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Protection for Thorax Injury Severity in 90° Lateral Collision

The thoracic trauma index (TTI) and the viscous criterion (VC) are injury criteria intended for the prediction of torso injury severity. The criteria were assessed in two series of experiments: 90° (lateral) car to car collisions and controlled left trunk impacts against either a rigid or padded wall. Forty-two belt restrained human cadavers in the age range 18–65 years, located in the near-side front passenger seat, were used. The impact velocity was between 40 and 60 km/h. Left and right side impacts were simulated using standard or modified car side structures. With the second series of experiments, the left side of each subject was impacted under one of two different test conditions: 24 km/h rigid wall or 32 km/h padded wall. The thorax deformation was evaluated through the double integration of the accelerated difference at the fourth and eight ribs, near and far side. Deformation maxima of 6–138 mm (mean 69 mm), VC values of 0.3–4.7 m/s (mean 1.6 m/s), and TTI values of 85–252 (mean 63) occurred. Torso abbreviated injury severity (AIS) values were between 0 and 5. Statistical analyses showed a stronger influence of age on injury severity than the injury criteria or biomechanical responses in the two series of experiments. The TTI showed the highest correlation with thoracic AIS and the number of rib fractures, while VC was the better predictor of abdominal AIS. The results are discussed critically and the strength and robustness of the injury criteria analyzed.

INTRODUCTION

There is still considerable discussion regarding the most suitable injury criterion for use in 90° (lateral) vehicle collisions. The thoracic trauma index (TTI) is a chest acceleration based measurement combined with anthropometric data that was developed by the National Highway Traffic Safety Administration (Eppinger et al., 1984; Morgan et al., 1986). TTI is included in the Federal Motor Vehicle Standard 214 (FMVSS 214) for side impact protection. In FMVSS 214 the TTI(d) limit is 85 for four-door cars and 90 for two-door cars.

Lau and Viano (1986) proposed the viscous criterion (VC), a temporal function formed by the product of deformation velocity, $V(t)$, and instantaneous compression, $C(t)$. At present VC is being considered as a criterion for European side impact protection.

The aim of the article was to investigate the suitability of the above-mentioned criteria for the prediction of injury severity in realistic loadings of the human trunk.

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METHOD

Test Subjects

The human test surrogates used were unembalmed uninjured human cadavers in the age range 18–65 years (mean 40 years).

Test Equipment

The tests were performed on the Institute's deceleration sled device using two different configurations. In total 63 tests were performed in both impact configurations in the following test matrix:

Car/Car Side Impact	Impact Velocity (km/h)					Wall Impact	Impact Velocity (km/h)		
Impact side	40	45	50	60	Σ	Wall	24	32	Σ
Left	3	8	3	1	15	Padded	0	5	5
Right	2	8	17	0	27	Rigid	7	9	16
Σ	5	16	20	1	42	Σ	7	14	21

90° Car/Car Lateral Collision. The striking vehicle consisted of the sled with a deformation element simulating the deformation behavior of the front of a European middle class vehicle (Gebbels, 1985) mounted on the front of the sled. The mass of the striking vehicle was 950 kg (Fig. 1). The impact velocity of the striking vehicle was 40–60 km/h.

The struck vehicle was a two- or four-door car body shell of a lower or upper medium class vehicle mounted on a moveable platform (dolly). The mass of the struck vehicle, including the cadaver, was between 950 and 1100 kg. In some tests each vehicle was impacted only on the right side; in the remaining tests both sides were impacted.

Each test subject was located in the near-side front passenger seat and restrained by a 3-point belt. Preimpact the struck vehicle was stationary (Fig. 1).

Controlled Torso Impacts. A bench seat with an instrumented side panel was mounted on the sled transverse to the direction of travel. The side panel was instrumented with load cells at the thoracic and pelvic levels. Each subject was positioned on the bench seat distal to the side panel and remained in this position until the sled began to decelerate. The subject then slide across the bench finally impacting against the side panel at approximately the predeleration sled velocity. All tests were performed with the subject's arm down on the impact side. A lateral low friction sliding movement was achieved by dressing the subject

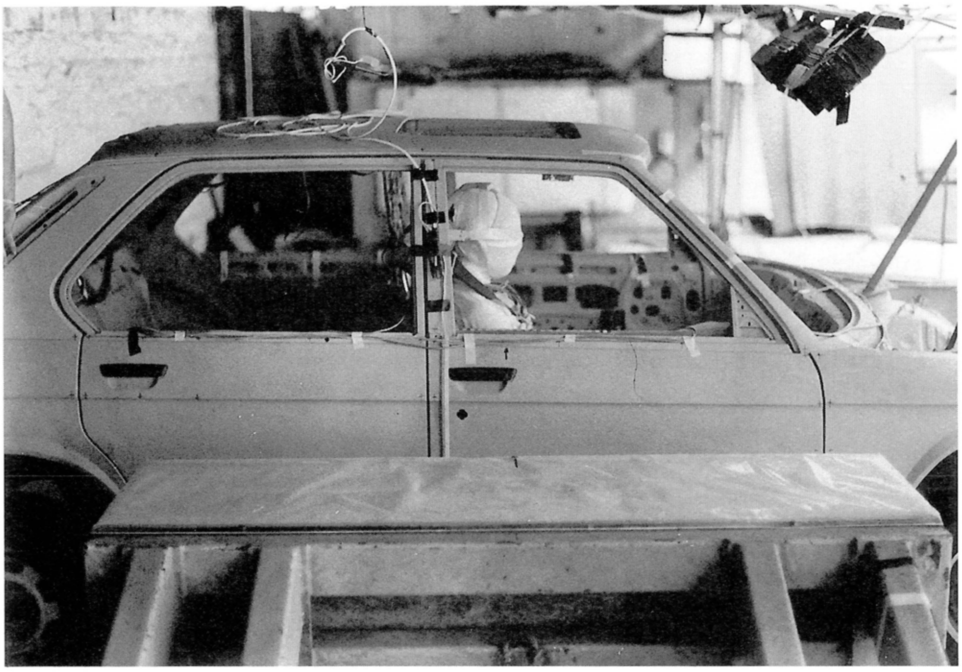


FIGURE 1 90° car/car lateral collision.

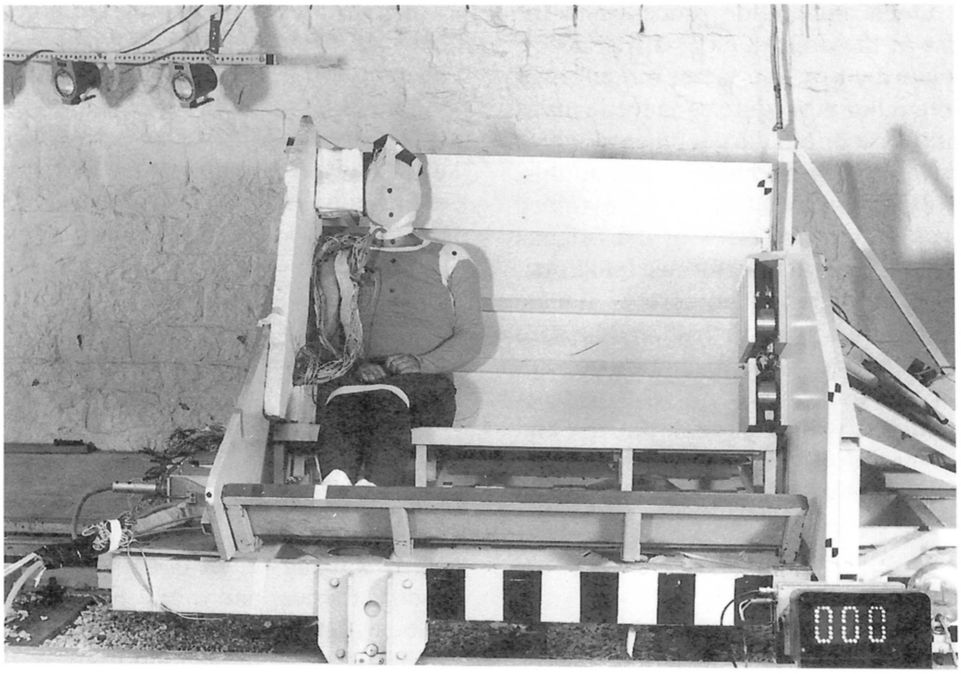


FIGURE 2 Rigid wall lateral collision.

and sitting it on two plastic sheets. The mass of the fully assembled sled with subject was 710 kg (Fig. 2).

