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Chest deflection tolerance to blunt anterior loading is sensitive to age but not load distribution

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Abstract

Ninety-three human cadaver tests are used in the development of thoracic injury risk functions with consideration of age and restraint condition. Linear logistic regression models are developed with the set of potential predictors including the maximum chest deflection, the age of the cadaver at death, gender, and the loading condition on the anterior thorax: blunt hub (41 tests), seat belt (26 tests), air bag (12 tests), and combined belt-and-bag (14 tests). Predicted outcomes were the probability of any rib fractures (onset of injury) and the probability of greater than six rib fractures (severe injury). The analysis shows that the injury risk function was not dependent on the loading condition, but was strongly dependent on age. A significant injury risk model with good ability to discriminate injury from non-injury tests ($P < 0.0001$, chi-square $= 21.49$, area under receiver operator characteristic curve (ROC) $= 0.867$, Kruskal's Gamma $= 0.732$) is presented using only maximum chest deflection and cadaver age as predictors of injury risk. The 50% risk of any rib fractures is found to occur at 35% chest deflection for a 30-year-old, but at 13% deflection for a 70-year-old. The 50% risk of severe injury is shown to occur at 33% chest deflection for a 70-year-old, but at 43% for a 30-year-old.

Keywords: Thoracic injury; Risk functions; Aging; Automotive trauma; Air bag injury; Seatbelt injury

1. Introduction

Injury metrics measured by anthropomorphic test dummies (ATDs) in crash tests are used to educate the car-buying public about relative safety performance of competing vehicles and to legislate performance standards for manufacturers. ATD measurements are also used by federal policy groups to justify legislation and to estimate societal benefit from motor vehicle safety standards [1] and by researchers to assess the economic and injury-reducing impact of proposed legislation or consumer information crash testing [2]. Finally, the interpretation of ATD metrics in crash reconstruction tests aids in establishing the probability of a hypothesized injury mechanism. In order to translate ATD measurements into meaningful real-world injury probabilities, however, it is necessary to have well-defined and sufficiently descriptive functions relating the measurements to injury risk. The U.S. National Highway Traffic Safety Administration (NHTSA) recently published a compilation of injury risk functions for several measurements covering many body regions, but most of these functions do not consider factors such as age or the environment in which the measurement was taken [3].

The posterior displacement of the sternum relative to the spine is an established indicator of thoracic injury risk [4–10]. This displacement, commonly referred to as chest deflection, is measured by contemporary frontal impact ATDs and a chest deflection limit is specified in U.S. federal motor vehicle safety standard (FMVSS) 208. The injury risk associated with a particular magnitude of chest deflection is not, however, constant for all conditions. For example, Zhou et al. [11] showed that chest deflection tolerance decreases with increasing age. One purpose of this paper is to expand on the analysis of Zhou et al. by developing closed form, continuous functions that describe thoracic injury risk as a function of age. The second purpose is to evaluate how the

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nature of the loading on the chest influences the age-dependent chest deflection injury tolerance. Contemporary automotive restraints generate a complex loading environment on the chest. Interaction with an air bag results in a well-distributed, nearly constant pressure field on essentially the entire anterior chest, the neck, and the head. In contrast, the shoulder belt generates concentrated forces on fewer anatomical structures (clavicle, sternum, ribs). Steering wheel loading involves yet a third distinct pattern. Further complicating the issue is the fact that many collisions will involve a combination of different loading patterns (e.g., belt and bag or bag and wheel). The significance of these diverse loading conditions has historically not been considered in the development of chest deflection injury risk functions [3]. If the chest deflection injury tolerance varies significantly as the loading environment changes from belt to hub to air bag loading, then the assessment of restraint systems must consider this sensitivity.

2. Methods

2.1. Dataset development

The literature was searched to identify cadaver tests having certain characteristics. Five inclusion criteria for the dataset were established:

1. The cadaver must have been subjected to anterior loading (i.e., lateral impacts were not considered).
2. The age and gender of the cadaver must be known.
3. The number of rib fractures resulting from the loading must be known.
4. The loading must be directed through the sternum.
5. The chest deflection must have been measured reliably.

