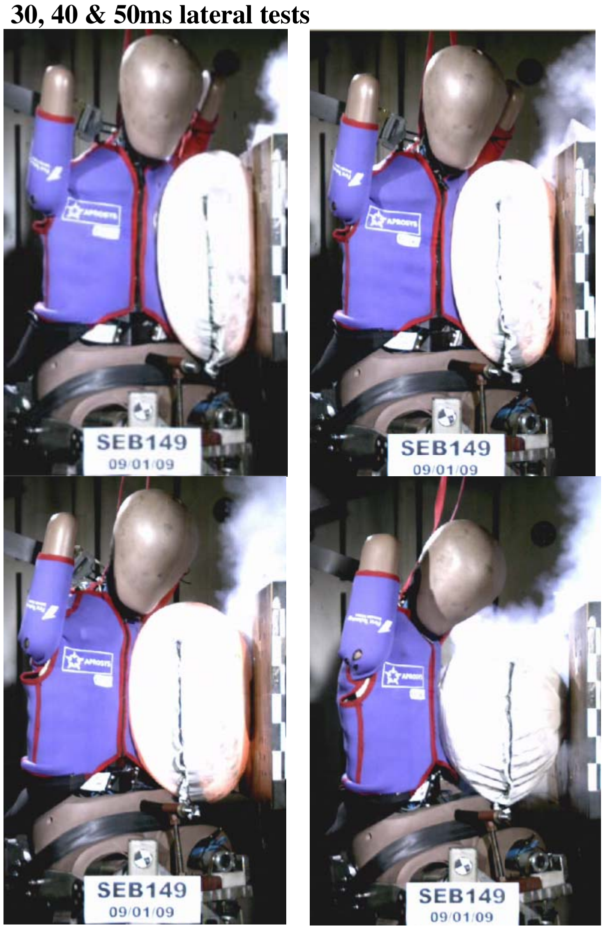

Figure 39: Sequence of high speed video stills 20, 30, 40 & 50ms, 30° frontal oblique test

vector of force is not directed to the centre of gravity, causing rotation of the dummy's chest. It is believed that the counter reactive force within the dummy has a much larger forward-backward component, causing rearward rib rotation and highly reduced lateral compression. The rotation inertia does not provide the internal counter reactive force against which the ribs are compressing. The restriction in rotation around a vertical axis at the pelvis is not working for the dummy, as the lumbar spine is developed to allow human like shear motion and is not validated for moment about the vertical axis. The rotation of the chest is the 'easy way out' for the dummy and only restricted by the rotation inertia of the chest, neck and head. The rotation component is confirmed by the asymmetrical loading which is observed on the airbag plate forces: the forces at the back of the plate are higher than the forces at the front for the 30° forward loading, indicating a moment reaction. For pure lateral tests, the plate forces are almost equal between back and front, indicating pure lateral loading.

Synthesis drop & pendulum tests and airbag tests

Generally there is a good correlation between the Drop test and Pendulum test results. The IR-Tracc compression, Dy, and lateral deflection, Y, remain at the same level when the impact angle is varied between about lateral and 15° forward oblique. This means that when the dummy is loaded close to the lateral axis direction, there is no problem with the current deflection measurement system, the IR-Tracc.

With further deviation from the lateral, the output of the lateral deflection is reduced. The Y displacements remain at a higher level than the compression Dy of the IR-Tracc alone over a wider impact angle variation. The drop test and pendulum results indicate that the Y displacements remain within 80% of the lateral test output between impact angles ranging between 20° forward oblique and 15° rearward oblique, and about 70% between 30° forward and 25° rearward oblique impacts. The Y displacement appears to be a simple but efficient parameter to improve the sensitivity to oblique impacts.

The resultant displacement was also tested for oblique impact sensitivity. Due to the large forward displacements of the ribs in rearward oblique impacts, the resultant displacement becomes very large and comes into the range of resultant displacement of higher severity tests under lateral test conditions. The R parameter is not able to discriminate between a high severity lateral impact and mid severity rearward oblique test.

The situation for rearward oblique is different from forward oblique. This has to do with the construction of the WorldSID thorax, with outer ribs mounted to the rear of the spine-box and free floating connections between left and right ribs in the front. Forward rib motions in rear oblique impact are larger than rearward motion in forward oblique impacts. This results in forward rib displacements, even under pure lateral tests. The test results indicate that the turning point is at around 0° – +15° forward oblique, which impact angle leads to more or less pure lateral deflections. All of these observations were made possible by the addition of the rotation sensor and calculation of rib trajectories in the X-Y plane of the ribs.

