PREDICTION OF THORACIC INJURIES IN FRONTAL COLLISIONS

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Paper Number98-S7-O-04

ABSTRACT

The frontal collision is the most frequent collision type observed in real accident investigations. The impact severity depends on the overlap of the vehicle with the obstacle which also determines the average deceleration of the car and subsequently the loading of the car occupant. The injury severity depends upon anthropometric parameters and the mechanical response. To investigate these relationships 46 frontal collisions with cadavers were performed. The impact velocity was 47-55 km/h, the average sled deceleration 10-20 g. The subjects, 36 males and 10 females, were aged between 19 and 65 years and were protected with 3-point standard belts, driver air bag - knee bolster, 3-point belt combined with air bag. The injuries were defined through medical investigation during the autopsy in situ or on isolated body parts in a more detailed manner later; the injury severity was coded in accordance with the AIS 90.The most injured body part was the thorax, usually rib fractures were found. The number of rib fractures includes uninjured cases up to 17 rib fractures with thoracic injury severity between AIS 0 and AIS 4. The fracture pattern was characteristic for the restraint system used. Logistic regression analysis was used to predict the probability of injury severity for the explanatory variables. To further restrain the subset of predictors Kruskal-Wallis and F-test were applied. Chest accelerations are suitable parameters to predict thoracic injury severity. By modelling the data with logistic regression models the best biomechanical predictor for the thoracic injury severity according to different goodness of fit criteria was the acceleration measured at the 1st thoracic vertebra. These evaluations take into account only the injury severity and the mechanical response, independent of the restraint system used and the impact severity.

INTRODUCTION

The frontal collision is the most frequently occurring accident type and is the accident type towards which the majority of safety measures have been directed. Due to extensive developments in passive safety and the effective combination of active and passive safety systems, a high standard of injury reduction for frontal collisions has been achieved. The aim of this study is to investigate the behaviour of the standard 3-point belt, an air bag only, and belt plus air bag systems in frontal collisions. The collision characteristics of 47 km/h to 55 km/h with a mean sled deceleration between 10g and 20g were chosen to represent common accident severities.

Method

Test Subjects - The test subjects were 46 unembalmed cadavers in the age range 19 to 65 years.

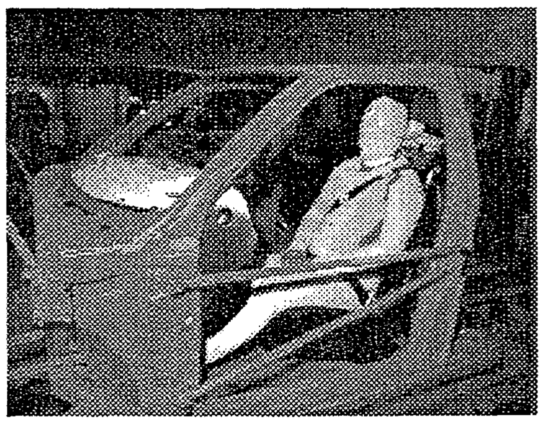


Figure 1:Test configuration

Test Equipment - The tests were performed on the University of Heidelberg's deceleration sled. Mounted to the sled was the front part of a passenger compartment of a mid-sized car. Test subjects were positioned in the driver's seat and restrained by either a 3-point belt, a driver side air bag-knee bolster, or a 3-point belt with supplemental driver side air bag combination. Figure 1. illustrates the experimental configuration. Frontal collisions were simulated with impact velocities of 47 to 55 km/h and a trapezoidal deceleration pulse with an average value of 10 g to 20 g. A test matrix according to the restraint system is given in table 1.

Table 1: Impact conditions according to the restraint system used

Restraint system		3-pt-belt	Air bag	3-pt-belt & Air bag
n		29	7	10
Impact speed [km/h]	range	48-55	47-50	47-53
	mean	50	49	49
Average sled dec. [g]	range	10-20	10-17	10-18
	mean	15	14	13
Age [years]	range	19-63	25-55	32-65
	mean	36	37	49

Instrumentation - In a part of the tests, the subject's thorax was instrumented with a twelve-accelerometer array (Eppinger et al., 1978). In some of the tests, a tri-axial accelerometer array was attached to Th 6. Furthermore tri-axial accelerations at the pelvis and shoulder belt forces were measured.

Autopsy / Injury Severity - For each cadaver, a full autopsy was performed. The injuries were coded according to the AIS 1990.

Statistical Methods

The statistical analysis aims at investigating the factors which influence the thoracic injury severity (AIS-level) and explain it on the basis of the cadaver anthropometric data and the most relevant biomechanical data (anthropometric and mechanical predictors).

As the different AIS values are measured on the ordinal scale (0 to 5), the analysis of variance based on rank scores (F-Test) (Agresti, A., 1984; Lehmann, E.L., 1979) has first been performed in order to determine whether the distribution of the predictors have the same location parameters across the injury levels. The Kruskal-Wallis chi-square approximate statistic (H-Test) (Bikel, P. J. and Doksum, K.A. ,1977; Hosmer, D. W. Jr. and Lemeshow, S., 1989), based on the empirical distribution has also been considered. Further, graphical statistical methods (box plots, Agresti, A., 1984) have been used for making distributional comparisons.

For modelling the data, logistic regression models (Draper, N. and Smith, H., 1981) have been applied to the most suitable explanatory variables. The regression part of these models, i.e. a linear combination of the values of the explanatory variables and the regression coefficients, is a logistic transformation of the probabilities of the response categories given by the function:

$$Y=ln(x/(1-x)),$$

which transforms the interval between 0 and 1 on the real axis ($-\infty$; $+\infty$), so that probabilities transformed by the logistic function will be *stretched* out over the complete real axis. For a binary response probability p the linear regression model becomes:

$logit(p)=ln(p/(1-p))=\alpha+\beta\cdot x$. Therefore, letting $LOW=(AIS\leq 2)$ and $HIGH=(AIS\geq 3)$ our model reduces to:

$logit(p(HIGH))=\alpha+\beta x$. For the ordinal response AIS with values $0,1,2,...,5$ the logistic model has the form:

$$logit(p(AIS<=i))=\alpha i+\beta i\cdot x \qquad 0<=i<=4$$

where $\alpha 0,\ \alpha 1,...\alpha 4$ are the intercept parameters of the four parallel regression lines and is based on the cumulative distribution probabilities of the AIS levels. For a value of the independent variable x in the fitted model, the estimated probability of the response is given by replacing the regression coefficients $\alpha,\ \beta,\ \alpha i,\ \beta i$ *by their Maximum Likelihood Estimator.*

Prediction Ability and Quality of Fit Criteria (Cox, D.R. and Snell, E. J., 1989, Draper, N. and Smith, H., 1981, Linhart, H. and Zucchini, W., 1977). For comparing different models and assessing model fit the following criteria have been considered.The *-2log Likelihood* statistic:

$$-2log\ L=-2\sum_j log(pj)$$

where the estimate pj of the probability $P(Y=yj)$ is obtained by replacing the regression coefficients by their Maximum Likelihood Estimate (MLE). $-2log\ L$ has a chi-square distribution under the hypothesis that the explanatory variables in the model are zero, therefore the p-value for this statistic gives a test for the effects of the covariates.