Ninety-three tests were available for consideration after eliminating those that failed one or more of the criteria listed above (Appendix A). The tests can be conveniently grouped into four primary loading conditions:

1. Blunt hub loading (41 tests).
2. Seatbelt loading (26 tests).
3. Distributed loading (12 tests).
4. Combined belt-and-bag loading (14 tests).

The blunt hub loading condition involved cadavers with either a fixed or free back loaded by a 15.2-cm diameter circular hub at the approximate location of the fourth interstitial space. All but one of these tests were first described by Kroell et al. [4,12], but the values used here were taken from Viano [6], who summarized the tests in a convenient form. One blunt hub test was performed by Kent et al. [13] The seatbelt loading condition involved cadavers positioned supine on a flat loading table with a narrow belt passing diagonally over the anterior thorax [13–15]. The distributed loading tests were of three types—seven tests come from a series of static, out-of-position air bag deployment tests [16], three tests come from a series of sled tests with an air bag and no shoulder belt [9], and two were bench-top tests [13]. The combined belt-and-bag loading condition involved cadaver sled tests from several sources [9,17,18].

Table 1
Models developed and evaluated

Model	Outcome	Predictors
1	>6 Rib fractures	Age, gender, loading cond., Cmax, age × gender
2	>0 Rib fractures	
3	>6 Rib fractures	Age, Cmax
4	>0 Rib fractures	

2.2. Analysis

Four mulivariate linear logistic regression models were used to evaluate whether the injurious level of maximum chest deflection (Cmax) was sensitive to the age of the cadaver at death or to the loading condition (Table 1). Two outcomes were modeled. In both cases, the outcome variable was a binary response. In one set of models, cases with any rib fractures ($fx > 0$) were coded as ‘injury’ ($Y = 1$) and cases with no rib fractures ($fx = 0$) were coded as ‘no injury’ ($Y = 0$). In another set of models, cases with more than six rib fractures ($fx > 6$) were coded as ‘severe injury’ ($Y = 1$) and cases with six or fewer fractures were coded as ‘no severe injury’ ($Y = 0$). Abbreviated injury scale (AIS) coding could not be used because many of the tests were published prior to the advent of the AIS scale and the fracture locations were not presented in sufficient detail to determine AIS.

For each outcome level, a full model was developed. The full models included all available parameters that have a biomechanical justification for potentially influencing injury threshold: Cmax, the age of the cadaver at death, the loading condition, gender, and an age × gender interaction term. Based on the results of the full models, reduced models were developed for each outcome level using only those predictors that were found to be significant in the full model. Generalized Wald tests were performed to verify the validity of removing these variables. For all models, the relative importance of each covariate was assessed using the covariate’s Wald chi-square statistic minus its degrees of freedom (DOF).

Gender (1 = male) and the loading condition were treated as classification variables in the analysis, while age (years) and Cmax (percent of initial anterior-posterior chest depth) were treated as continuous covariates.

The logit of the probability of injury, $P(\mathrm{I})$, was modeled as a linear function of the value of the predictors, x_i:

$$P(\mathrm{I}) = \frac{1}{1 + \mathrm{e}^{-q}} \tag{1}$$

where

$$q = \alpha + \sum_i \beta_i x_i \tag{2}$$

is the logit function, α is the intercept, x_i are the model predictors, and β_i are the coefficients associated with each predictor.

Several parameters were utilized to evaluate the predictive ability of the various models, including percent concordance and discordance, Kruskal's Gamma, and the area under the receiver operator characteristic curve (ROC) [19–21]. For a predictor or set of predictors that produces an area under the ROC value of 0.50, the utility of the model to correctly classify the outcomes is no better than basing the classification on the flip of a fair coin, while perfect discrimination corresponds to an area under the ROC of 1.0. As a general guideline, models that produce an area under the ROC within the range of 0.50–0.60 are considered to have little or no utility as a discriminating tool, 0.60–0.70 poor utility, 0.70–0.80 moderate utility, 0.80–0.90 good utility, and 0.90–1.0 excellent utility.

3. Results

The dataset includes 93 tests, of which 71 resulted in at least one rib fracture and 39 resulted in more than 6 rib fractures. The age range is 17–86 years (median 60.2, standard deviation 13.3) and the majority of the subjects (66) are male. A distribution of injury and non-injury (both levels of injury) cases is present for each loading condition.