Instrumentation

The cadavers were instrumented with the 12 accelerometer thoracic array as developed by Robbins et al. (1976), and used by Eppinger et al. (1978), to instrument the ribs, sternum, and thoracic vertebrae. All rib accelerometers were mounted so that lateral rib accelerations were measured. The sacrum was instrumented with a triaxial accelerometer.

Autopsy: Injury Severity

A detailed autopsy was carried out with special attention given to shoulder, thoracic, abdominal, and pelvic injuries. The injuries were coded according to abbreviated injury severity (AIS) 1990 (AAAM, 1990).

CALCULATION OF TTI

Data from the accelerometers mounted on the ribs and spine were digitized at 10,000 samples per second and digitally filtered using a finite impulse response (FIR) filter with a bandpass frequency of 100 Hz. TTI was calculated according to the following formula:

$$\mathrm{TTI} = 1.4 \cdot \mathrm{age} + 0.5(\mathrm{RIB}y + \mathrm{Th12}y)\frac{\mathrm{mass}}{M_{\mathrm{std}}}$$

where age is the age of the test subject (in years); RIBy, higher maximum acceleration value of the fourth or eighth rib struck side; Th12y, maximum acceleration value of the 12th thoracic vertebrae, y direction; mass, subject's mass (kg); and M_{std}, standard mass (75 kg).

CALCULATION OF VC

Rib acceleration data were filtered with a Butterworth channel class 180 digital filter. A curve was constructed for both the fourth and eighth ribs from the acceleration difference (ADIF) between accelerometers mounted at the impact side (AIMP) and the opposite side (AOPP).

$$\mathrm{ADIF}(t) = \mathrm{AIMP}(t) - \mathrm{AOPP}(t).$$

This curve was then integrated twice producing deformation (DEF) at the level of the fourth and eighth ribs with respect to time.

$$\mathrm{DEF}(t) = \int \int \mathrm{ADIF}(t)\, dt.$$

Due to the double integration process and the inherent noise in the original data, it was necessary to calculate a correction factor for deformation. The integration procedure produced curves that constantly rose or fell during times at which deformation was no longer possible. Due to this, and to simplify the procedure, it was assumed that there was a constant error in the original acceleration data that was transformed into a quadratic function through the process of double integration. Because deformation should be zero before and after the impact, a satisfactory polynomial function was found using the least squares method. A parabola was fit through the first and last points on the deformation curve. This parabola was then subtracted from the deformation curve to estimate the actual deformation. Finally, the VC was calculated in the normal manner from this corrected deformation data.

$$\mathrm{VC}(t) = \frac{\delta D(t)}{\delta t} \cdot \frac{D(t)}{D}.$$

$D(t)$ is the deformation and D the breadth of the body in millimeters. This mathematical method was validated with 15 European side impact dummy (EUROSID) tests in which VC values from measured (VC_m) and calculated (VC_c) thoracic deformations were compared (Mattern et al., 1995).

STATISTICAL METHODS

The data was first examined using a Spearman correlation analysis. The analysis was performed with the more important anthropometric data and biomechanical responses. To further investigate relationships between the independent variables (cadaver anthropometric data, TTI, and VC) and the discrete dependent variable (AIS score), the logistic regression model was used. Logistic regression is a form of statistical modeling that is appropriate for binary or ordinal outcome variables. It describes the relationship between the categorical response variable and a set of continuous explanatory variables. If the independent variable is ordinal, the logistic regression model uses the explanatory variables to predict the probability that the response variable is equal or lower than a given value. By calculating the differences between these cumulative probabilities, one gets the probability that the response variable takes on a specific value.

To ensure that the predicted probabilities are between 0 and 1, an appropriate link function g must be used. Then the basic assumption is that the function g of the mean of the response variable, the probability to get an AIS equal or lower than a given value i, is linearly related to the explanatory variables. The most common link function, also used in this study, is the logit transformation,

$$\mathrm{logit}(p) = \log\left(\frac{p}{1-p}\right).$$

Therefore the model looks like

$$\mathrm{logit}(p\ \mathrm{AIS} \leq i)) = \alpha_i + \beta \cdot \mathbf{x},$$

where $\mathbf{x}$ is the vector of explanatory or independent variables, and α and β are the parameters to be estimated.

Because the variables of interest, the different AIS values, are measured on an ordinal scale (levels 0–5), the method of logistic regression was chosen to fit several statistical models.

Both univariate and multivariate models were assessed using the following goodness of fit models.

GOODNESS OF FIT CRITERIA

To compare the different fit models several goodness of fit criteria were calculated. These criteria are based on a comparison of the predicted to the actual observed responses. Hence they are measures of the predictive accuracy of the different models.

COUNT (total number of correctly predicted observations): If the predicted AIS value for an observation is exactly the same as the observed value, the observation is predicted correctly.

PRED (percentage of correctly predicted observations): This is just the ratio of COUNT of the total number of observations.

PAIRS (percentage of concordant pairs): For all pairs of observations with different values of the response variable, a pair is concordant if the observation with the larger ordered value of the response has a lower predicted event probability than does the observation with the smaller ordered value of the response. For example, observation A has an observed AIS value of 3 and a predicted value of 2; observation B has an observed AIS value of 4 and a predicted value of 3. Although neither of the two observations is predicted correctly, the order of the values is preserved and hence the pair (A, B) is a concordant pair.

AISDIF (mean absolute difference between the observed and predicted AIS values): For all observations the absolute differences between the predicted and the observed AIS values are summed up. This value is then divided by the total number of observations.

PDIF (mean probability difference): For each observation the logistic regression model estimates a probability for every unique value of the outcome variable based on the actual values of the explanatory variables. Then the level with the highest estimated probability is chosen as the predicted value. For example, observation A has an observed AIS value of 2. The estimated probabilities are

$$p(\text{AIS} = 0) = 0.05, \quad p(\text{AIS} = 1) = 0.1,$$
$$p(\text{AIS} = 2) = 0.3, \quad p(\text{AIS} = 3) = 0.4,$$
$$p(\text{AIS} = 4) = 0.1, \quad p(\text{AIS} = 5) = 0.05$$

(note that the values always sum up to 1).

Because 0.4 is the highest estimated p value, the predicted AIS value for this observation is 3. The actual observed AIS value is predicted with a p value of 0.3. Hence the difference between these two values (PDIF) is 0.1.

