OBLIQUE AND SIDE IMPACT PERFORMANCE OF THE THOR DUMMY

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ABSTRACT

A preliminary study was conducted to evaluate the side and oblique impact performance of the Thor thorax, pelvis and shoulder. After evaluating Thor's response, minor modifications were made and the response of the modified dummy was evaluated. Test protocols defined by ISO 9790 were used to conduct side pendulum impact studies on the thorax, shoulder and pelvis. Oblique impact tests were conducted using test protocols developed by the Medical College of Wisconsin (MCW) to test cadavers.

Details of test protocols used and comparisons of the dummy responses with appropriate cadaver corridors are presented.

KEY WORDS

Biomechanics, Thor, Side Impact, Thorax, Pelvis

THE THOR ADVANCED FRONTAL DUMMY was designed under funding from the National Highway Traffic Safety Administration (NHTSA). There were several features incorporated into the current Thor design which offered promise that the design could (with suitable modification) function well in the multidirectional test environment. These features included realistic thoracic ribcage geometry, accurate pelvic geometry, and multidirectional neck design. In addition, a pedestrian dummy named Polar was developed under funding from Honda, R&D, Japan. Polar was based on Thor. Polar exhibited quite human like response in pedestrian impact tests in what could be called "side impact like" conditions [Huang, 1999, Akiyama, 1999]. Therefore, a preliminary study was undertaken to assess the non-frontal performance of the Thor ATD.

The objectives of the testing were:

1. To evaluate the baseline performance of the existing Thor design in non-frontal conditions, and to assess the extent of design modifications required to bring Thor into compliance with established biomechanical corridors for these conditions.
2. More generally, to evaluate the feasibility of modifying and adapting the existing Thor ATD design to serve as a multidirectional test device.

This paper describes the test set ups in side and oblique impacts and the response of Thor. Response of the dummy is also compared with available cadaver corridors.

METHODOLOGY

A summary of test conditions, test set-ups and instrumentation used are provided in Table 1.

Table 1 : Test conditions

Test	Vel. , m/s	# of tests	Test Instrumentation
Lateral (23.5 kg impactor with 150 mm diameter rigid plate) impact to thorax. Arm removed on the impact side. [ISO N455; Section 4.2]	4.3 m/s, 6.7 m/s	20 20	a. T1 tri-axial accel. b. Mid sternal uni-accel. c. Impactor accel d. Impactor load cell e. Impactor LVDT (external deflection) f. Side ways CRUX (internal lateral deflection)
Lateral (17 kg impactor with a spherical 150 mm diameter rigid face) impact to pelvis. [ISO N455; Section 4.3]	4 speeds between 5.5 & 9.1 m/s	30	Same as above.
Lateral (23.5 kg impactor with 150 mm diameter rigid plate) impact to shoulder. [ISO N455; Section 4.1]	5.5 m/s	6	a. T1 tri-axial accel. b. Impactor accel c. Impactor load cell d. Impactor LVDT
Oblique (158 with a 23.5 kg impactor with 150 mm diameter padded plate) impact to lower thoracic cage. [Yoganandan, 1997].	4.3 m/s	20	a. CRUX upper and lower b. Impactor accel. c. Impactor LVDT d. Impactor load cell. e. Rear CRUX (dummy rigid body motion)

In each series of tests, the first few tests were conducted with the standard Thor to evaluate its response. After the first few reference tests, and if the Thor's performance was lacking, the following changes were made in the dummy and the tests repeated:

1. Confor foam was placed on the lateral aspect of the dummy's ribs. If Confor foam improved the performance of the dummy, it could be reasonably easily introduced into the jacket of the dummy.
2. The thoracic flexible joint (with two cables running through it for lateral stability) was replaced with one which had a single cable running through the centre. The single cable provides additional lateral flexibility and the design proved successful in producing the correct kinematics of the Polar pedestrian dummy [Huang, 1999].
3. Rib stiffeners were removed to evaluate their effect on the dummy's response.
4. Literature revealed that a Teflon sheet was often placed below the test subject's buttocks. Selected tests were repeated with the Teflon sheet placed under the buttocks of the dummy to evaluate the effect of using a Teflon sheet.

Dynamic test data were recorded on a PC based DAS system at 10,000 Hz. and filtered appropriately before analysis.