For assessing the predictive ability of a model, the following indexes of rank correlation between the observed responses and predicted probabilities have been calculated: *Somers'D, Goodman-Kruskal Gamma* and *Kandall's Tau-a.* For the binary response models, *HIGH/LOW* the 2x2 frequency table of observed and predicted responses has been calculated. The response *HIGH* is predicted to be an event if the estimated probability p is greater than, or equal to the critical level 0,5 otherwise it is predicted to be a no event. The classification table is therefore obtained by counting the number of observations for each of the following four categories:

	Observed	Predicted
1	event	event
2	event	no event
3	no event	event
4	no event	no event

Sensitivity is the proportion of event responses that were predicted to be *event*.

Specificity is the proportion of *no event* that were predicted to be *no event*.

A pair of input observations with different response *LOW/HIGH* is, said to be concordant if the observation with response *HIGH* has the lower predicted event probability. Therefore, the association between predicted probabilities and observed responses can also be measured on the basis of the number of concordant and discordant pairs carried out by categorizing the predicted probabilities into intervalls of lenght 0.002.

To compare different models it is important of course to look at different criteria simultaneously, since a good model should not be too bad in any one of the choosen criteria.

RESULTS

Mechanical Response - Figures 2 & 3 show the mean maxima and 3ms values of the measuring locations. The highest values were found at the lower sternum by using air bag restraint systems. The highest values at the left lower rib were measured by using 3-point-belt systems. Generally the values measured at the spine and pelvis are higher for airbag restraints. Also the measuring location upper sternum shows higher mean values for air bag restraints. The lowest mean values were observed at the left and right upper ribs for all restraint systems used. The combination 3-point-belt and air bag show generally the lowest values of the restraint systems used.

Medical Findings

Injury Pattern - Figures 4 - 6 show characteristic fracture patterns for the three restraint systems used. By using 3-point-belt systems the fractures are located mainly at the shoulder belt path, whereby by using only air bag restraints the front axillar line is involved. By using a standard belt in combination with a driver air bag the shoulder belt mainly defines the fracture pattern.

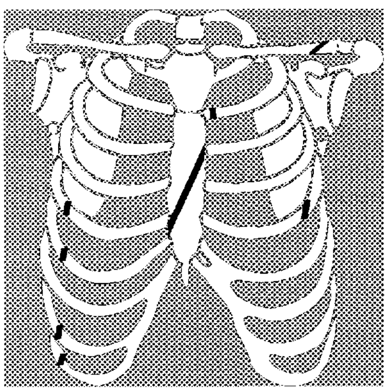


Figure 4: Injury pattern 3-point belt

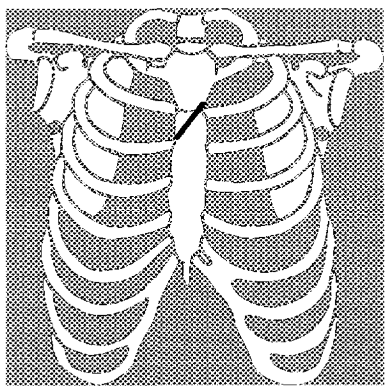


Figure 5: Injury pattern 3 point belt-air bag

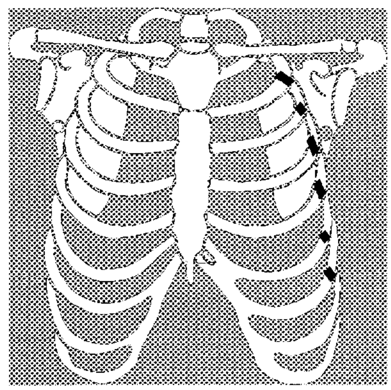


Figure 6: Injury pattern driver air bag

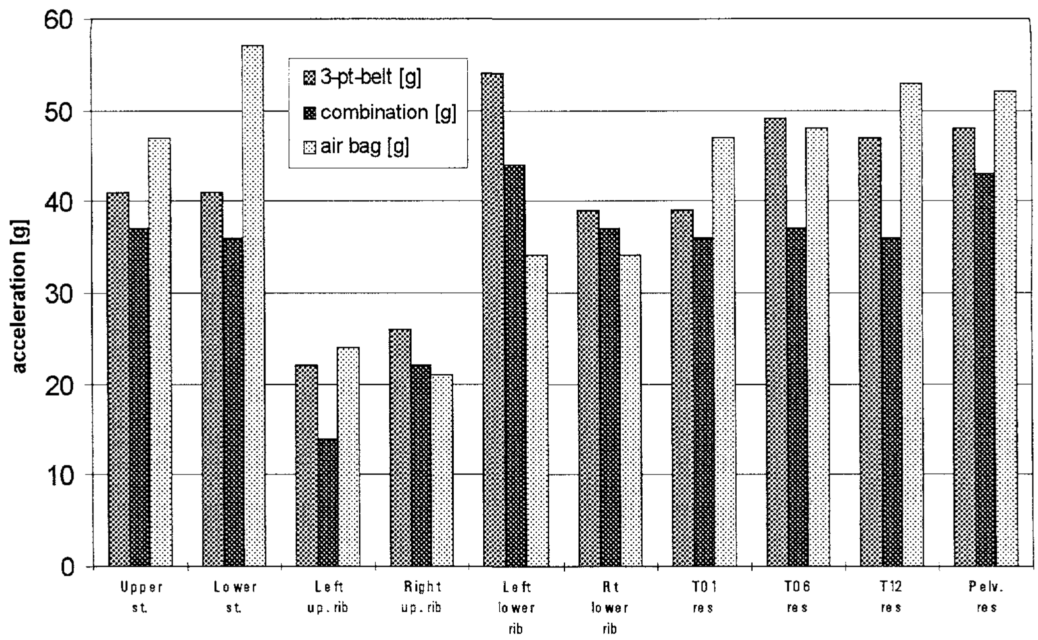


Figure 2: Maxima mean values of the measuring locations for the restraint system used