COUNT and PRED are probably the criteria that are easiest to understand, but in terms of statistical sensitivity they are certainly not optimal. A model may have a large number of correctly predicted values but the resting observations could be predicted totally wrong. For a sensitive model at least the order of the most observations should be preserved (PAIRS). Also it should be taken into account how much the prediction differs from the observed value for incorrectly predicted observations (AISDIF).

It should make a difference whether an incorrect prediction is caused by a very small or rather a large difference in the estimated probabilities (PDIF). For example, let the estimated p values of an observation with an observed AIS of 3 be as follows:

$$p(\text{AIS} = 3) = 0.399 \quad \text{and} \quad p(\text{AIS} = 4) = 0.4.$$

Of course the model would predict an AIS value of 4, although the p value for an AIS of 3 (the correct value) is almost the same.

Therefore, it is important to look at different criteria simultaneously. A good model should not be too bad in any of them (Agresti, 1984; Andersen, 1991; Freeman, 1987; Hosmer and Lemeshow, 1989; SAS Institute Inc., 1994, 1995a,b).

RESULTS

Mechanical Responses

Figure 3 presents the frequency distributions for measured and derived biomechanical responses. The largest magnitude accelerations were measured at the level of the eighth impacted rib. Accelerations at the fourth rib and 12 thoracic vertebra (Th12) were of similar magnitude [Fig. 3(a,b,g)]. Greater acceleration at the level of the eighth rib resulted in greater magnitude chest deflections in this region (80–120 mm) in comparison to the level of the fourth rib (45–90 mm) [Fig. 3(c,d)]. VC behaves in a similar fashion with values greater when measured at the eighth rib [Fig. 3(e,f)].

Medical Findings

The thoracic injury severity was defined by the number of rib fractures. Fractures were located predominantly on the side exposed to impact. Fractures on the contralateral trunk were rarely observed. Up to 36 rib fractures were found per subject [Fig. 4(d)]. The most frequent number of rib fractures observed was 11–20 (40%). For thorax AIS the most frequent injury levels were AIS 3 (25.4%) and AIS 4 (38.1%) as shown in Figure 4(a).

The trunk injury severity was defined as the highest AIS score for the thorax and abdomen. In all cases the thoracic AIS was greater than the abdominal injury severity. Therefore injuries of AIS 3 and 4 observed with the bony thorax were most frequent [30.2% and 36.5%, Fig. 4(b,c)]. Rib fractures were found to be dependent upon subject age. The Spearman correlation coefficients between age and number of rib fractures was 74% [Fig. 5(d)], with the thorax AIS at 70% [Fig. 5(a)] and the trunk AIS at 72% [Fig. 5(b)]. Correlations of 58% were observed with age-dependent TTI and the number of rib fractures, the thorax AIS, and trunk AISs [Fig. 5(a,b,d)].

No abdominal trauma was observed in 63.5% of the cases. The most frequent injury (16%) was

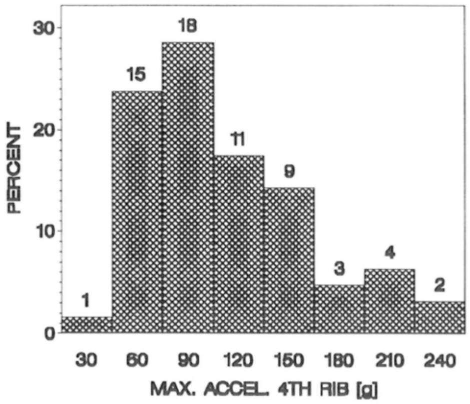
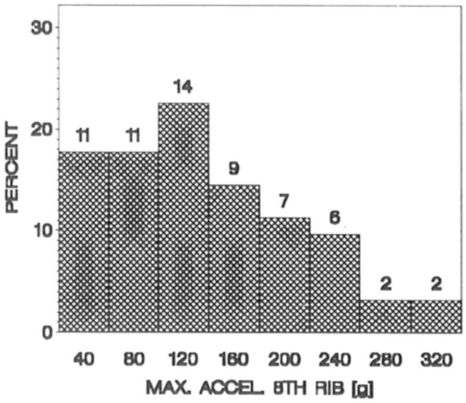


Figure 3a.



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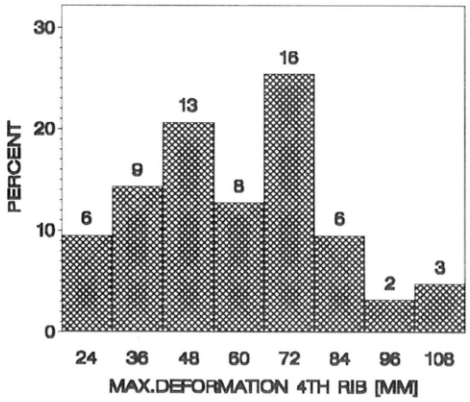
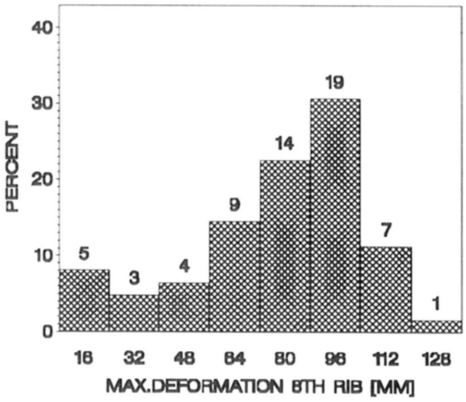


Figure 3c.



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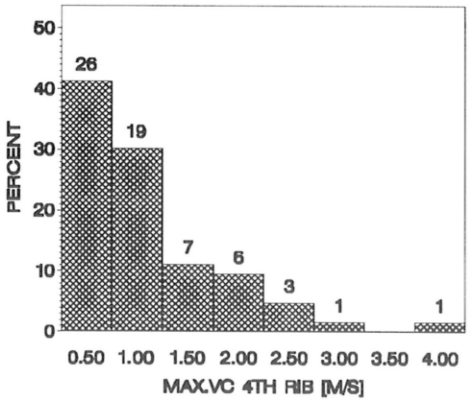

Figure 3e.

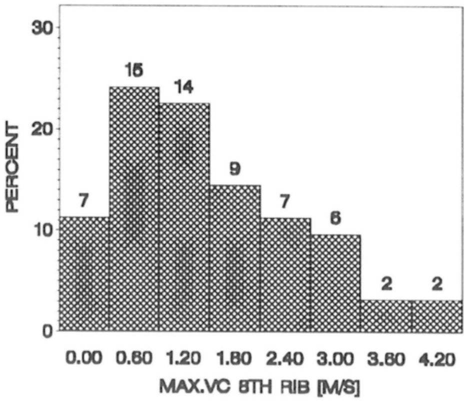

Figure 3f.

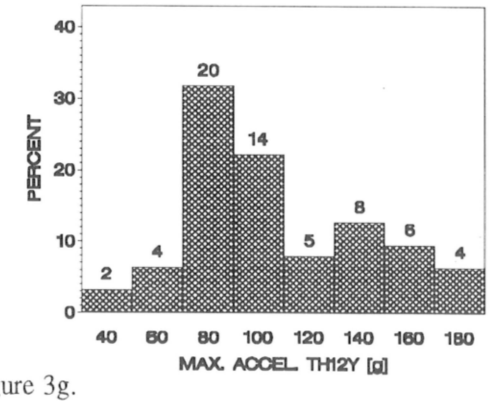

Figure 3g.