The model coefficients for Model 1 and Model 2 and their standard errors (S.E.) are presented in Table 2 and the analysis of variance (ANOVA) is presented in Table 3. Model 1 is a significant model of the outcome ($P = 0.0033$), but only two of the covariates (age and Cmax) are significant to the $P = 0.05$ level. Gender, loading condition, and the age × gender interaction term are not significant covariates. The chi-square minus DOF ranking indicates that Cmax is the most important covariate in terms of predicting severe injury outcome, followed by age, gender, and age × gender. The loading condition is the least important of the predictors. Model 2 is also a significant predictor of the outcome. The ANOVA results are similar to the findings for Model 1: age and Cmax were the only significant covariates and ranked as the most important predictors in the model. Again, the loading condition is the least important predictor in the model. Fig. 1 illustrates the load condition insensitivity of the injury risk functions.

The generalized Wald test showed no significant change in the predictive ability of Model 1 or Model 2 when the variables gender, loading condition, and age × gender were dropped (Model 1, $P = 0.6390$ and Model 2, $P = 0.3456$). The model coefficients and S.E. for these reduced models

Table 2
Model coefficient estimates and S.E. for Model 1 and Model 2

Coefficient	Model 1 (rib *fx* > 6)		Model 2 (rib *fx* > 0)	
	Estimate	S.E.	Estimate	S.E.
Intercept	−7.0223	2.7625	−14.6737	5.2166
Age (years)	0.0204	0.0289	0.1870	0.0785
Gender = male	−5.1708	3.1596	6.0046	4.2944
Load cond. = seatbelt	−0.1178	1.0003	1.4037	1.0143
Load cond. = istributed	0.0895	0.7581	1.4564	0.9362
Load cond. = combined	−0.3674	1.0413	2.5619	1.6376
Cmax (%)	0.1781	0.0499	0.1875	0.0503
Age × gender = male	0.0720	0.0497	−0.1273	0.0804

Table 3
ANOVA Wald chi-square statistics for Model 1 and Model 2

Predictor	Model 1 (rib *fx* > 6)			Model 2 (rib *fx* > 0)		
	Chi-Square	DOF	*P*	Chi-Square	DOF	*P*
Cmax	12.7631	1	<0.01	13.8960	1	<0.01
Age	5.8047	2	0.05	9.2504	2	0.01
Gender	3.1399	2	0.21	2.5064	1	0.11
Age × gender	2.1023	1	0.15	2.9023	2	0.23
Load cond.	0.1966	3	0.98	3.6775	3	0.30
Total	21.3644	7	<0.01	17.7368	7	0.01

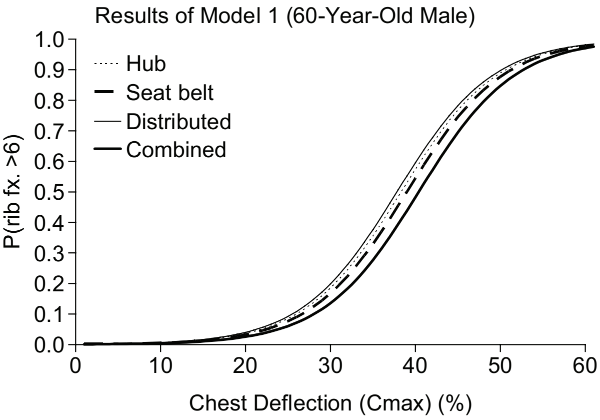

Fig. 1. Results of Model 1 showing load condition insensitivity of Cmax injury threshold.

Table 4
Model coefficient estimates and S.E. for Model 3 and Model 4

Coefficient	Model 3 (rib *fx* > 6)		Model 4 (rib *fx* > 0)	
	Estimate	S.E.	Estimate	S.E.
Intercept	−9.3189	2.0965	−6.7508	1.8814
Age (years)	0.0474	0.0215	0.0720	0.0230
Cmax (%)	0.1838	0.0423	0.1302	0.0345

(Model 3 and Model 4) are presented in Table 4 and the ANOVA results are presented in Table 5. Both reduced models were significant. Age and Cmax were significant predictors in both models and Cmax remained a more important predictor than age.