Even though a number of tests were conducted with several modifications to the dummy, only results from tests with modifications that yielded the best results are reported in this paper. The configurations of Thor that yielded the best results were :

1. **Configuration used in all lateral rib impact tests - Thor T6 (see Fig. 2)** : Thor modified without upper abdomen, with single cable thoracic and lumbar flex joints, compliant shoulder, 33 mm of Confor foam taped around the ribs in the impact area. A Teflon sheet is introduced under the buttocks of the dummy for tests.
2. **Configuration used for lateral impacts on the pelvis - Thor P2 (see Fig. 3)** : Thor T6 is modified with a sheet of Sorbathane wrapped around the upper femur brass piece, 33 mm thick Confor foam was inserted in the cavities in the upper femur flesh, a rubber puck of Shore A durometer 50 is used to replace the acetabular load cells on the impact side. *Thor P1 is the same as P2 except that it did not have acetabular rubber pucks.*
3. **Configuration used for MCW type tests - ThorA:** The upper abdomen of theThor was filled with a 114 mm block of blue Confor foam with a silicon pad in front to distribute the loads.

TEST SET-UP - THORAX LATERAL IMPACTS : Figure 1 shows the set-up used for the thorax lateral impact tests and Fig. 2 shows Thor T6 with the Confor foam pad in place.. For these tests, the thoracic pitch changing mechanism was set to achieve an erect position of the dummy. The dummy was seated in an erect posture on a flat, horizontal, rigid surface with legs straightforward and parallel to each other. Both arms were raised about the head. The centre of the impactor face was midway between the front and back of the dummy at the level of the lateral point of rib number 4. The set-up used here is similar to the one used by Robbins, et al [1979].

Figure 1 : Thor T6 set up for Lateral Impact

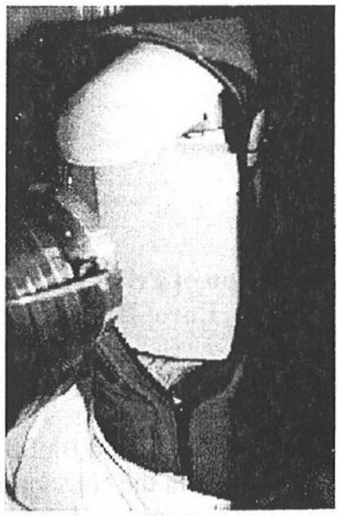


Figure 2 : Thor T6 showing Confor Foam

TEST SET-UP - PELVIC LATERAL IMPACTS : Figure 3 shows the modifications made to Thor pelvis. The rubber puck that was used to replace the acetabular load cells is visible. In addition, the upper femur brass piece seen in the Figure was wrapped with a sheet of Sorbathane and about 33 mm of Confor foam was inserted into the cavities in the upper femur flesh covering.

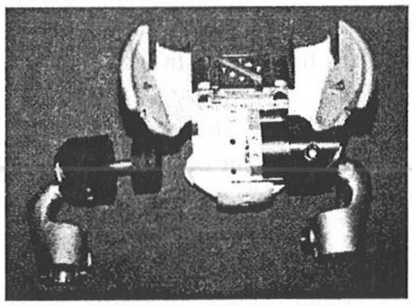


Figure 3 : Thor P2 Pelvis showing Acetabular Rubber Puck

Lateral impact tests were set up as required in ISO 9790. The 17.3-kg rigid impactor used was a segment of a sphere used in ONSER lateral pelvic tests. Impact was to the area of the greater trochanter. Four tests were performed with impact velocities between 5.5 and 9.1 m/s.

TEST SET-UP - MCW TYPE TESTS : The dummy is seated facing the impactor and rotated from right to left by 15 8. The dummy is placed in a slouched position on a Teflon sheet with no back support and was clothed in long underwear. The lower and upper extremities are stretched forward. The dummy is impacted at the anterior region of the right side at the level of rib 6. The impactor was covered with a 40-mm thick ensolite padding.

DISCUSSION OF RESULTS

PELVIS TESTS - Results of pelvis (Thor P1 and Thor P2) lateral impacts at various velocities are summarised in Figs 4 and 5. In addition Fig. 6 shows a comparison of the response of Thor P2 in repeated impact tests. Figure 7 shows a comparison of the impact response of the Thor P2 in right and left side impacts.