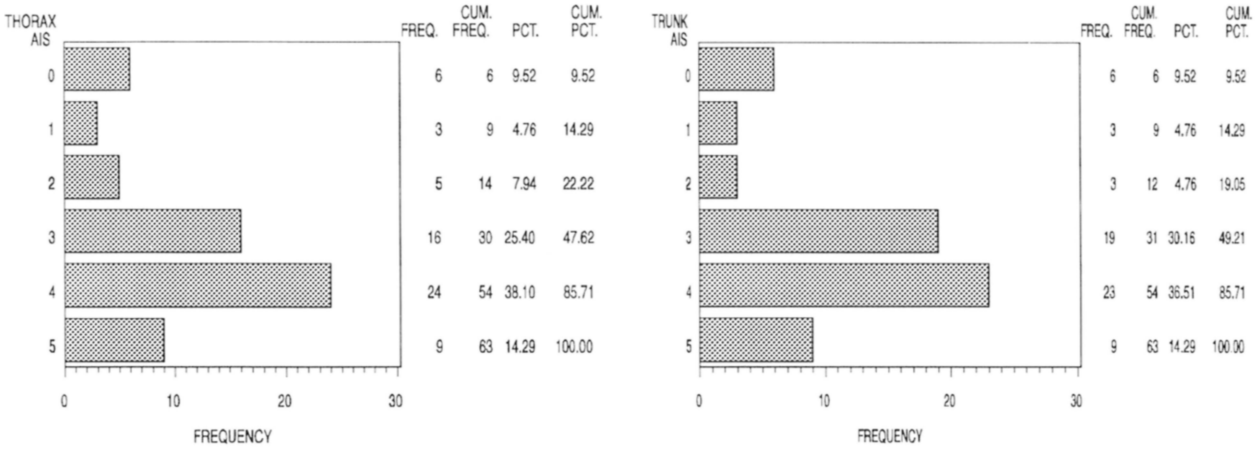

Figure 4a. Thoracic injury severity

Figure 4b. Trunk injury severity

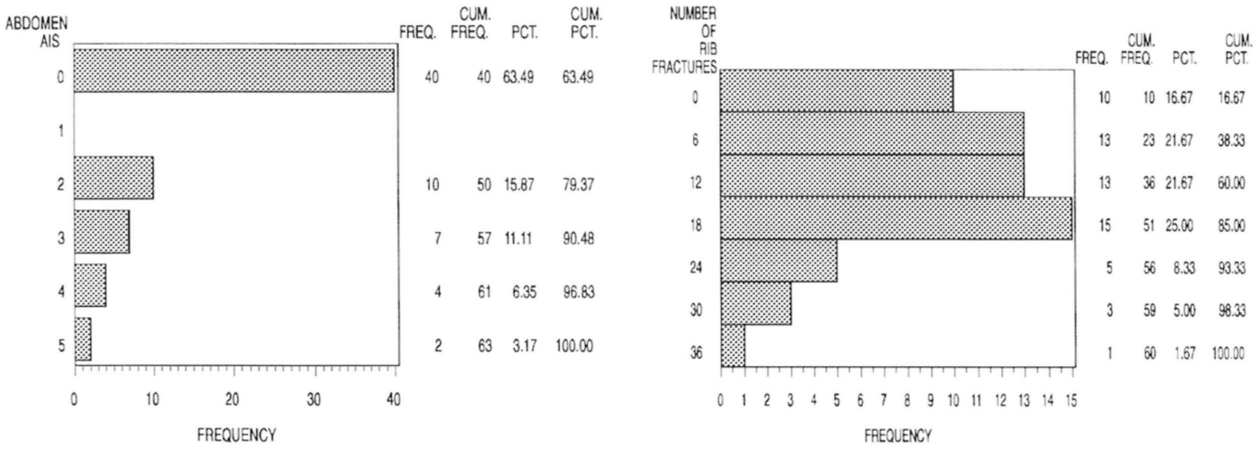

Figure 4c. Abdominal injury severity

Figure 4d. Number of rib fractures

FIGURE 4 Frequency of the injury severity of (a) thoracic, (c) abdominal, (b) trunk injuries, and (d) number of rib fractures.

laceration of the capsule of the liver with a depth less than 3 cm; injury severity was AIS 2. In 11% of the cases an abdominal AIS of 3 was found, i.e., laceration of the liver or spleen [Fig. 4(c)].

In contrast to the thorax, abdominal injury severity was influenced by the side of the body impacted and was independent of the age. Liver ruptures occurred most frequently in right side impacts. Furthermore no high correlations were found between the abdominal AIS and biomechanical responses. The highest correlation with abdominal AIS was observed with VC calculated at the level of the fourth rib, $r = 52$ and 44% for left side and side independent impacts, respectively, followed by TTI ($r = 43$ and 38%), and the deflection calculated at the level of the fourth rib ($r = 44$ and 37%) [Fig. 5(c,e)]. In right side impacts only correlations between injury severity and the tested independent variables were found to be lower [Fig. 5(f)].

FIGURE 3 Frequency distributions of measured and evaluated mechanical responses: (a) acceleration at the fourth impacted rib; (b) acceleration at the eighth impacted rib; (c) deformation at the level of the fourth impacted rib; (d) deformation at the level of the eighth impacted rib; (e) VC at the level of the fourth rib; (f) VC at the level of the eighth rib; and (g) acceleration at the 12th thoracic vertebrae.

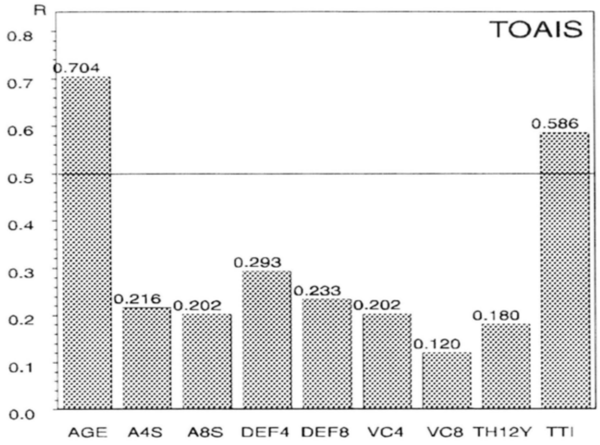

Figure 5a. Thoracic injury severity

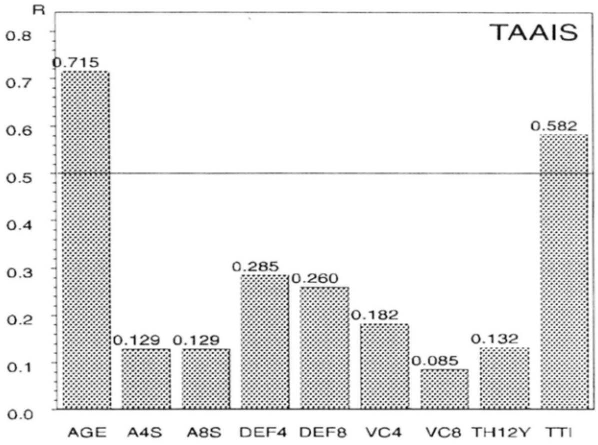

Figure 5b. Trunk injury severity

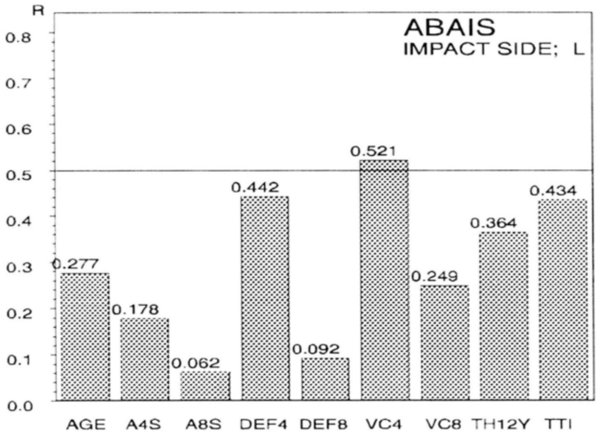

Figure 5c. Abdominal injury severity (left side impact)