The most important determinant of the validity of our model reduction strategy is whether the reduced models remained equally able to discriminate tests with injury from those without. As shown in Table 6, very little injury predictive ability is lost with the removal of the non-significant covariates. The indicators of discrimination decrease slightly for the injury onset models (Model 2 versus Model 4) while, for the severe injury outcome (Model 1 versus Model 3), the performance is unchanged.

The injury risk functions from Model 3 and Model 4 are plotted in Fig. 2. The top plot shows the risk functions for both injury outcomes along with their 95% confidence intervals. The bottom plot illustrates the age sensitivity of both outcomes.

Table 6
Predictive performance of all four models

	Model 1	Model 2	Model 3	Model 4
Percent concordance	86.56	90.27	86.61	87.71
Percent discordance	13.44	9.73	13.39	12.29
Percent ties	0	0	0	0
Kruskal’s Gamma	0.73	0.81	0.73	0.75
Area under ROC	0.87	0.90	0.87	0.88

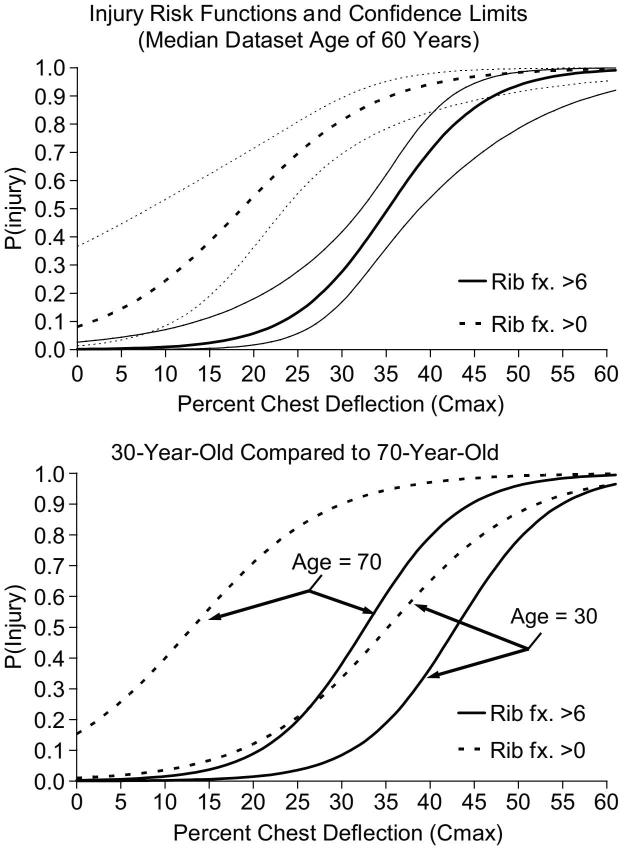

Fig. 2. Injury risk functions from Model 3 and Model 4. Top plot shows injury onset risk function and severe injury risk function along with 95% confidence intervals for a 60-year-old. Bottom plot compares injury onset risk and severe injury risk for two ages.

Table 5
ANOVA Wald chi-square statistics for Model 3 and Model 4

Predictor	Model 3 (rib *fx* > 6)			Model 4 (rib *fx* > 0)		
	Chi-square	DOF	*P* value	Chi-square	DOF	*P* value
Cmax	18.8401	1	<0.01	14.2762	1	<0.01
Age	4.8644	1	0.03	9.8290	1	<0.01
Total	21.4868	2	<0.01	17.7748	2	<0.01

4. Discussion

This study has shown that the chest deflection injury threshold is strongly dependent on the age of the subject. This is true regardless of whether injury onset or severe injury is considered. A 30-year-old has a 50% risk of sustaining one rib fracture at a chest deflection level of 35%. This threshold drops to 13% deflection for a 70-year-old. A 30-year-old has a 50% risk of sustaining more than six rib fractures at a deflection level of 43%, while a 70-year-old can tolerate only 33% deflection before reaching this threshold. These findings are consistent with other studies [11] and are presumably due to multiple characteristics of aging. First, the failure strain of both cortical and trabecular bone decreases with age. Second, geometric changes associated with aging may predispose ribs to fracturing for older subjects under conditions where they might deflect non-injuriously in a younger subject. These geometric changes include a decrease in the proportion of the rib cross-section that is cortical bone [22] and a general decrease in rib slope [23]. Finally, material changes such as calcification of the costal cartilage and decreasing bone mineral density also are likely contributors to the decreased chest deflection tolerance.