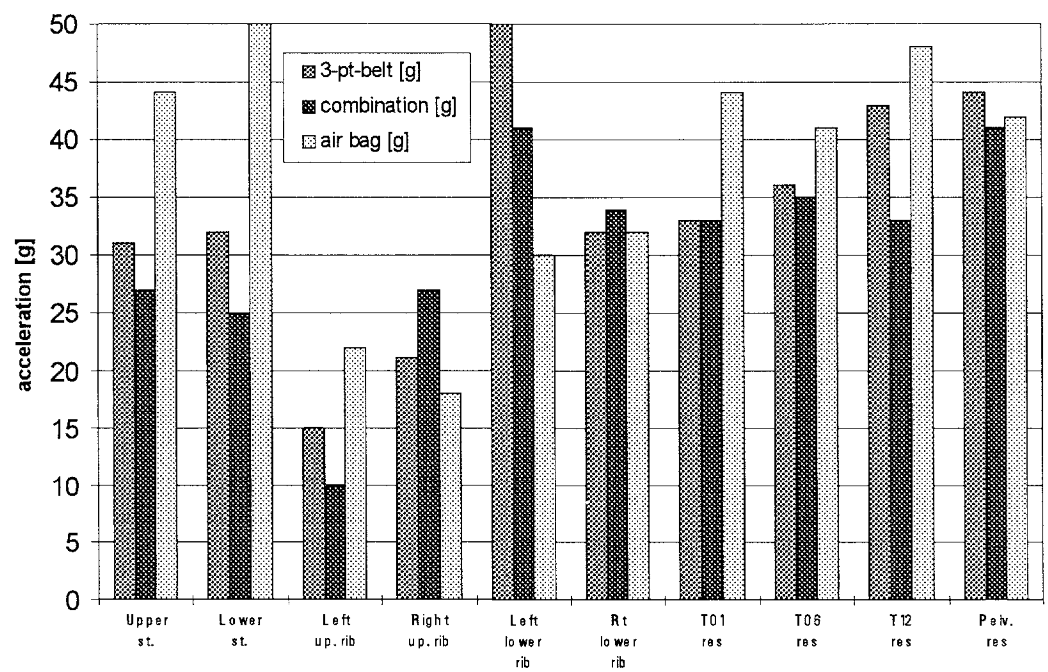


Figure 3: 3ms mean values of the measuring locations for the restraint system used

Skeleton Fractures - Thirty-four of the fourty-six tests conducted show thoracic injuries. The most frequent injury type were rib fractures, which also defined the thoracic injury severity; up to 17 rib fractures were observed, which were usually incomplete fractures.The number of rib fractures and the injury pattern is influenced mainly by the type of restraint system used. Figure 7 shows the frequency of the fractures of each rib for the three restraint systems used. The highest numbers of the rib fractures were observed when a 3-point belt was used. The first to ninth rib are involved, whereby the most fractured ribs were the second and the third one. By using only an air bag restraint system in one case the 2nd to 7th left rib at the front axillary line were broken, in a further case a fracture of the 6th right rib at the front axillary line was observed. The second most frequently fractured bones were the sternum and in some cases also the clavicle; in both of these bones the fracture pattern was defined through the belt path.

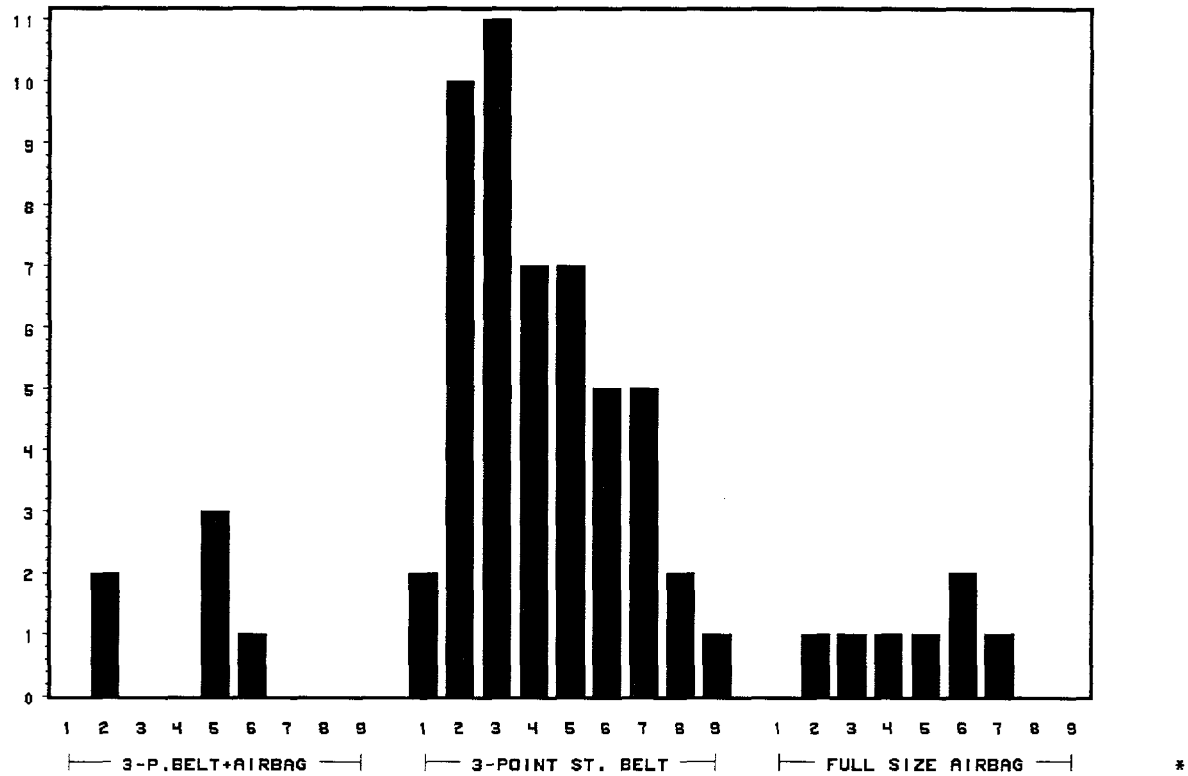


Figure 7: Frequency of the number of rib fractures according to the restraint system

Thoracic Injury Severity - The thoracic injury severity was rated according to the AIS 90 and our own biomechanical experience. Essential for the injury severity was the number of rib fractures. Soft tissue injuries like transfixing of the pleura or the lungs were rare. The collective with the 3-point belts is the most frequently injured sample and includes AIS severities between 2 and 4, whereby the AIS 2 and AIS 3 degrees are more frequent, the AIS 4 was concerned in 17% of the whole group. In the collective using only the air bag a case with AIS 1 (one rib fracture) and a second one with AIS 3 (six rib fractures) were observed. The sample using the combination of 3-point belt and air bag shows also lower thoracic injury severities than the one using only 3-point belt (Fig. 8).