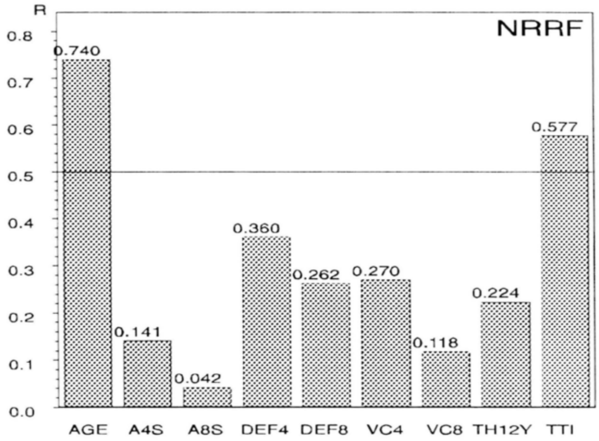

Figure 5d. Number of rib fractures

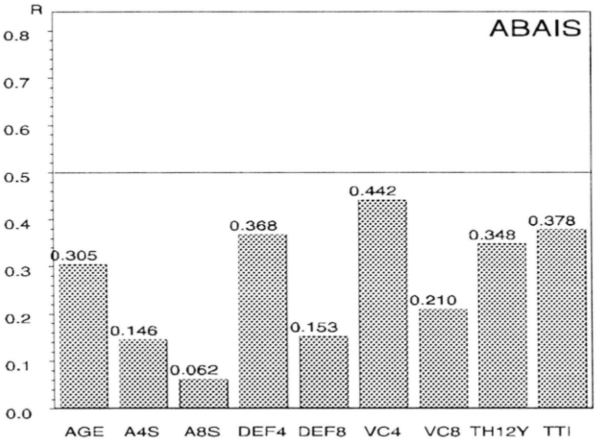

Figure 5e. Abdominal injury severity

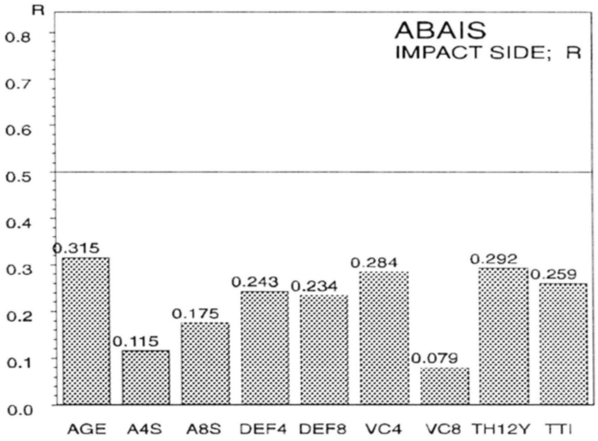

Figure 5f. Abdominal injury severity (right side impact)

FIGURE 5 Spearman correlation of thoracic, trunk, and abdominal injury severity vs. age, measured, and evaluated mechanical responses.

Table 1. Probability Analysis of Thoracic Injury Severity According to Four Chosen Goodness of Fit Criteria: TOAIS 0–5

Model	PRED	PAIRS	AISDIF	PDIF
Age	0.49	0.80	0.70	0.13
TTI	0.52	0.75	0.81	0.13
VC4	0.40	0.58	1.06	0.13
VC8	0.39	0.54	1.08	0.14
DEF4	0.37	0.62	1.10	0.13
DEF8	0.40	0.59	1.08	0.13
Th12y	0.40	0.57	1.06	0.13
A4S	0.39	0.58	1.08	0.13
A8S	0.38	0.58	1.10	0.13
C4	0.37	0.58	1.08	0.13
C8	0.39	0.52	1.07	0.14
Age, VC4	0.56	0.83	0.75	0.13
Age, VC8	0.52	0.83	0.71	0.14
Age, DEF4	0.46	0.83	0.81	0.14
Age, DEF8	0.50	0.81	0.79	0.15
Age, A4S	0.52	0.81	0.73	0.13
Age, A8S	0.53	0.80	0.71	0.14
Age, C4	0.52	0.84	0.74	0.14
Age, C8	0.51	0.83	0.77	0.16
Age, Th12y	0.60	0.84	0.60	0.13

Injury Criteria

Uni- and multivariate logistic regression analyses were performed to assess which independent variable(s) best described the dependent variable(s). The independent variables tested were anthropometric data (age) and biomechanical responses, i.e., peak acceleration, chest compression, VC, and TTI. The discrete dependent variables were AIS at the thorax and abdomen, and trunk injury severity. Table 1 shows the probability analyses ordered according to the four chosen goodness of fit criteria. In the analysis all severities of injury were observed, i.e., AIS 0–5.

In the univariate models the most reliable predictor of thoracic injury severity was the subject's age (49% correctly predicted observations, 80% correctly ordered pairs). The next most reliable predictors were deflection at the level of the eighth rib; y-axis acceleration maximum at Th12; VC evaluated at the level of the fourth rib; the acceleration maximum at the fourth rib impacted side; VC8; the acceleration maximum at the eighth rib impacted side; and the least successful predictor, compression at the level of the fourth rib (37% correctly predicted observations, 58% correctly ordered pairs). TTI, which combines the subject's age and biomechanical responses, better predicts the observed injury severity: 52% correct predicted observations and 75% correctly ordered pairs. The model that best predicted AIS was a multivariate model that included the following covariates: maximum acceleration at Th12 (y axis and age (60% correctly predicted observations, 84% correctly ordered pairs).

Thoracic injury severity was simplified as a dichotomous variable ($AIS < 4$ and $AIS \geq 4$) and assessed using the logistic regression model. A higher number of correctly predicted observations were found using this dependent variable. The best predictor from the assessed univariate models was age, which correctly predicted 86% of the observations. The best multivariate model included two covariates: age and compression at the level of the fourth rib. This model correctly predicted 89% of the observations (Table 2).

The models investigated to describe abdominal injury severity exhibited a larger number of correctly predicted observations in comparison to the thoracic AIS models. This is probably due to the high number of cases without abdominal injury. The sample investigated included 40 cases without abdominal injury, and these were correctly predicted by the models (Table 3). The same observations were made if abdominal injury was classified as a dichotomous variable, i.e., abdominal injury severity = 0, or AIS

Table 2. Probability Analysis with Dichotomous Variable: TOAIS < 4 and TOAIS ≥ 4

Model	COUNT	PRED
Age	54	0.86
Th12y	32	0.51
TTI	45	0.71
A4S	37	0.59
A8S	36	0.57
C4	33	0.52
C8	35	0.56
DEF4	36	0.57
DEF8	34	0.54
VC4	36	0.57
VC8	36	0.57
Age, Th12y	54	0.86
Age, A4S	54	0.86
Age, A8S	55	0.87
Age, C4	56	0.89
Age, C8	55	0.87
Age, DEF4	55	0.87
Age, DEF8	55	0.87
Age, VC4	55	0.87
Age, VC8	54	0.86

Table 3. Probability Analysis of Abdominal Injury Severity According to Four Chosen Goodness of Fit Criteria: ABAIS 0–5