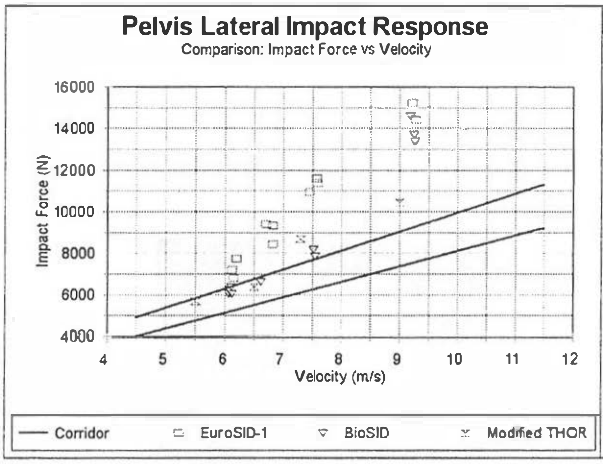


Figure 4 : Comparison of Pelvis Lateral Responses - Thor P2, EuroSID 1, BioSID

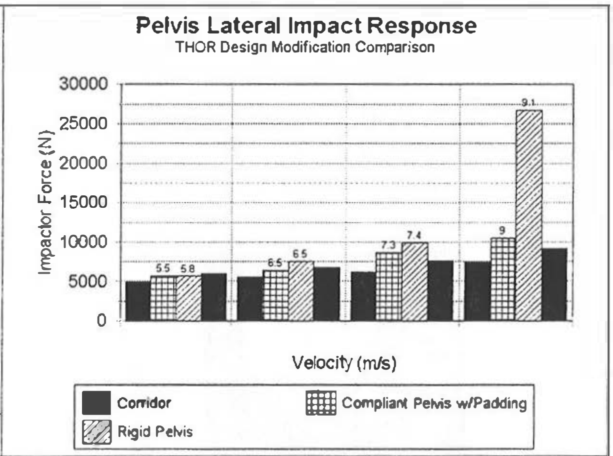


Figure 5 : Comparison of Responses Thor P1 and P2

Figure 4 shows the desired corridor together with the responses of Thor P2, BioSID and EuroSID-1 dummies. In these tests, Thor dummy has been modified as discussed in the Methodology section. This shows that Thor and BioSID are in the corridor for impact velocities upto 6.5 m/s. None of the three dummies are in the corridor above that impact velocity though at higher impact velocities (above 7.4 m/s), Thor response is closer to the corridor than the other dummies. It is seen that at about 9 m/s, the desired force level is about 9,000 N. Thor P2 shows a response of about 10,500N where as the BioSID's force level is around 13,500 N and that of the EuroSID-1 is about 14,300N. This might indicate that some more minor modifications to the design of the Thor pelvis and pelvic flesh might allow Thor to respond in a biofidelic fashion over the desired range of velocities.

Figures 5 shows a comparison of the impact response of Thor P1 (rigid pelvis) with that of Thor P2 (compliant pelvis w/padding). It is seen that the response of Thor P1 is somewhat similar to Thor P2 at the lower velocities but becomes increasingly stiffer above 7.4 m/s. At 9 m/s, the impact force for Thor P1 is approximately 26,500 N and Thor P2 is 10,500 N. The significant increase in force at 9 m/s is likely due to the upper femur flesh pad bottoming out in Thor P1, while in Thor P2, the acetabular rubber puck provides additional lateral compliance.

Figures 6 and 7 illustrate that the response obtained from Thor P2 is repeatable. Figure 6 shows the impactor force as a function of time for 3 tests on the left side of the dummy. It is seen that the response is quite repeatable. Figure 7 shows a comparison of the Force-time response of Thor P2 for left and right side impacts. Figure 7 illustrates minor discrepancies in the response of Thor P2 to right and left side impacts. This could be caused by minor differences in the set-up and also in configuration of the dummy.