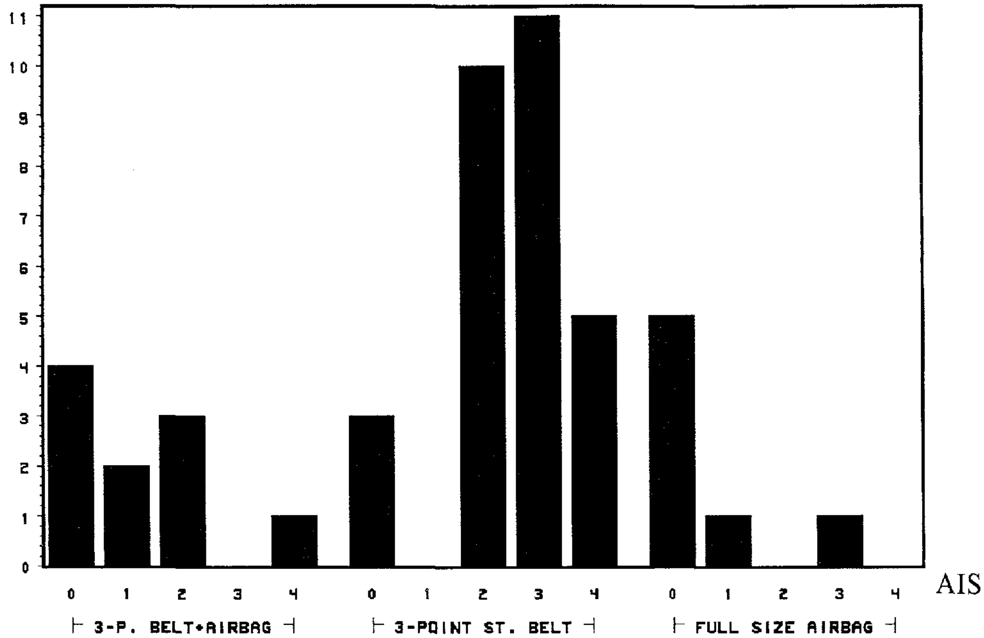


Figure 8: Frequency of the thoracic injury severity according to the restraint system

__Location of the Thoracic Skeleton Fractures__ - Fig. 9 shows the location of the thoracic skeleton fractures. By using 3-point standard belt the complete front of the skeleton beginning at the front axillar line left to the front axillar line right includes fractures. The highest frequencies were observed at the sternum (M11, Fig. 10) and the parasternal region left and right (L09, R06, Fig. 10).

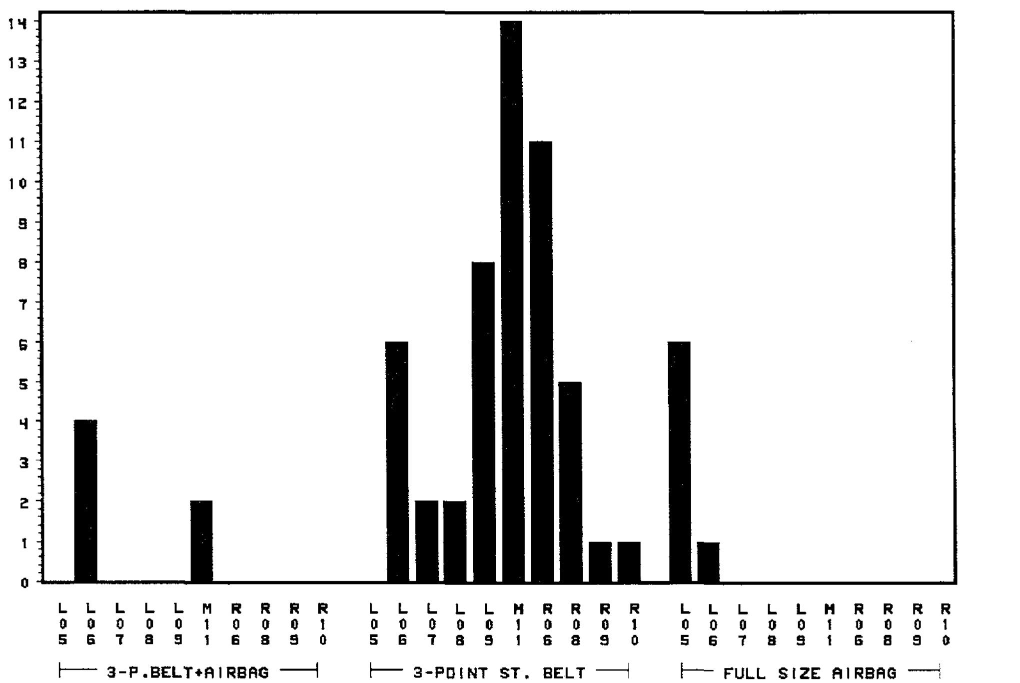


Figure 9: Frequency of the location of the rib fractures according to the restraint system

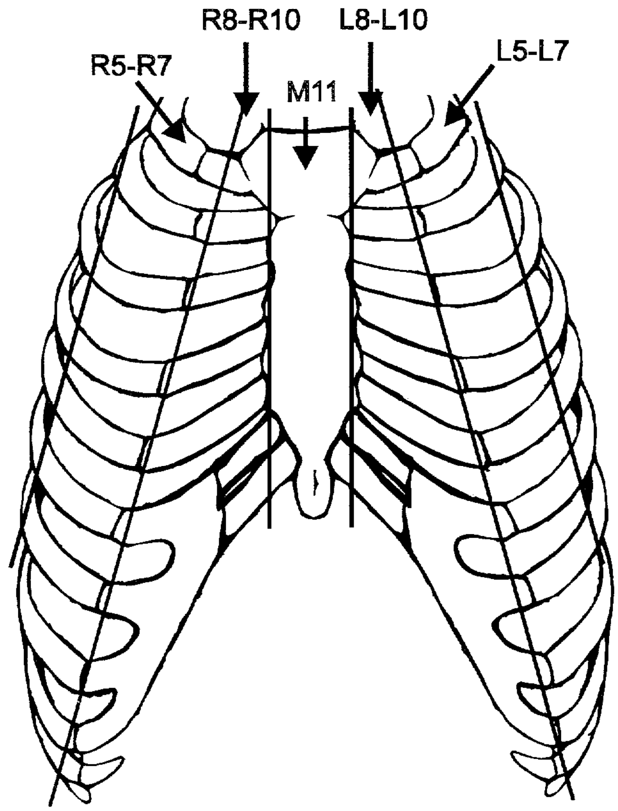


Figure 10: Location of the skeleton fractures by using 3-point belts.