Model	PRED	PAIRS	AISDIF	PDIF
Age	0.63	0.65	1.06	0.16
TTI	0.62	0.70	1.11	0.16
VC4	0.63	0.73	1.00	0.16
DEF4	0.65	0.70	0.92	0.14
Th12y	0.65	0.68	1.02	0.16
C4	0.65	0.69	1.00	0.15
Age, DEF4	0.63	0.74	0.95	0.13
Age, C4	0.62	0.74	0.95	0.13
Age, VC4	0.65	0.78	0.86	0.13
Age, Th12y	0.60	0.77	1.13	0.13

Table 5. Probability Analysis of Trunk Injury Severity According to Four Chosen Goodness of Fit Criteria: TAAIS 0–5

Model	PRED	PAIRS	AISDIF	PDIF
Age	0.44	0.78	0.83	0.13
TTI	0.46	0.75	0.87	0.13
VC4	0.32	0.58	1.13	0.11
DEF4	0.37	0.62	1.08	0.11
Th12y	0.37	0.58	1.08	0.11
C4	0.33	0.58	1.11	0.11
Age, DEF4	0.52	0.82	0.75	0.13
Age, C4	0.54	0.83	0.69	0.14
Age, VC4	0.56	0.81	0.75	0.12
Age, Th12y	0.57	0.83	0.68	0.13
Age, VC8	0.51	0.82	0.73	0.13

severity > 0. However, the percentage of correctly predicted observations is lower in comparison to the statistical models for thoracic injury severity (Table 4).

For the trunk injury severity, i.e., the greater AIS severity at the thorax or abdomen, the model correctly predicted a lower number of observed trunk injury severity scores (Table 5). The probability of severe thoracic injury (AIS ≥ 4) versus age and selected biomechanical response derived from the logistic regression models are shown in Figure 6(a–i). A 50% likelihood of a thoracic injury of AIS ≥ 4 is associated with age = 38 years, acceleration at the fourth near side rib = $95g$, acceleration at the eighth near side rib = $120g$, deflection at the level of the fourth rib = 57 mm, deflection at the level of the eighth rib = 68 mm, acceleration at the level of the 12th thoracic vertebra, y direction = $90g$, VC at the level of the fourth rib = 0.83 m/s, VC at the level of the eighth rib = 0.5 m/s, and TTI = 155.

Table 4. Probability Analysis with Dichotomous Variable: ABAIS = 0 and ABAIS > 0

Model	COUNT	PRED
Th12y	40	0.63
TTI	40	0.63
A4S	41	0.65
A8S	41	0.65
C8	42	0.67
C4	43	0.68
DEF8	40	0.63
DEF4	42	0.67
VC4	43	0.68
VC8	39	0.62
Age, Th12y	48	0.76
Age, A4S	41	0.65
Age, A8S	42	0.67
Age, C4	48	0.76
Age, C8	44	0.70
Age, DEF4	48	0.76
Age, DEF8	41	0.65
Age, VC4	48	0.76

Figure 7 presents the logistic plots of the probability of thoracic injury of AIS ≥ 4 for the biomechanical responses Th12y and VC4. Both variables correctly predict a significant number of observations. To demonstrate age related trends the data is separated into three fixed age groups: 20, 40, and 60 years. The 50% probability of injury is significantly influenced by subject age, i.e., 20-year-old subjects tolerate higher VC values [Fig. 7(b)] and higher magnitude acceleration at Th12y [Fig. 7(a)].

Plots for the predicted probability of thorax AIS versus the combination of subject age and Th12 y-axis acceleration maximum are shown in Fig. 8. This multivariate logistic regression model demonstrates the greatest number of correctly predicted observations. The most frequently predicted injury severities are AIS 3 and AIS 4 with less success at the AIS 5 and AIS 0 severities; for example, when $z = 7.2$, then 10% probability of AIS 0 and 50% of AIS 3 exist, or for $z = 10$, the highest probability of 70% is predicted for AIS 4, during which, for a z value higher then 12 higher probabilities for AIS 5 are also expected.

DISCUSSION

Sixty-three side impact tests with human cadaver subjects in two different test configurations were performed. It was found that rib fracture location

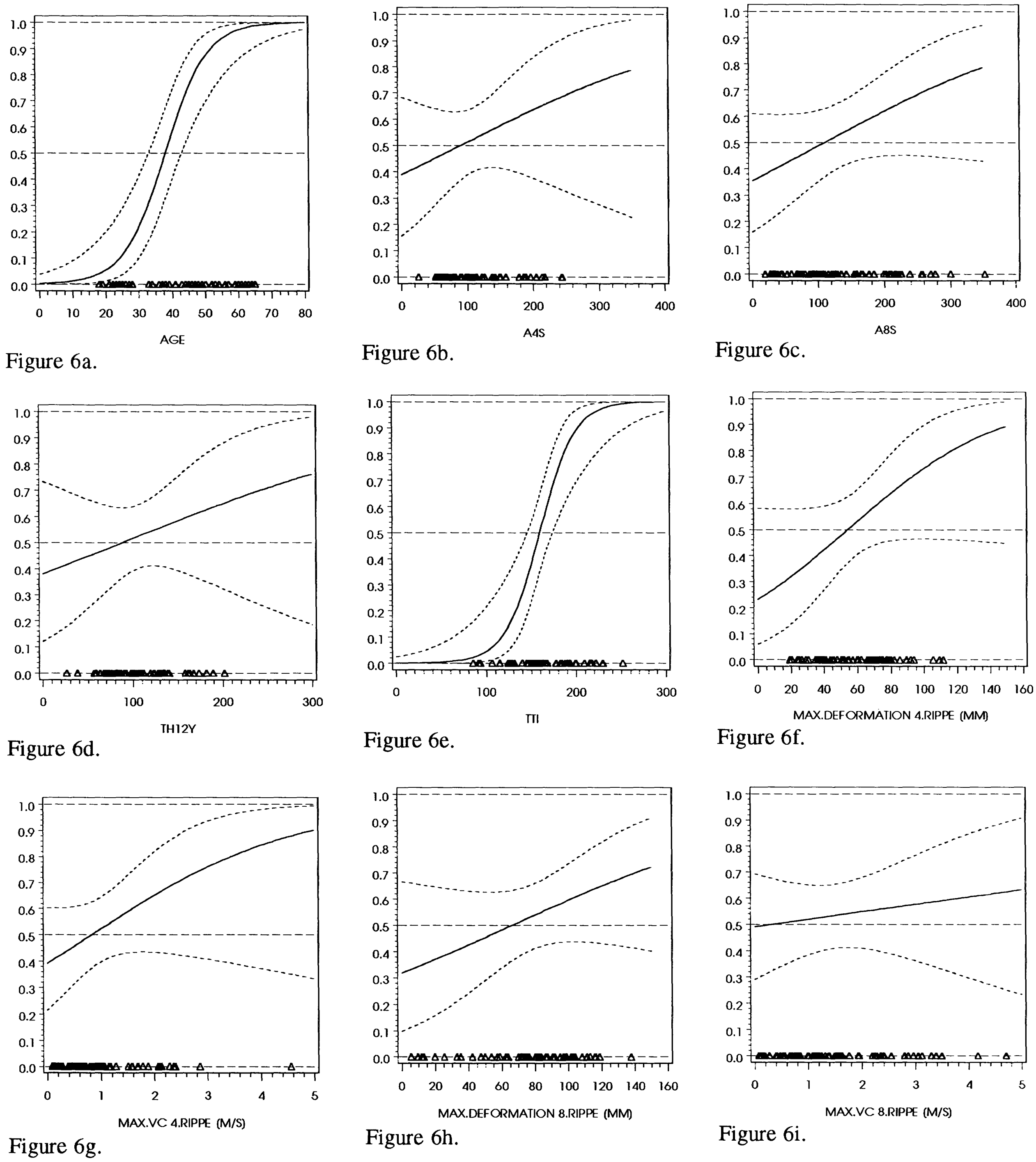

Figure 6a.