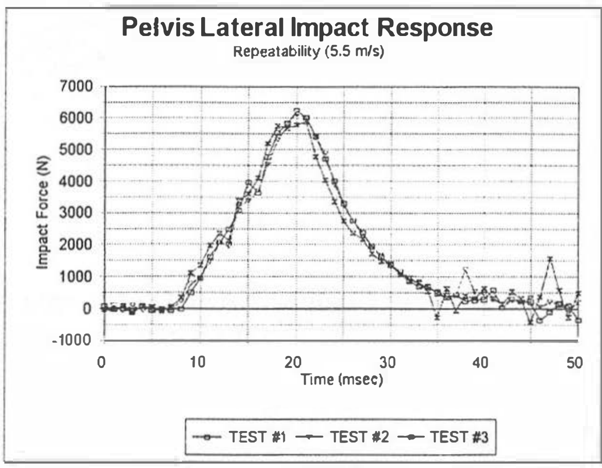


Figure 6 : Repeatability of Thor P2 Lateral Pelvis Tests at 5.5 m/s

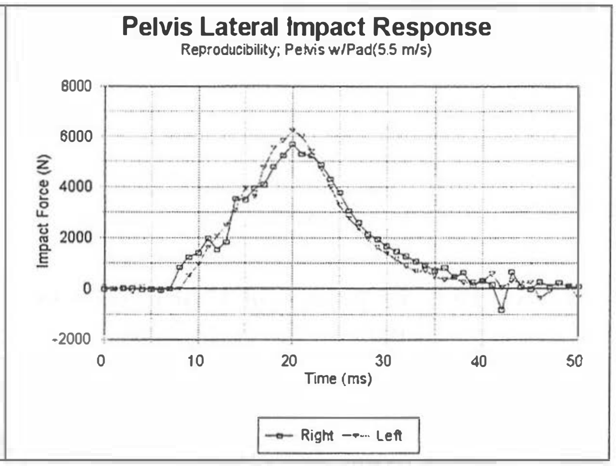


Figure 7 : Left and Right Side Thor P2 Lateral Pelvis Tests at 5.5 m/s

THORAX TESTS AT 4.3 m/s - Results of thorax lateral impact tests at 4.3 m/s are shown in Figs. 8 through 11. Figure 8 shows impactor force as a function of time for the BioSID, EuroSID and Thor T6. Figure 8 shows a comparison of the impactor force vs. time plots for Thor T6, BioSID and EuroSID - 1 and the desired response corridor. It is seen that Thor T6 stays in about the middle of the corridor through the impact event. A similar trend is seen in Figure 9 which compares the T1Y acceleration vs. time response of Thor T6, BioSID and EuroSID - 1. In Fig. 9 too, the acceleration of Thor T6 is closer to the corridor than the other two dummies.

