INJURY BIOMECHANICS RESEARCH
Proceedings of the Forty-Ninth NHTSA Workshop on
Human Subjects for Biomechanical Research

Thoracic Injury Criteria Considerations for the THOR 5th ATD

E.L. Lee and M. Craig
National Highway Traffic Safety Administration, Washington DC, USA

ABSTRACT

The purpose of this paper is to develop preliminary female-specific injury risk functions suitable for use with the Test device for Human Occupant Restraint (THOR) 5th percentile adult female anthropomorphic test device (ATD), or THOR-05F. To that end, NHTSA has conducted testing using small female post mortem human subjects (PMHS) to study the thoracic injury tolerance of females and develop female-specific injury risk functions applicable to the THOR-05F.

PMHS-based injury risk functions (IRFs) were investigated using logistic regression and survival analysis for two primary datasets: 1) A recent series of thirty-seven sled tests with small female subjects (subsequently called "small female" dataset); 2) The "small female" dataset plus additional female subjects from prior studies (subsequently called "all female" dataset). Next, THOR-05F specific IRFs were investigated using matched pair tests conducted for the "small female" dataset. Predictor variables examined included the maximum deflection at any of the four IR-TRACCs (Upper Left, Upper Right, Lower Left, Lower Right) in the X-axis, X-Y resultant and X-Y-Z resultant.

Age, mass and stature were not significant explanatory variables for either PMHS or ATD-specific functions. Results demonstrated that peak THOR-05F deflections tended to underpredict peak PMHS deflections. Overall, model fit statistics demonstrated that the proposed female-specific risk functions matched the available data well. However, this work identified gaps in the available data for which additional testing in realistic restraint conditions and from younger aged subjects would be beneficial.

INTRODUCTION

Thorax injuries remain prevalent in frontal crashes, despite current crash tests, conducted by the National Highway Traffic Safety Administration (NHTSA) and other vehicle safety programs around the world, using the Hybrid III family of crash dummies. In addition, females may have greater risk of thorax injury than males in a comparable crash (Kahane, 2013; Forman et al., 2019; Parenteau et al., 2013). NHTSA's mission is to save lives, prevent injuries and reduce traffic-related health care and other economic costs. A key component of this mission is the development of evaluation tools, such as anthropomorphic test devices (ATDs), that can be used to study crash injury risk and improve vehicle safety. NHTSA has been researching advanced frontal ATDs since the early 1980s, beginning with the 50th percentile adult male ATD, and later expanding to the 5th percentile female ATD. The Test device for Human Occupant Restraint (THOR) 5th percentile female anthropomorphic test device (ATD), referred to as THOR-05F, is the most recently developed advanced frontal dummy (https://www.regulations.gov/docket/NHTSA-2019-0107). The THOR-05F is capable of measuring three-dimensional deflections at four different locations on the rib cage, using Infrared Telescoping Rod for Assessment of Chest Compression (IR-TRACC) devices. Biofidelity of the THOR-05F thorax was evaluated in sternal impact and lower ribcage oblique impact and rated as "good" (Wang et al. 2018), using NHTSA's Biofidelity Ranking System (BioRank). For the THOR-05F to be used as a tool for development of vehicle safety countermeasures or evaluation of vehicle safety performance in frontal crashworthiness testing, injury criteria need to be developed. To that end, NHTSA has conducted testing using small female post mortem human subjects (PMHS) to study the injury tolerance of females in realistic, simulated crash conditions. The purpose of this paper is to use these data to develop female-specific injury risk functions suitable for use with the THOR-05F ATD.

METHODS

Experimental Data

To develop female-specific injury criteria, a series of thirty-seven sled tests were conducted with thirty-one small female PMHS. THOR-05F ATD matched pair tests were also conducted for each test series for ATD-specific injury criteria development. In addition to this recent test data, female data from prior studies were considered for inclusion. See Appendix for specimen information and associated test reference numbers for locating the associated test data in the NHTSA Biomechanics Test Database (NHTSA, 2022).

Gold standard, frontal. This series was conducted in what is commonly known as the "gold standard" sled buck (Shaw et al. 2016; Crandall, 2016; Crandall, 2018). The subjects were positioned in a rigid seat back and bottom, with the lower extremities restrained by rigid knee bolsters that were in contact with the tibia at the start of the event (**Figure 1).** The subjects were restrained using a lap and shoulder belt with a custom force-limiter. The frontal (0°) sled tests were conducted at three speeds (30 km/h, 20 km/h and 10 km/h), with custom belt force limits of 2kN and 1.3 kN for the 30 and 20 km/h speeds, respectively. The target specimen anthropometry was that of a 5th percentile female (**Table 1**). Chest deflections (sternum, left rib 4, left rib 7, right rib 4, right rib 7) were measured with respect to the T8 vertebrae, using Vicon motion tracking markers mounted directly to the ribcage.