Figure 6b.

Figure 6c.

Figure 6d.

Figure 6e.

Figure 6f.

Figure 6g.

Figure 6h.

Figure 6i.

FIGURE 6 Logistic plots of probability of thoracic injury severity vs. age and selected biomechanical responses: (a) age; (b) acceleration at the fourth rib; (c) acceleration at the eighth rib; (d) acceleration at the 12th thoracic vertebrae; (e) TTI; (f) deformation at the level of the fourth rib; (g) VC at the level of the fourth rib; (h) deformation at the level of the eighth rib; and (i) VC at the level of the eighth rib. (The triangles at the bottom mark the range of the corresponding data.)

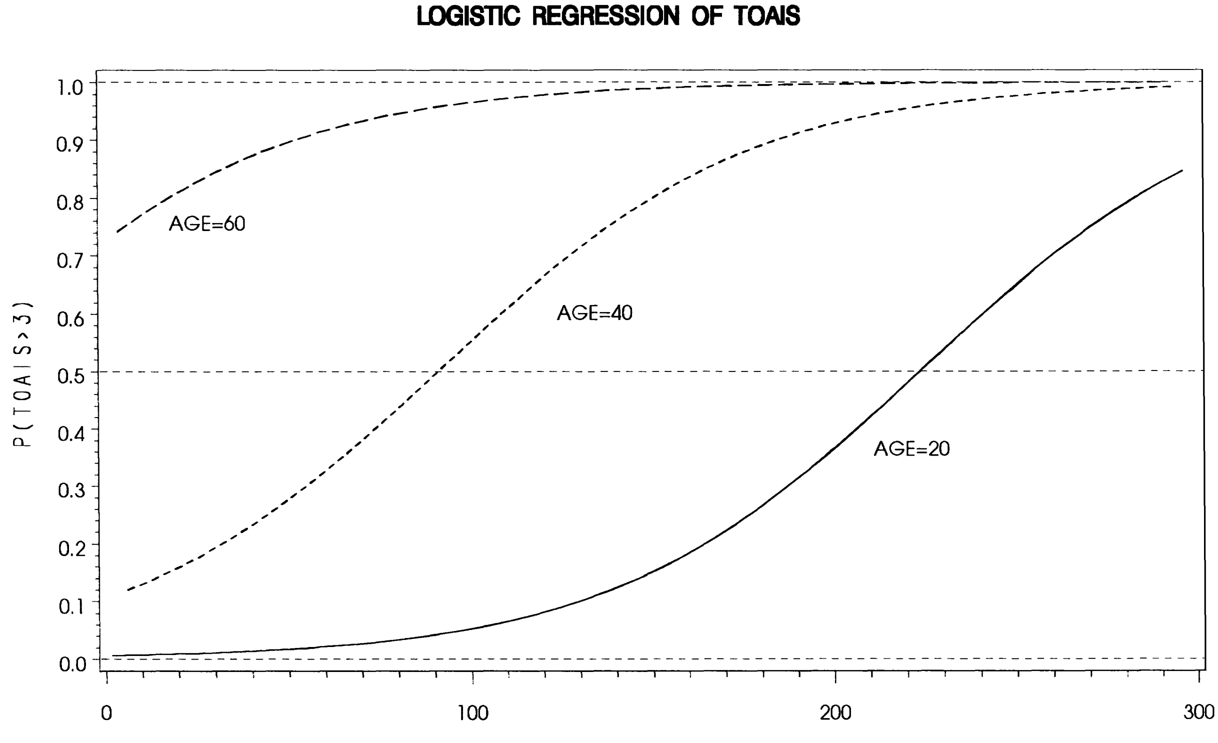

Figure 7a.

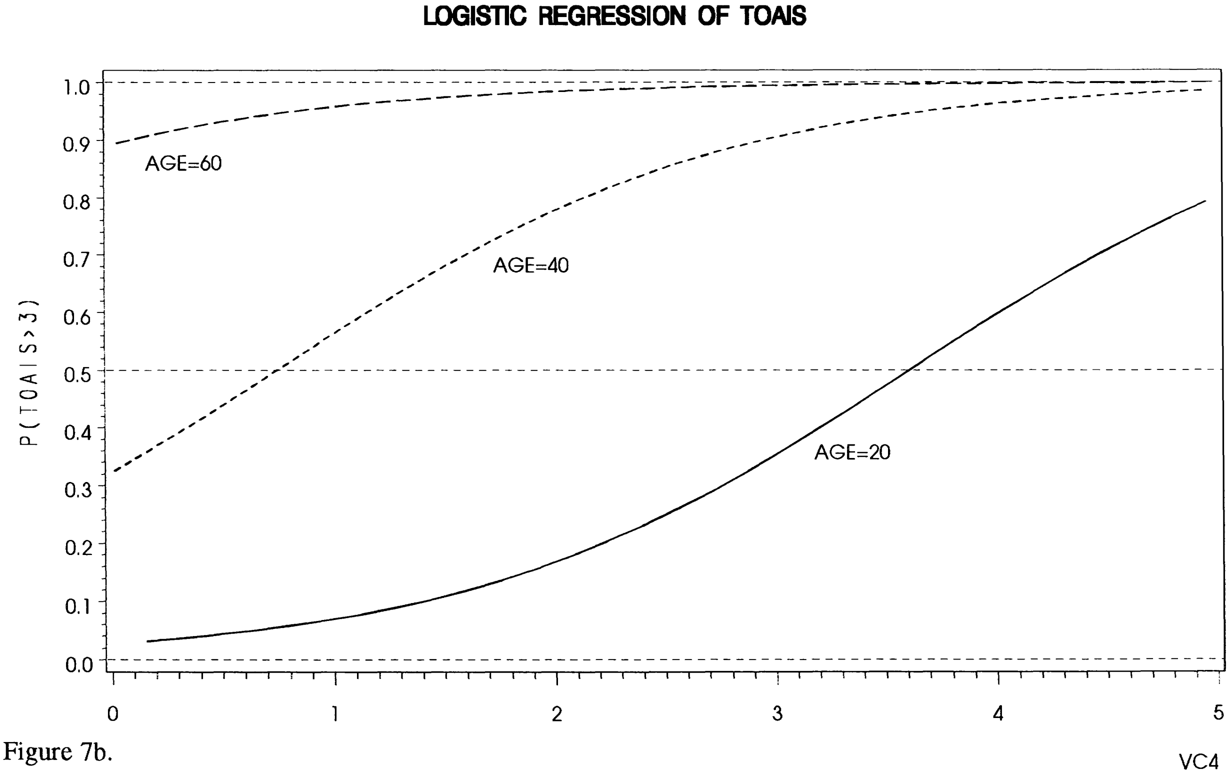

Figure 7b.

FIGURE 7 Logistic plots of probability of thoracic injury severity vs. the mechanical responses (a) Th12y and (b) VC4 by fixed ages 20, 40, and 60 years.