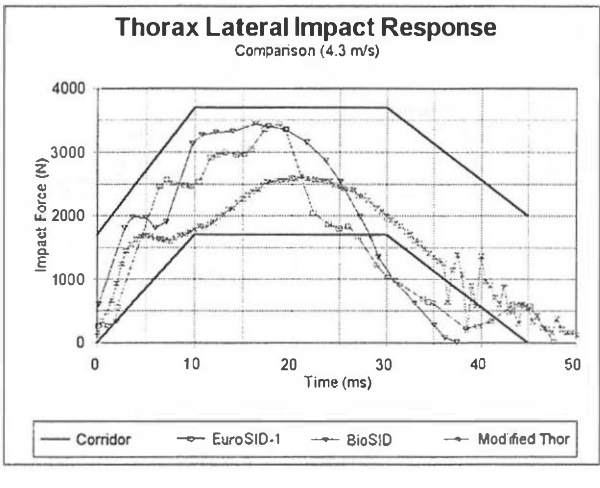


Figure 8 : Thorax Lateral Response at 4.3 m/s Impactor Force Vs Time

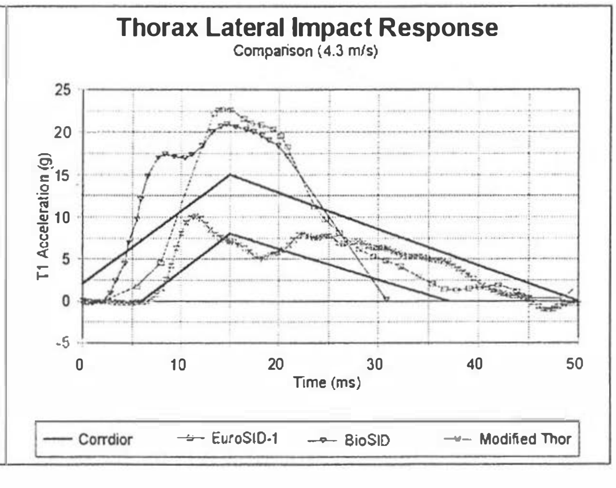


Figure 9 : Thorax Lateral Response at 4.3 m/s T1Y Vs Time

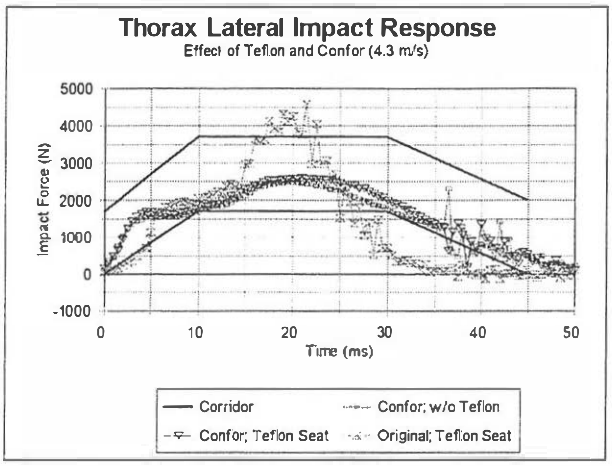


Figure 10 : Comparison of Thor Responses Impactor Force Vs Time

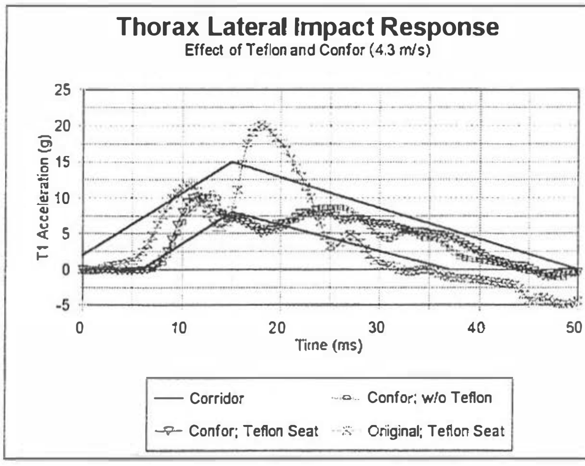


Figure 11 : Comparison of Thor Responses T1Y Vs Time

Figure 10 shows a comparison of the impactor force vs. time response of the unmodified Thor dummy with Thor T6. This plot also compares the response of Thor T6 with and without a Teflon sheet under the dummy's pelvis. It is seen that unmodified Thor's rib structure is stiffer than that of Thor T6.

A similar comparison of the T1Y accelerations is illustrated in Fig. 11. The levels of T1Y acceleration do not seem to depend on the presence or the absence of the Teflon sheet. A comparison of data plotted in Figs. 9 and 11 show that the T1Y acceleration of unmodified Thor (peak value 20g at about 18 ms is similar those of BioSID (peak value 20g at about 15 ms) and EuroSID-1 (peak value of 22g at about 14 ms).

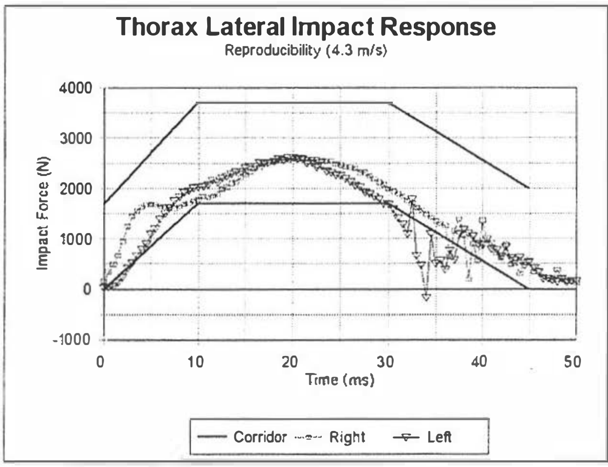


Figure 12 : Repeatability of Thor T6 Thorax Lateral Tests at 4.3 m/s

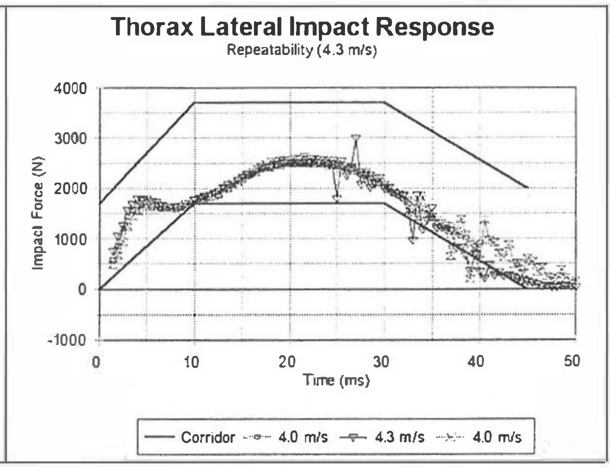
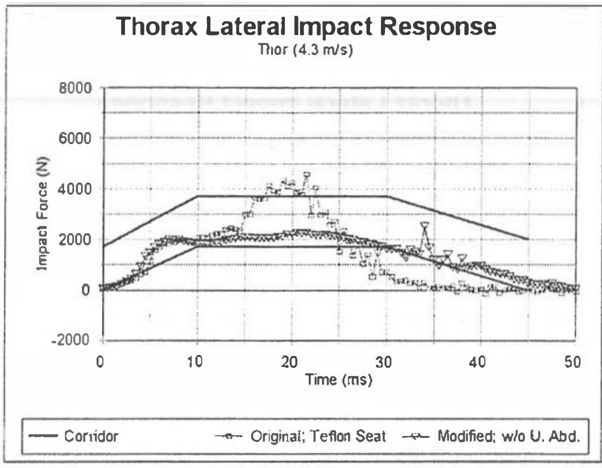


Figure 13 : Right and Left Hand Lateral Impacts on Thor T6, 4.3 m/s

Repeatability of Thor T6's response is illustrated in Fig. 12. In this figure, impactor force is plotted against time for 3 impact tests. The response corridor is plotted for comparison.