Gold standard, oblique. This series (Humm et al. 2018) was also conducted in the "gold standard" sled buck (Figure 1). The subjects were instrumented and seated in the same position as the Gold Standard, frontal tests. The sled buck was oriented ±30° from the acceleration of the sled, resulting in near-side and far-side oblique conditions. Tests were conducted at two speeds (30 km/h and 15 km/h), with a 2 kN belt load limit targeted for all tests. The target specimen anthropometry was that of a 5th percentile female (**Table 1**).

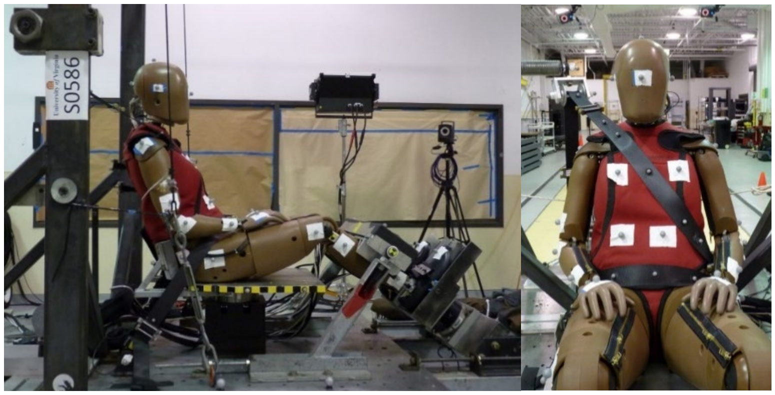


Figure 1. THOR-05F positioned in the "gold standard" sled buck.

Frontal tests in driver's seat and rear seat. This series simulated a frontal impact in an actual driver's seat and an actual rear passenger seat (Toyota Yaris, 2nd generation, MY 2005-2013, **Figure 2**). The driver's seat buck was equipped with OEM 3-point belt with pretensioner and front airbag. The pretensioner and airbag were activated 10 ms into the event. The rear passenger seat buck was equipped with OEM 3-point belt (no pretensioner or load limiter). The sled pulse had a delta-V of 48 km/h with a peak acceleration of 20 g. The target specimen anthropometry was that of a 5th percentile female (**Table 1**).

External chest deflections were measured using two 59-gauge chestbands, located at the levels of ribs 4 and 7. Deflections were measured at the sternum, and left and right locations, using CrashStar software (v2.5). The deflection of gauges located closest to the left and right rib 4 costochondral joints and sternum for the upper band and the left and right rib 7 costochondral joints for the lower band were calculated with respect to the reference (center of the T8 vertebrae).

The subjects tested in this series had previously been tested in the low speed (15 km/h) oblique gold standard condition. Between tests, a full set of computed tomography (CT) scans and x-rays were obtained, and manual examination by a clinician was performed to determine if any injuries were sustained. The subjects sustained between zero and two fractured ribs during the low speed tests and were therefore deemed acceptable to test in the higher speed frontal condition.

Figure 2. THOR-05F positioned in the front seat (left) and rear seat (right) sled bucks.

Table 1. Series of thirty-seven sled tests conducted with small female post-mortem human subjects.

Test condition	Orientation	Restraints	Speed (km/h)	Mean (s.d.) age, yr	Mean (s.d.) mass, kg	Mean (s.d.) stature, cm	Number of PMHS tested	Chest Deflection method
Gold standard	Frontal	3-pt Force Limited belt (2 kN)	30	74 (13)	42.4 (9.1)	157.5 (5.9)	10	Vicon
Gold standard	Frontal	3-pt Force Limited belt (1.3 kN)	20	59 (5)	47 (11.3)	159.7 (4.0)	3	Vicon
Gold standard	Frontal	3-pt Belt	10	54 (8)	44.5 (4.9)	153.5 (2.1)	2	Vicon
Gold standard	Near-side	3-pt Force Limited belt (2 kN)	30	70 (12)	47.2 (7.8)	160.3 (4.8)	5	Vicon
Gold standard	Near-side	3-pt Force Limited belt (2 kN)	15	82 (11)	43.8 (5.7)	155.6 (7.7)	5	Vicon
Gold standard	Far-side	3-pt Force Limited belt (2 kN)	30	73 (10)	47.4 (6.5)	152.4 (2.5)	3	Vicon
Gold standard	Far-side	3-pt Force Limited belt (2 kN)	15	76 (16)	48.1 (9.8)	159.2 (3.8)	3	Vicon
Driver's seat	Frontal	Airbag, 3-pt Belt (pretensioner)	48	76 (16)	48.1 (9.8)	159.2 (3.8)	3	Chestband
Rear seat	Frontal	3-pt Belt	48	82 (11)	43.8 (5.7)	155.6 (7.7)	3	Chestband