Spinal Column Injuries - The second frequent type of injuries observed were the vertebral column injuries. They were located from the middle cervical spine to the upper thoracic vertebral column. The most frequent injuries were haemorrhages of the intervertebral discs, lacerations of the ligaments and compression fractures of the vertebral bodies. Also for this type of injuries the collective of the 3-point belt usage shows higher frequencies, the lowest numbers were found, if an air bag was used.(Fig.11). The injury severity was scaled according to the AIS 90 for the vertebral column and ranged from AIS 0 to AIS 3.

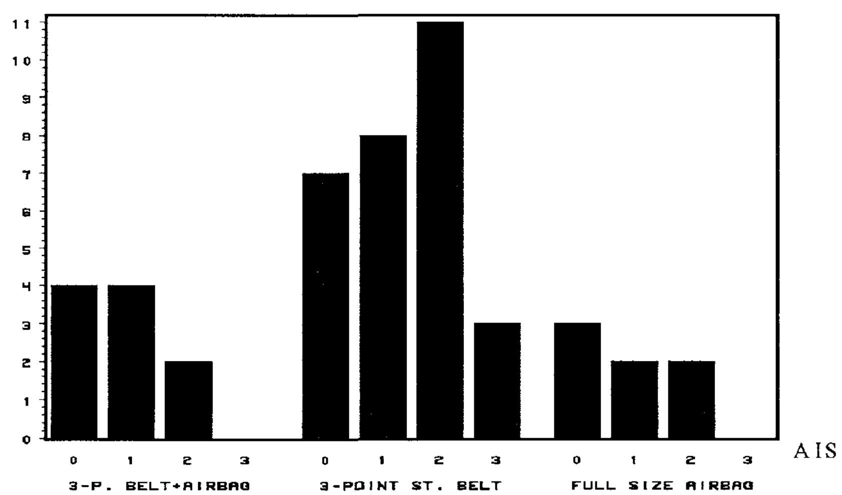
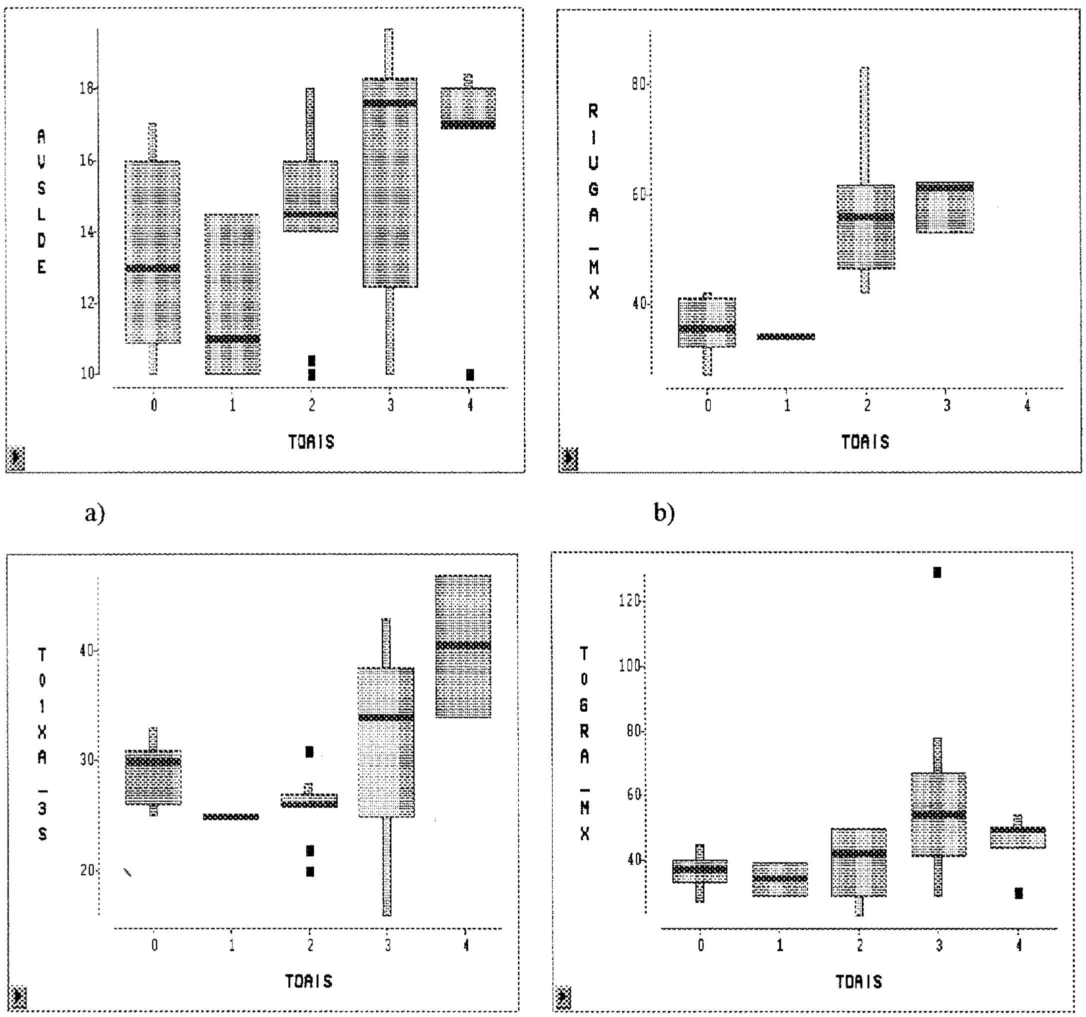


Figure 11: Frequency of the spinal column injury severity according to the restraint system

Abdomen Injuries - Only in 5 cases abdominal injuries were observed if a 3-point belt was used. In four tests liver ruptures sized between 2 cm long and 5 mm deep to 30 cm long (laceration of the capsule) and 3 cm deep were found, in one case a 1*1 cm sized laceration of the small intestinal mucosa was observed.

Statistic Evaluations

Figure 12 illustrates the parallel box plots of some of the variables which show good correlations with the thoracic AIS levels. The plots indicate the median (AIS levels, bold line), the upper and lower quantiles Q(.5), Q(0.25) (box) of the empirical distributions over the AIS levels. The mechanical response maximum acceleration at the fourth left rib (RIUGA_MX) shows distribution differences among the AIS levels: the median values increase clearly with the thoracic injury severity degree



c) d)

Figure 12: Box plots over the thoracic Injury Severity levels (TOAIS) for
a) Average Sled Deceleration (AVSLDE)
b) Max. Acceleration at Left Upper Rib (RIUGA_MX)
c) 3ms X-Acceleration at the 1st thoracic vertebra (T01XA_3S)
d) Max Res. Acceleration at the 6th thoracic vertebra (T06RA_MX)

The results of the statistical analysis suggest that the thoracic injury severity does not depend on the cadaver anthropometric parameters. Table 2 shows the significance levels of the Kruskal-Wallis and F-Test for the choosen variables.