Impact tests were conducted on the left and right hand sides of Thor T6 to evaluate its side to side performance. Figure 13 shows a plot of impactor force against time. It is felt that the minor differences in the impactor force could be due the slight differences in set-up and configuration of the dummy.



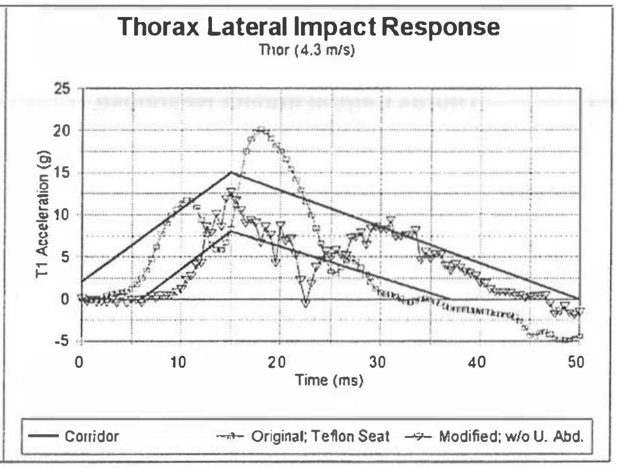


Figure 14 : Effect of Removing Abdomen on T6 Impactor Force Vs Time

Figure 15 : Effect of Removing Abdomen in T6 T1Y Vs Time

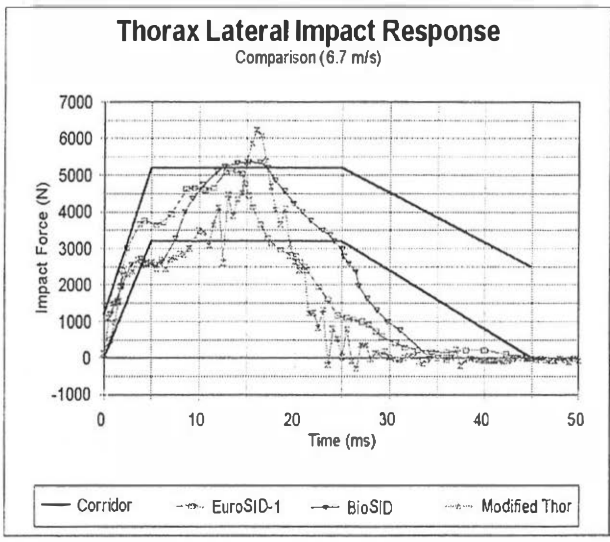
Since our aim was to investigate as many possible simple design changes within time and budgetary constraints, it was decided to evaluate the performance of Thor when the upper abdomen was removed. In Thor, the upper abdomen in the form of a bag containing foam is attached to the lower 3 ribs. This serves to couple the two sides of the thorax quite closely. Figures 14 and 15 illustrate the effect of removing the upper abdomen. In these figures, impactor forces and T1Y acceleration, respectively, of Thor with a single cable lumbar spine are compared with an unmodified Thor sitting on a Teflon sheet. The results of this indicate that the stiffness of the Thor thorax can be modified significantly by the removal of the upper abdomen.

THORAX TESTS AT 6.7 m/s - Results of tests conducted at 6.7 m/s on Thor T6 are shown in Figures 16 through 18.

Figure 16 shows a comparison of the force vs. time response of Thor T6 with that of the BioSID and EuroSID-1 dummies. It is seen that the force level of Thor T6 is about 20% higher than the corridor. It also points out a need for an improvement in the pulse width.

T1Y acceleration vs. time responses for all three dummies are shown in Fig. 17. A comparison of the time to peak acceleration and force in Figs. 16 and 17 seem to point out that the rib structure is strongly coupled to the spine. This kind of coupling between peak T1Y acceleration and peak impactor forces is also seen in cadaver tests.

As in the 4.3 m/s tests, the upper abdomen of Thor was removed and the dummy tested at 6.7 m/s in this configuration. Figure 18 shows impactor force vs. time trace for this test. A comparison of data in Figs. 16 and 18 indicates that removal of the upper abdomen does not modulate the impactor force quite as much as in the tests at 4.3 m/s.