The second important finding of this study is that the chest deflection injury tolerance is insensitive to the loading condition. This finding greatly simplifies the relative assessment of injury risk for different restraint systems (belt-only, air bag-only, combined belt-and-bag) since Cmax, as measured on the human, can be considered to be an objective injury criterion for different restraint conditions (as long as the loading is concentrated through the sternum rather than, for example, through the abdomen and lower rib cage). We have not shown, however, that chest deflection as measured by a dummy has a relationship to injury threshold that is insensitive to the restraint type. In fact, recent studies have found marked sensitivity, [24,25] presumably due to a lack of ATD biofidelity for restraint loading. The interpretation of dummy-based chest deflection is a logical extension of the current study.

As more data become available, it may become possible to develop models that include significant covariates for gender and an age × gender interaction. Future studies should also consider the effect of cadaver mass, body composition (such as changes in the depth of superficial soft tissues), and pulmonary cycle. Furthermore, a Cmax sensitivity to load condition may eventually be shown once sufficient data are collected to overcome the inherent variability in cadavers, which currently overwhelms any sensitivity to loading condition.

5. Conclusions

The chest deflection injury tolerance is strongly dependent on age and this study has quantified this dependence for two levels of injury severity—rib fracture onset and greater than six rib fractures. This study has also shown that the chest deflection injury tolerance is insensitive to the loading condition on the chest within the range of conditions considered (blunt hub, seat belt, air bag, combined belt-and-bag). This insensitivity does not necessarily apply to chest deflection as measured by an ATD.

Acknowledgements

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Appendix A. Dataset of cadaver tests used in the analysis

Loading cond.	Cmax (%)	Number of Rib fractures	Age	Gender	Test ID	Reference
Blunt hub	32.9	9	59	m	172/43fm	[6][a]
Blunt hub	32.1	0	61	m	171/42fm	[6][a]
Blunt hub	31.5	10	64	m	177/45fm	[6][a]
Blunt hub	26.9	9	66	m	200/60fm	[6][a]
Blunt hub	25.7	3	75	m	189/53fm	[6][a]
Blunt hub	37.3	4	53	m	203/63fm	[6][a]
Blunt hub	37.1	6	72	m	204/64fm	[6][a]
Blunt hub	39.3	9	80	m	69/15fm	[6][a]
Blunt hub	44.4	12	81	m	65/13fm	[6][a]
Blunt hub	42.0	14	67	f	61/12ff	[6][a]
Blunt hub	43.5	6	76	f	66/14ff	[6][a]
Blunt hub	32.8	6	48	m	104/37fm	[6][a]
Blunt hub	45.9	11	51	m	93/31fm	[6][a]