Variable Name	Variable Label	Kruskal-Wallis Test:Prob>CHISQ.	F-Test: Prob>F
AGE	Age	0.0175	0.0014
AVSLDE	Average Sled Deceleration	0.0471	0.0570
RIUGA_MX	Max. Acceleration at upper Left Rib	0.0088	0.0007
T01XA_3S	3ms X-Acceleration at 1st vertebra vertebra	0.2374	0.0532
T06RA_MX	Max. Acceleration at 6th vertebra	0.1380	0.2020

Table 2: Analysis of variance, Tests results: Kruskal Wallis Chi square and F Test for the more relevant covariates.

We have found that, while the parameter **Age of Test Subject**, is for the thoracic injury severity significant at level 0.02 according to both Tests, modelling the data using only this parameter does not provide good prediction results.

The Kruskal-Wallis Test is not significant for **T01XA_3S** (3Ms X-Acceleration at the 1st thoracic vertebra) and **T06RA_MX** (Max. Res.-Acceleration at the 6th thoracic vertebra), which indicates that, because of high number of missing values, statistics based on empirical distributions schould not be considered.

Table 3 shows the M.L.E. for α and β in the logistic regression model by predicting thoracic injury severity ≥ 3. For all covariates the Estimates β are below 0.3 which means that the considered covariates influence the prediction of thoracic injury severity ≥ 3.

Model	Estimate α	Estimate β
TOAIS3=AVSLDE	-4.7668	0.2925
TOAIS3=RIUGA_MX	-5.7512	0.0797
TOAIS3=T01XA_3S	-7.2478	0.2067
TOAIS3=T06RA_MX	-4.1978	0.0991

Table 3: M.L.E Estimates for α and β, prediction of thoracic injury severity ≥ 3.

Tables 4 to 5 show the probability analyses according to the choosen criteria.

Variable	-2 Log L	Prob>CHISQ
AVSLDE	63.866	0.0071
RIUGA_MX	14.967	0.0322
T01XA_3S	19.892	0.0152
T06RA_MX	27.342	0.0070

Table 4: Prediction of thoracic injury severity ≥ 3, regression analysis: Testing Global Null Hypothesis: $\alpha=\beta=0$.

Table 4 shows that for all the choosen covariates the global null hypothesis $\alpha=\beta=0$ should be rejected.

Variable	Prob>CHISQ for Estimate α	Prob>CHISQ for Estimate β
AVSLDE	0.0299	0.0701
RIUGA_MX	0.0099	0.0139
T01XA_3S	0.0323	0.0579
T06RA_MX	0.0412	0.0374

Table 5: Prediction of thoracic injury severity ≥ 3, regression analysis: analysis of MLE

Table 5 shows that for all the covariates the Chi square test for the estimates α and β is significant, which means that the null hypothesis $\alpha=0$ or $\beta=0$ should be rejected.

Among all the accelerations at ribs and spine the best predictors for **Injury Severity ≥ 3** are **RIUGA_MX** (Max. Acceleration at Left Upper Rib), **T06RA_MX,** and most notably **T01XA_3S** which achieved by *81.8%* the highest proportion of correct predicted *event/no event* by critical probability level 0.5 (Table 6). As shown in Table 6 the model has also the highest specificity value.

Variable	Sensitivity%	Specificity%	Correct predicted
AVSLDE	68.4	85.7	78.7
RIUGA_MX	25.0	93.3	78.9
T01XA_3S	33.3	100.0	81.8
T06RA_MX	76.9	75.0	76.0

Table 6: Prediction of thoracic injury severity ≥3, regression analysis: classification table at critical probability level 0.5.

The highest correlation between predicted and observed probabilities according to both Sommers'D and Gamma statistics has been reached by modelling the data with **RIUGA_MX** (Table 7).

Variable	Concordant %	Discodant %	Sommers' D	Gamma
AVSLDE	72.9	22.7	0.502	0.525
RIUGA_MX	83.3	13.3	0.700	0.724
T01XA_3S	83.3	16.7	0.667	0.667
T06RA_MX	78.2	21.2	0.571	0.574

Table 7: Prediction of thoracic injury severity ≥3, regression analysis: association of predicted probabilities and observed responses.

An other important predictor is also the **Average Sled Deceleration**. Although values of correlation between predicted and observed probabilities remain below the value of 0.53 the model has a high sensitivity and provide also good results according to the other choosen criteria (Table 7).

Figures 13-16 show the logistic regression plots with the upper and lower confidence curves of probability of thoracic injury severity ≥3 modelled by the choosen covariates. Looking at the confidence bands, one can notice that the prediction accuracy remains good over all values of the average sled acceleration. For the other covariates because of the number of missing observations the accuracy goes down by higher values.

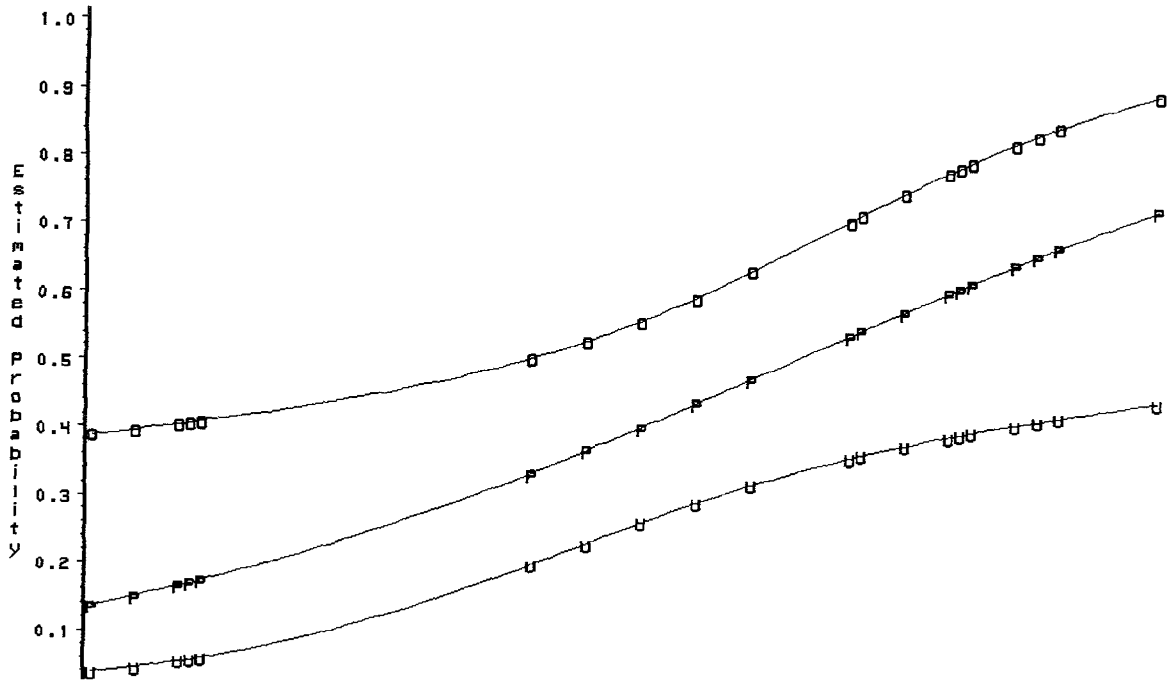


Figure 13: Logistic Plots of probability of thoracic injury severity ≥3 modelled by the Average Sled Deceleration (AVSLDE).