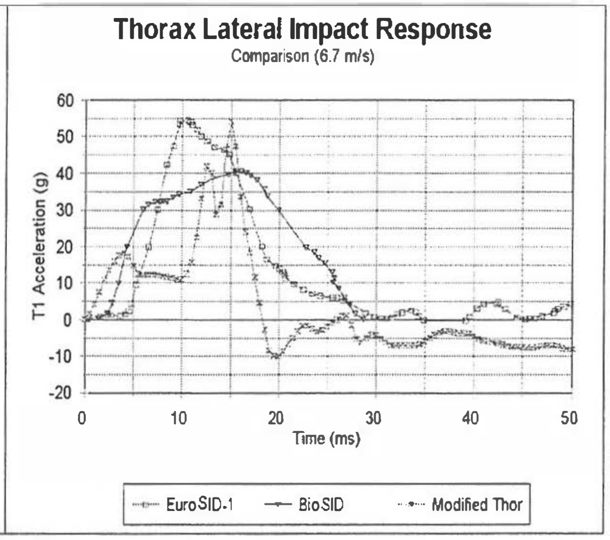
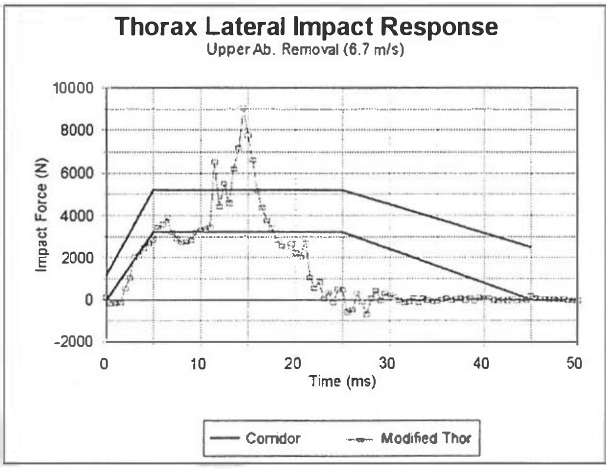


Figure 16 : Comparison of Thor T6 Impactor Force at 6.7 m/s with BioSID and EuroSid 1

Figure 17 : Comparison of Thor T6 T1Y Acceleration at 6.7 m/s with BioSID and EuroSID 1



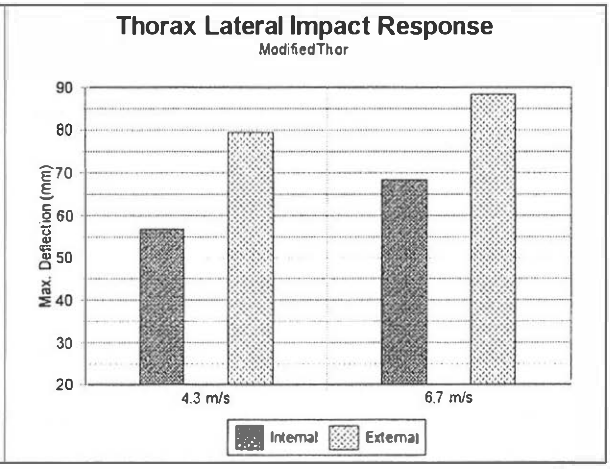


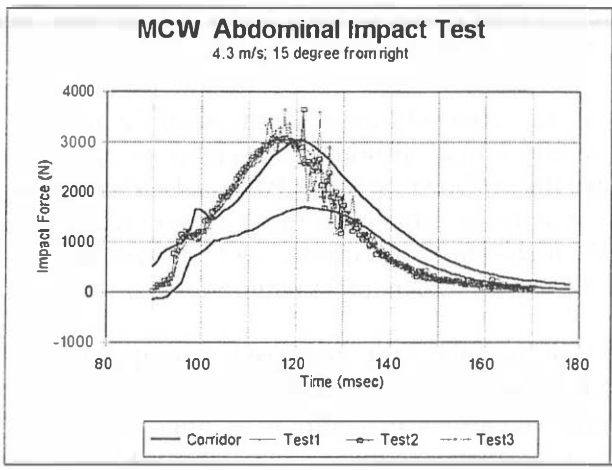
Figure 18 : Impactor Vs Time for Thor T6 with Upper Abdomen Removed

Figure 19 : Comparison of Thor T6 Internal And External Deflections at 4.3 & 6.7 m/s.

COMPARISON OF INTERNAL AND EXTERNAL DEFLECTIONS - Internal deflection at Rib 4 of Thor P6 was measured using the CRUX oriented side ways. In these tests, the travel of the linear impactor was also measured using a LVDT. Figure 19 shows a comparison of the internal and external rib peak deflections in Thor T6 at 4.3 m/s and at 6.7 m/s. It is pertinent to note that the internal deflection of about 70-mm at 6.7 m/s is comparable to the upper limits set for calibration tests of the BioSID.