Prior studies in varying restraint conditions. The data presented in the development of the thoracic injury criterion for the H3-50M as presented by Eppinger et al. (1999) were reviewed. This set of 71 data points, of which 63 were ultimately used in the risk function, included PMHS sled tests at velocities of between 23 km/h and 59 km/h in various restraint configurations including belt-only (2-point and 3-point), airbag only, and belt and airbag conditions. In each test, chestbands were used to measure external chest deformation, which was presented at five different locations: left, center, and right at the vertical level of rib 4, and left and right at the vertical level of rib 8. Of the original 71 specimens, 21 were female and were included in the current study. The 21 females ranged in size (mean stature: 162.8 ± 8.6 cm; mean mass: 65.5 ± 15.8 kg).

In addition, data presented in the development of the injury criteria for the THOR-50M was reviewed (Craig et al. 2020). Included in this dataset were four female PMHS sled tests at 48 km/h for which sufficient data was available for inclusion (mean stature: 158.5 ± 3.5 cm; mean mass: 61.6 ± 11.9 kg). These were a front passenger condition with a 3-point force-limited belt and airbag (Bolton et el. 2000) and a front passenger condition with 3-point standard belt and airbag (Bolton et al. 2006). In each test, chestbands were used to measure external chest deformation at the levels of ribs 4 and 8. The peak external deflection for the upper and lower chestbands were reported.

Data Analysis and Injury Risk Function Development

Two main datasets were evaluated for risk function development: 1) The recent series of thirty-seven sled tests with small female subjects (subsequently called "small female" dataset); 2) The "small female" dataset plus additional female subjects from prior studies (subsequently called "all female" dataset). The maximum deflection at any of five locations (Upper Left-UL, Upper Right-UR, Lower Left-LL, Lower Right-LR, sternum) was investigated as the predictor variable. The experimental data included two methods of measuring chest deflection: chestband and Vicon motion tracking. Because the chestband measures external deflection, these data were adjusted by subtracting 8 mm to account for soft tissue. This method has been used previously (Eppinger et al. 1999). For the Vicon data, three-dimensional deflections were recorded at each site. To combine with the chestband data, which does not capture thorax deflection in the Z-direction, an X-Y resultant deflection was calculated for the Vicon data.

The presence of 3 or more fractured ribs, corresponding to an Abbreviated Injury Scale (AIS) 3+ injury was used as the primary dependent measure. Dependent measures based on higher number of fractured ribs (NFR) were also investigated. Covariates of subject age, mass and stature were investigated using stepwise logistic regression. Normalization was not used for the "small female" model because the subjects were all similar to a 5th percentile female in size. For the "all female" dataset, stature- and mass-based scaling techniques were also investigated to see if those techniques would improve the model fit (given that all female specimens were not necessarily small in size). Normalization factors were used corresponding to 5th percentile stature and mass, as shown below.

ScaledDeflection (stature) = Deflection (150.8/Stature)

ScaledDeflection (mass) = Deflection (50.3/Mass)

The risk curves in this study were developed using a process outlined by Hasija et al. (2011), in which logistic regression was first used to differentiate between non-correlated and well-correlated datasets. Model fit indicators described by Hasija et al. (2011), specifically maximum loglikelihood (-2 Log L), area under the Receiver Operating Characteristic curve (AUROC), and Hosmer-Lemeshow Goodness-of-Fit test (H-L Pr>ChiSq), are reported for the logistic regression models.

Once model correlation was established, injury risk functions were then developed using survival analysis, assuming a Weibull distribution. Exact censoring was not available for any specimen. Non-injured specimens were treated as right-censored, injured specimens were treated as left-censored, and the six specimens tested twice were considered interval censored (all six were not injured at the AIS 3+ level in the first test, and were injured at the AIS 3+ level in the second test). Analysis was performed using SAS (v9.4).