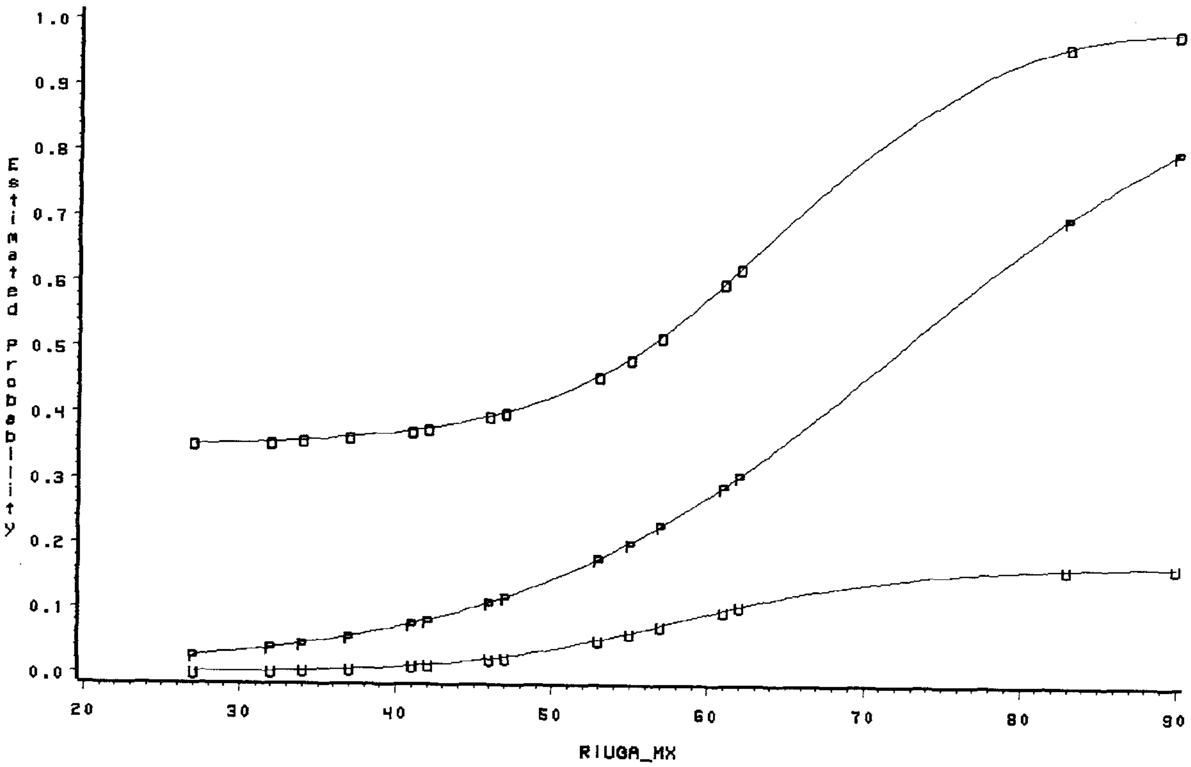


Figure 14: Logistic Plots of probability of thoracic injury severity ≥3 modelled by the Max Aceleration at Upper Left Rib (RIUGA_max).

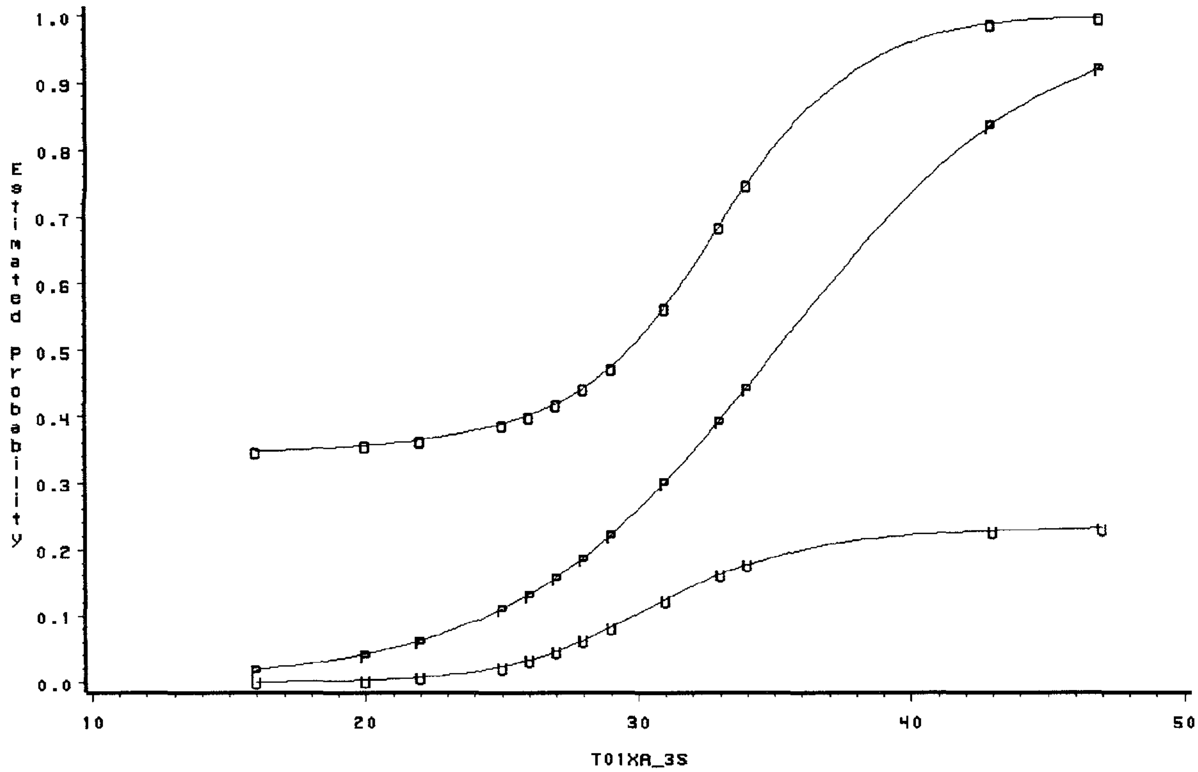


Figure 15: Logistic Plots of probability of thoracic injury severity ≥3 modelled by the 3ms Acceleration at the 1st thoracic vertebra(T01XA_3S).