A discrepancy was found between the Airbag tests on one hand and Pendulum and Drop tests on the other hand. The output of the deflections sensors under forward oblique tests, both from IR-Tracc and 2D IR-Tracc, were much further reduced in the Airbag tests (~25-30% from pure lateral) than the Pendulum and Drop tests (~60-70% from pure lateral). The differences in dummy response between the drop table and pendulum tests on hand, and airbag tests on the other hand can be explained from the difference between the test conditions. The pendulum and drop tests involve loading with high inertia loading devices, which will not easily deviate from their path of travel. The dummy ribs and the impactor mass are well coupled by the friction in the pendulum tests (to lesser extend in 3m/s drop tests by use of PTFE sheet), therefore, at impact, the rib displaces more or less in the direction of travel of the impactor.

The airbag on the contrary is a low mass loading device, with energy content in the form of lightweight expanding gasses and airbag fabric at high velocity. It appears that the expanding gasses can more easily deviate from the path of travel and can take the easy escape route, wherever the lowest restrictions are. This is reflected in the airbag response trajectories (Figure 27), where the displacement of the rib deviates from the impact direction right from the start.

No matter the difference between these test conditions, also in the airbag tests the 2D IR-Tracc results proved to be very helpful indeed to study the phenomena taking place. Still many questions remain from these tests, but in any case the 2D IR-Tracc offers a good tool to study them.

CONCLUSION AND RECOMMENDATIONS

Conclusions

The 2D IR-Tracc was assessed for oblique sensitivity in three test conditions: on a drop table with rib components, in full dummy pendulum tests and static deployment airbag tests. The impact angle and impact severity was varied in the test conditions and the outputs of the two-dimensional chest deflection sensor were analysed.

The 2D IR-Tracc proved to be very useful indeed in understanding phenomena taking place under various lateral oblique impact conditions and could not have been understood with the current (1D) compression sensor. The reduced sensitivity of the conventional IR-Tracc compression (Dy) to oblique impact was confirmed in this study.

Three calculated displacement parameters from the 2D IR-Tracc were assessed and compared to the standard measurement parameter. The calculated lateral displacement Y offered a simple and straightforward parameter to improve the sensitivity to oblique impacts, as compared to the current single axis deflection sensor. The drop test and pendulum results indicate that the Y displacements remain within 80% of the lateral test output between impact angles ranging between 20° forward oblique and 15° rearward oblique, and about 70% between 30° forward and 25° rearward oblique impacts.

The forward-rearward displacement X parameter offers very good indication of the loading direction of the dummy. The smallest forward-rearward displacements were found under 10°-15° forward-oblique impacts. Large forward displacements were found under rearward-oblique impacts and these were generally larger than the lateral displacement from -10° impact angles and beyond.

The 2D IR-Tracc resultant displacement parameter, R, correlates well with the displacements found in impact direction in the drop table tests and provides information on the magnitude of the rib deformation in impact direction. However this parameter is not useful as injury assessment parameter, as it does not discriminate between impact severity under all impact conditions, especially rearward oblique impacts.

The objective of improving the oblique loading sensitivity has been met with the development of the 2D IR-Tracc. Further research is necessary to develop an injury criterion based on its output that correlates well with injury under lateral and lateral-oblique loading conditions.

In this study only test-to-test comparisons were done by variation of the test condition with one dummy. The important open item is, the comparison of the PMHS chest deflection in the X-Y plane with those of the dummy in the same test condition. So far, as far as the authors are aware, no two-dimensional deflection data have been derived. Maltese et.al. [6] used the chest band device to obtain deflections in the cross sections of PMHS chests in sled tests; however, only single parameters of lateral deflection were published. It could be useful to re-analyse this database for two-dimensional rib displacements. Yoganandan et.al. 2007 [7] expanded the Maltese test conditions with an oblique mounted force plate for the thorax, to obtain lateral-oblique human response data. It would be useful to install 2D IR-Traccs in the WorldSID 50the male dummy and subject it to the same test conditions.

The objective of improving the oblique loading sensitivity has been met with the development of the 2D IR-Tracc. Further research is necessary to develop an injury criterion based on its output that correlates well with injury under lateral and lateral-oblique loading conditions.

Some inconsistencies were identified when the dummy is loaded by an airbag. More investigations are needed to understand the inconsistencies.

Recommendations

It is recommended to validate further the dummy oblique thorax response with available human response data. It should be considered to develop the 2D IR-Tracc so as to be suitable for the WorldSID 50th percentile male dummy and explore its potential benefits for this dummy. Also application in other dummies, such as the Q3s and Q6s, the Q-dummy side impact family should be considered.

ACKNOWLEDGEMENTS

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