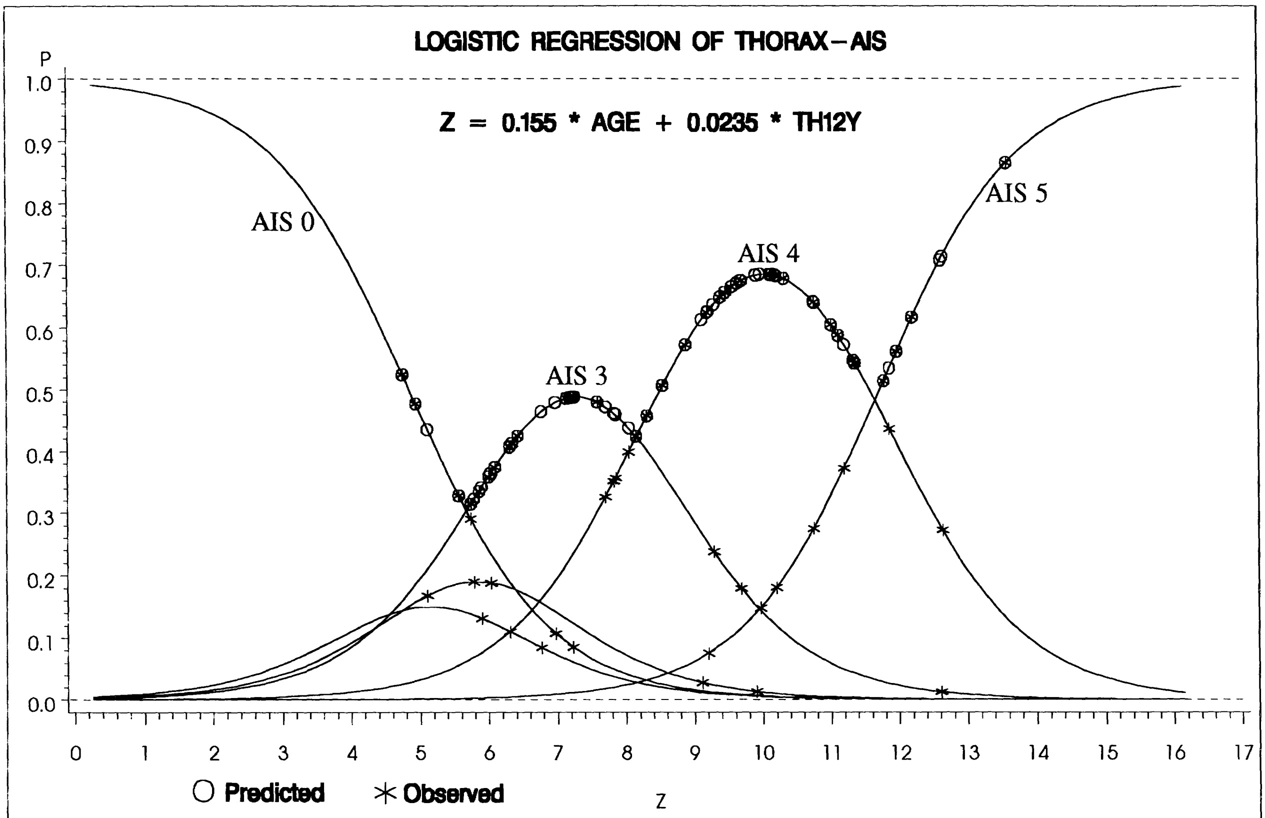

FIGURE 8 Probability curves of thoracic injury severity vs. the combination of age and the acceleration at the 12th thoracic vertebrae.

was independent of the body side impacted and abdominal injuries were more severe in right side impacts. These observations are in accordance with Brun–Cassan et al. (1987). The covariate that was associated most highly with the number of rib fractures was the subject's age. Due to the greater AIS of rib fractures, these injuries determined the AIS for the thorax and the trunk injury severity. Therefore, higher severity AIS 4 and AIS 5 injuries, such as flail chest, were only observed when older test subjects were used or during higher severity impacts. The number and severity of cases with liver injuries were reduced when vehicles with improved side impact protection (stiff and bolstered side structures) were used.

It was observed that in the impact severity range of Δv = 24–30 km/h, the subject's body underwent high magnitude acceleration. The highest was found at the level of the eighth near side rib. It is probable that high impact forces were applied in the region of the eighth rib. The greatest amount of deformation was also observed at this level. In 22 cases deformation at the eighth rib amounted to between 80 and 100 mm. Acceleration maxima at the 12th thoracic vertebra (y axis) were lower than those measured at the eighth rib acceleration, due to energy absorption within the thorax.

The deformation at the level of the fourth and eighth rib was evaluated through twofold integration of the acceleration difference of near and contralateral side measurements. This method appears to have the same accuracy as cinematic methods. In the future the chest band (Eppinger, 1989) will be used to determine thoracic deformation.

The Spearman correlation analyses showed that the subject's age was most highly correlated with thoracic and trunk AIS, and specifically the number of rib fractures (r = 0.7). The second highest correlation (r = 0.6) was found between TTI and thoracic and trunk AIS. These findings are in contrast to those of Talantikite et al. (1993), who found in more controlled abdominal impacts no correlation between TTI and the number of rib fractures ($r = 0.14$) and a high correlation ($r = 0.71$) between VC and AIS. In the Heidelberg study no correlation ($r = 0.085–0.270$) was found between VC (VC4 and VC8) and the number of rib fractures or thoracic and trunk AIS. Correlations between these injuries and deflections at the level of the fourth and eighth ribs were slightly higher.

A surprising observation was that there was a high correlation ($r = 0.44–0.52$) between VC evaluated at the level of the fourth rib and abdominal AIS, which was better than the correlation with VC measured at the eighth rib. This is in agreement with the study of Talantikite et al. (1993).

The study shows that TTI is the best predictor for thoracic injury severity. Thoracic deformation, compression, VC, and acceleration measured at the fourth and eighth rib near side and the y-axis acceleration at the 12th thoracic vertebra, were also found to be good predictors of thoracic injury. These observations differ with Viano (1989), who found VC to be the best predictor in impactor testing.

The 50% probability of thoracic injury of AIS ≥ 4 is associated with a TTI of 155. This is consistent with a TTI value of 143 for a similar injury published by Cavanaugh et al. (1993). For the same injury risk (50% probability of serious thoracic injury) a VC value of 0.83 m/s (level of the fourth rib) was observed. This compares to VC = 0.9 m/s reported by Cavanaugh et al. (1993) and VC = 1.6 m/s reported by Viano (1989) in controlled impactor tests. The y-axis maximum acceleration at the 12th thoracic vertebra of 90g for a 50% probability of serious thoracic injury is much greater than the value of 40g published by Cavanaugh et al. (1993).

Due to the great influence of the subject's age on thoracic injury severity, occupant age must be considered in an injury criterion. The evaluation of the probability of VC for fixed subject ages (20, 40, and 60 years) shows this influence. The 50% probability of serious thoracic injury with the VC, evaluated at the level of fourth rib, was equal to 3.65 m/s for a fixed age of 20 years in comparison to VC = 0.75 m/s for a fixed age of 40 years.

CONCLUSIONS

1. From all the tested covariates (biomechanical and anthropometric), only the subject's age demonstrated a high correlation with thoracic injury severity.
2. The best biomechanical predictor of thoracic injury severity was TTI, based on the logistic regression model.
3. Deformation, compression, VC, and acceleration measured at the fourth and eighth rib near side and the y-axis acceleration at the 12th thoracic vertebra, may be used as predictors of thoracic injury.

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