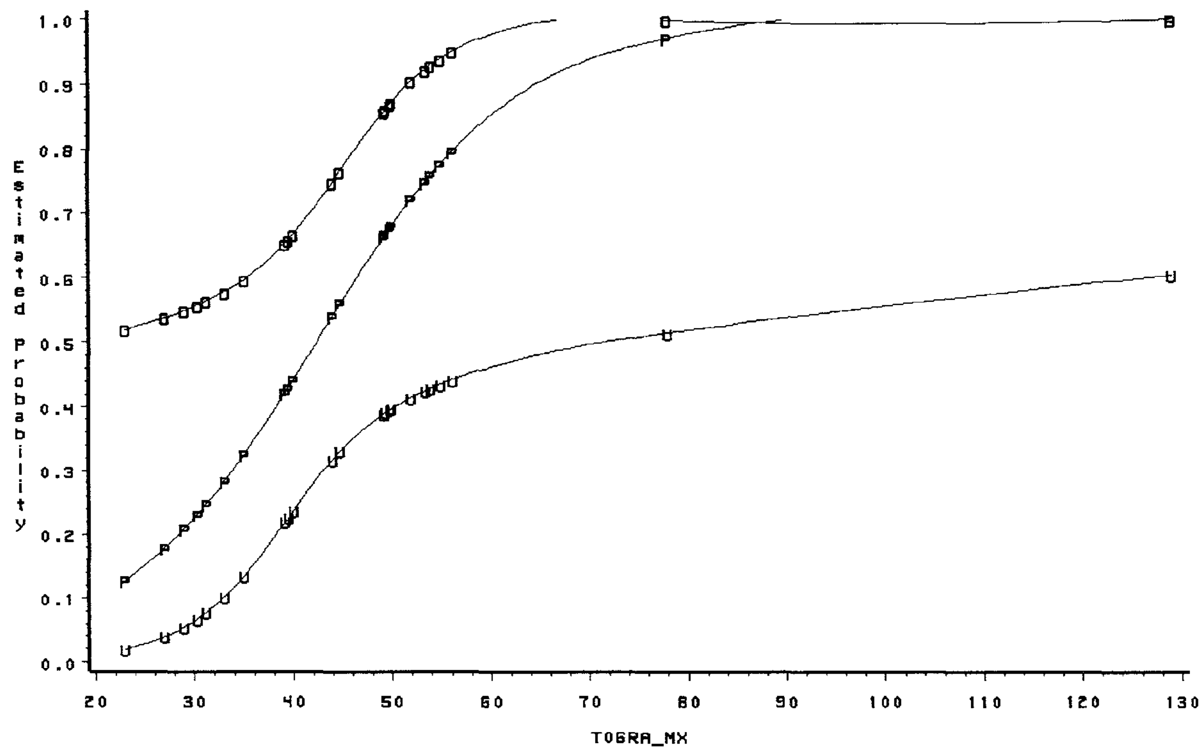


Figure 16: Logistic Plots of probability of thoracic injury severity ≥3 modelled by the Max R-Acceleration at the 6th thoracic vertebra (T06RA_MX).

Although we primarily focused on the mechanical parameters at the thorax for predicting an **Injury Severity ≥3,** other models have also be considered. Among these, one of the most relevant predictor for **Injury Severity ≥2** is **RIUGA_3S** suggesting that the 3ms-acceleration value at Left Upper Rib can be in general considered a reliable predictor for the thoracic injury severity.

DISCUSSION

A collective of 46 frontal collisions with 3-point belt, air bag and combined 3-point belt - air bag protected cadavers was investigated. The impact conditions ranged according to the velocity and the chosen sled deceleration with 47 to 55 km/h and 10 to 20 g in a wide area. The accelerations measured at the different locations of the chest are between 45 g and 60 g for all three restraint systems used.According the restraint system used , characteristic fracture patterns were observed. By using 3-point belts the fractures are located mainly at the shoulder belt path, whereby by using only air bag the front axillar line is involved.

By using the combination 3-point belt/driver air bag, the injury pattern of the 3-point belt predominated; this is thought to be a result of both the stiffness and path of the shoulder belt. The rib fractures resulting from air bag use are located at the front axillar or medio-clavicular line; this is in agreement with findings of Yoganandan et al. (1993).

The most fractures that were observed were infractions, a fracture type which is not visible at the chest front when using the conventional x-ray examination; these findings are now possible through autopsy and the touching of the ribs.

The most frequent fractured rib by usig 3-point belt was the 2nd and the 3rd rib. According the chest location the central front (sternum), the right axillar line and the left cartilage region were involved; more or lesser the fractures were distributed at the whole front of the chest.

Independed of the restraint system used; the statistics show good correlations between the mechanical responses, „ average sled deceleration, maximum acceleration at the left upper rib, maximum resultant acceleration at T6 and the 3 ms acceleration at T1in x-direction " with the thoracic injury severity.

In the study no good correlations between the age of the cadavers and the thoracic injury severity were found as observed in side impact investigations (Kallieris et al., 1996). According to Kruskal-Wallis and F-test the thorax injury severtity seems to be influenced by the age of the subject. But using this covariate to predict the injury severity in the logistic model yielded no good results according to the choosen goodness of fit criteria. The reason is the large range of the sled deceleration.

The highest correctly predicted observations (82%) shows the 3 ms acceleration at T1 in x-direction for the prediction of the thoracic injury severity ≥ 3. The next most reliable predictors, with the same correctly predicted observations were the average sled deceleration and the maximum acceleration at the right upper rib.

The 50% probability of thoracic injury of AIS ≥ 3 differs for the spinal accelerations and the acceleration at the left upper rib. It is associated for T1 with an acceleration of 35 g, for T6 with 43 g in comparison to the left upper rib with 70 g. The T1 value is in agreement with those given by Morgan et al., (1994) by using belt restraints. The acceleration values at the spine are significant lower than those proposed in the FMVSS 208 as chest acceleration criterion of ≤ 60 g.

CONCLUSIONS

- Injury patterns indentify the restraint system used.
- The subject's age was not a relevant predictor for the thoracic injury severity.
- Chest accelerations are suitable parameters to predict thoracic injury severity.
- The best biomechanical predictor for the thoracic injury severity was the acceleration measured at the 1st thoracic vertebra, based on the logistic regression model.
- Spine accelerations seem to be the most reliable parameters to predict thoracic injuries.

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