Appendix A. *(Continued)*

Loading cond.	Cmax (%)	Number of Rib fractures	Age	Gender	Test ID	Reference
Blunt hub	42.5	16	65	m	86/24fm	[6][a]
Blunt hub	45.8	13	75	m	94/32fm	[6][a]
Blunt hub	28.9	17	60	m	47/5fm	[6][a]
Blunt hub	32.5	11	83	m	50/6fm	[6][a]
Blunt hub	44.7	11	64	m	96/34fm	[6][a]
Blunt hub	40.7	7	49	f	190/54ff	[6][a]
Blunt hub	41.8	11	58	f	85/23ff	[6][a]
Blunt hub	39.5	10	65	m	87/25fm	[6][a]
Blunt hub	35.0	6	66	m	219/120fm	[6][a]
Blunt hub	37.0	10	69	m	218/119fm	[6][a]
Blunt hub	18.5	0	75	m	88/26fm	[6][a]
Blunt hub	19.4	0	54	m	92/28fm	[6][a]
Blunt hub	31.0	3	52	f	92/30ff	[6][a]
Blunt hub	37.7	0	60	m	187/51fm	[6][a]
Blunt hub	39.4	3	65	m	192/56fm	[6][a]
Blunt hub	48.6	9	65	m	188/52fm	[6][a]
Blunt hub	43.1	10	66	m	186/50fm	[6][a]
Blunt hub	39.0	4	68	m	196/58fm	[6][a]
Blunt hub	39.7	0	69	m	182/48fm	[6][a]
Blunt hub	37.5	0	19	m	77/19fm	[6][a]
Blunt hub	35.0	0	29	m	79/20fm	[6][a]
Blunt hub	41.7	17	72	m	83/22fm	[6][a]
Blunt hub	41.8	14	78	m	76/18fm	[6][a]
Blunt hub	31.0	0	46	m	178/46fm	[6][a]
Blunt hub	34.6	7	52	m	99/36fm	[6][a]
Blunt hub	40.7	8	46	f	191/55ff	[6][a]
Blunt hub	37.0	9	58	m	220/123fm	[6][a]
Blunt hub	41.4	6	54	m	145	[13]
Comb.	23.0	0	57	m	577	[9]
Comb.	25.0	4	69	f	578	[9]
Comb.	34.0	11	72	f	579	[9]
Comb.	28.0	0	57	m	580	[9]
Comb.	28.0	3	55	m	665	[9]
Comb.	32.0	3	69	m	666	[9]
Comb.	36.0	13	59	f	667	[9]
Comb.	14.5	1	67	f	533	[17]
Comb.	18.3	4	47	m	534	[17]
Comb.	31.5	16	57	f	535	[17]
Comb.	15.7	3	67	m	545	[17]
Comb.	26.7	1	63	f	C11	[18]
Comb.	23.8	2	58	m	C12	[18]
Comb.	28.2	0	50	m	C13	[18]
Seat belt	27.1	6	60	m	THC 75	[15]
Seat belt	26.1	6	64	f	THC 77	[15]
Seat belt	28.7	3	43	m	THC 79	[15]
Seat belt	27.4	10	63	m	THC 93	[15]
Seat belt	25.2	2	63	m	THC 91	[15]
Seat belt	11.8	0	64	f	THC 76	[15]
Seat belt	11.8	0	43	m	THC 78	[15]
Seat belt	10.2	0	63	m	THC 90	[15]

Appendix A. *(Continued)*

Loading cond.	Cmax (%)	Number of Rib fractures	Age	Gender	Test ID	Reference
Seat belt	12.1	0	63	m	THC 92	[15]
Seat belt	34.1	8	47	f	THC 11	[14]
Seat belt	35.4	0	17	f	THC 12	[14]
Seat belt	25.1	2	86	f	THC 13	[14]
Seat belt	29.8	17	69	m	THC 14	[14]
Seat belt	29.1	3	60	m	THC 15	[14]
Seat belt	35.4	4	59	m	THC 16	[14]
Seat belt	30.0	7	71	m	THC 17	[14]
Seat belt	9.5	0	72	m	THC 61	[14]
Seat belt	14.4	0	71	m	THC 64	[14]
Seat belt	11.3	0	40	m	THC 68	[14]
Seat belt	36.3	6	67	m	THC 18	[14]
Seat belt	28.4	4	83	f	THC 19	[14]
Seat belt	30.1	18	70	m	THC 20	[14]
Seat belt	22.8	4	72	m	THC 62	[14]
Seat belt	36.1	10	71	m	THC 65	[14]
Seat belt	30.6	1	40	m	THC 69	[14]
Seat belt	40.8	14	63	f	147	[13]
Dist.	29.6	9	61	f	386	[16]
Dist.	71.0	29	45	f	387	[16]
Dist.	36.6	4	34	f	388	[16]
Dist.	43.7	25	68	f	421	[16]
Dist.	40.6	17	67	f	422	[16]
Dist.	42.2	13	51	f	423	[16]
Dist.	55.2	20	55	f	424	[16]
Dist.	0.35	4	69	m	116	[26]
Dist.	0.35	0	29	f	143	[26]
Dist.	0.0	4	40	m	650	[9]
Dist.	11.0	0	70	m	651	[9]
Dist.	12.0	0	46	m	652	[9]

[a] These tests were published earlier, but were compiled in a convenient form by Viano.

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