LOWER THORACIC CAGE (MCW TYPE TESTS) : One of the design requirements for Thor was that it meet the corridors for oblique impact tests to the lower cage. The cadaver tests used to generate the corridors were conducted at the Medical College of Wisconsin (MCW). [Yoganandan, et al. 1997, Kuppa [1999]]. Protocol used in MCW cadaver tests was used to test the Thor dummy.

The original foam combination in the upper abdomen was replaced with a 114 mm block of blue confor foam. In addition, a thin layer of Silicone rubber (3.2 mm thick) was placed in front of the foam to distribute loading. The results of this test are shown in Figs. 20 and 21.



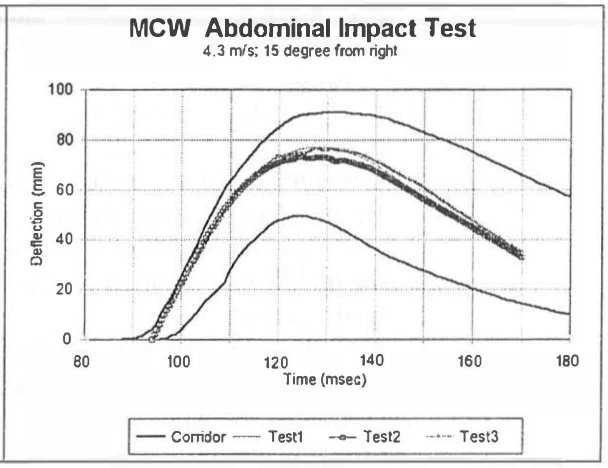


Figure 20 : Impactor force – Time Plot for ThorA in MCW Type Test

Figure 21 : Deflection – Time Plot for ThorA in MCW Type Test

Figure 20 compares the impactor force vs. time response of ThorA in MCW type tests with the cadaver corridor which has been adjusted to account for the effect of musculature [Kuppa, 1999]. The impactor loads are at the upper ranges of the corridor. The force peaks a little early. Figure 20 shows the results of 3 sets and it can be seen that the response is repeatable and is in the middle of the response corridor. The oscillation seen in the Force traces from test 3 was caused by a loose bearing on the impactor.

In these tests, the rigid body motion of the dummy was measured using a CRUX connected to the test stand at one end and the dummy spine at the other. The external deflection of the abdomen was measured using a LVDT connected to the impactor. Rigid body motion of the dummy was subtracted from the external deflection. The compression of the pad on the face of the impactor was then subtracted from this value to obtain, the corrected external deflection of the abdomen. Corrected external abdominal deflection for three tests is shown in Fig. 21.

SHOULDER IMPACT TESTS : Shoulder impact tests were conducted to evaluate the lateral impact performance of Thor shoulder. It was noted that the shoulder structure is quite stiff and needs improvement in its design.

OVERALL DURABILITY OF THOR - In all, about 40 tests on the thorax and about 50 tests on the pelvis were conducted as a part of this effort. No major damage to was observed to the ribs or to the pelvis. The pelvis flesh was slightly damaged possibly due to problems in the moulding process. Repeatability tests on the thorax conducted after about 10 tests (please see Fig. 9) and after about 20 tests on the pelvis (please see Fig. 4) seem to indicate that there were no structural damage to the dummy. In addition, approximately 20 MCW type tests were run with Thor without any observable damage to the dummy.

CONCLUSIONS

Lateral pendulum impacts of unmodified and appropriately modified Thor have been conducted using the requirements of the ISO 9790 and test results from the Medical College of Wisconsin as guides. The results of this preliminary study suggest that the modifications necessary to bring the current Thor ATD design into compliance with these requirements are feasible, and that the existing design provides a promising and workable platform for adaptation to multidirectional use. More specific results are as follows:

1. Simple modifications to Thor seem likely to bring its thoracic response closer to the requirements of ISO 9790. There is a need reduce to force levels and increase pulse width at 6.7 m/s. However, the dummy seems to perform very well in the 4.3 m/s tests.
2. Pendulum tests to the pelvis indicate that relatively simple changes can be made to the pelvic structure, pelvic and upper femur flesh to bring Thor closer to the required corridors (and also perhaps improve the performance of the Polar pedestrian dummy).
3. Response of the lower thoracic cage of the Thor is similar to the cadaver response. The impactor force levels are on the high side of the corridor while the deflection is in the middle of the corridor. Thus, the current design might require some modifications.
4. The shoulder structure of the Thor is quite stiff and needs modification. An improvement in the side impact response of the shoulder might improve the biofidelity of Thor's thoracic structure also. In addition, it might improve the kinematic performance of the Polar pedestrian dummy.
5. There are several other simple modifications such as changes in the shape and stiffness of the lumbar spine which have to be investigated.

ACKNOWLEDGMENT

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