THOR-05F Matched Pair Tests

The THOR-05F ATD was tested in each of the small female test conditions: Gold standard, frontal; Gold standard, oblique; and Frontal tests in driver's seat and rear seat. Three repeat ATD were performed in each condition, at each speed.

Injury risk functions specific to THOR-05F were developed using a similar approach to that of the PMHS-specific risk function described above. Predictor variables examined included X-axis deflection, X-Y resultant deflection and X-Y-Z resultant deflection, with maximum deflection at any of the four IR-TRACCs (UL, UR, LL, LR) being targeted. The PMHS injury state was the outcome that was matched with the ATD deflections.

RESULTS

PMHS Injury Risk Function

For the "small female" dataset, 18 specimens were uninjured and 19 sustained AIS 3+ injury. Of the 62 datapoints in the "all female" dataset, 39 had AIS 3+ injury and 23 were not injured.

Logistic Regression. For the stepwise logistic regressions, age, mass and stature were not significant explanatory variables for this sample, and therefore were not retained as covariates in the final models. Based on AUROC, the "small female" model had the best model fit. For the "all female" model, normalization of the data using stature and mass did not improve the model fit substantially (Table 2). Therefore, normalization was not used in the final analyses. Notably, the "all female" model was within the 95% confidence bounds of the "small female" regression model (**Figure 3**).

Table 2. Goodness of fit measures and model parameters for PMHS logistic regression analyses.

Dataset	Normalization	N	-2 Log L	AUROC	H-L Pr<ChiSq	Intercept, β_0	Deflection Parameter, β_1
Small female	None	37	25.4	0.927	0.24	-9.1229	0.221
All female	None	62	59.4	0.86	0.15	-3.6705	0.0946
All female	Mass	62	68	0.8	0.37	-2.5724	0.0693
All female	Stature	62	59.4	0.85	0.108	-3.7002	0.1001

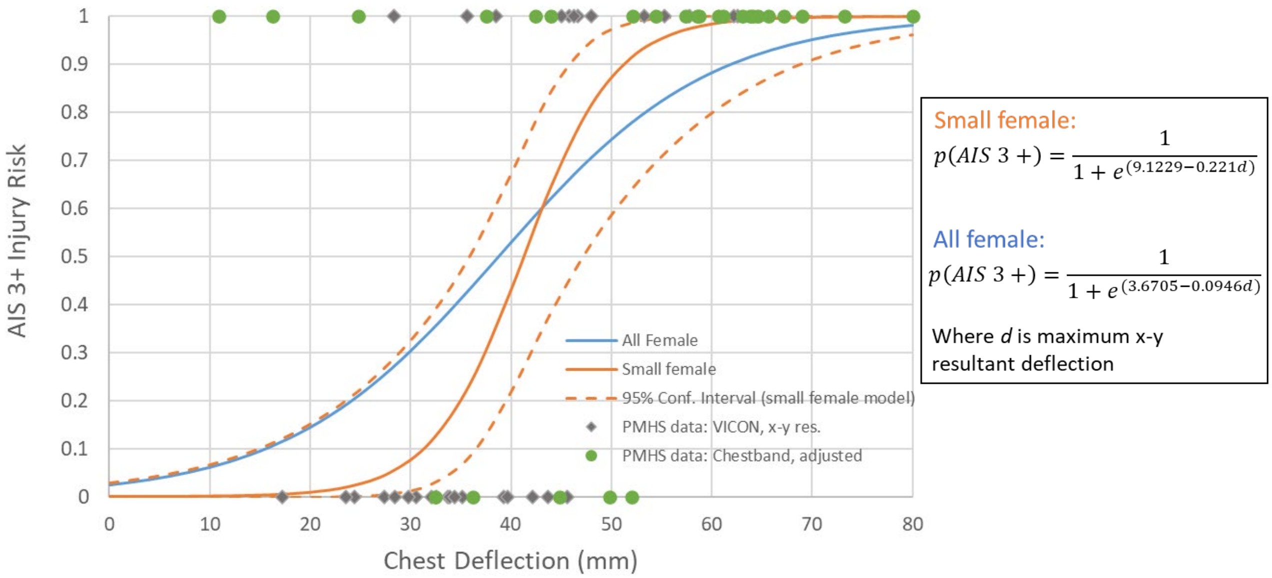


Figure 3. Small female logistic regression, with 95% confidence intervals. Also shown is the all-female regression.

Survival Analysis. The resulting Weibull risk functions, with 95% confidence intervals, are shown in **Figure 4**. The Weibull functions closely matched the logistic functions for both the "small female" and "all female" datasets.

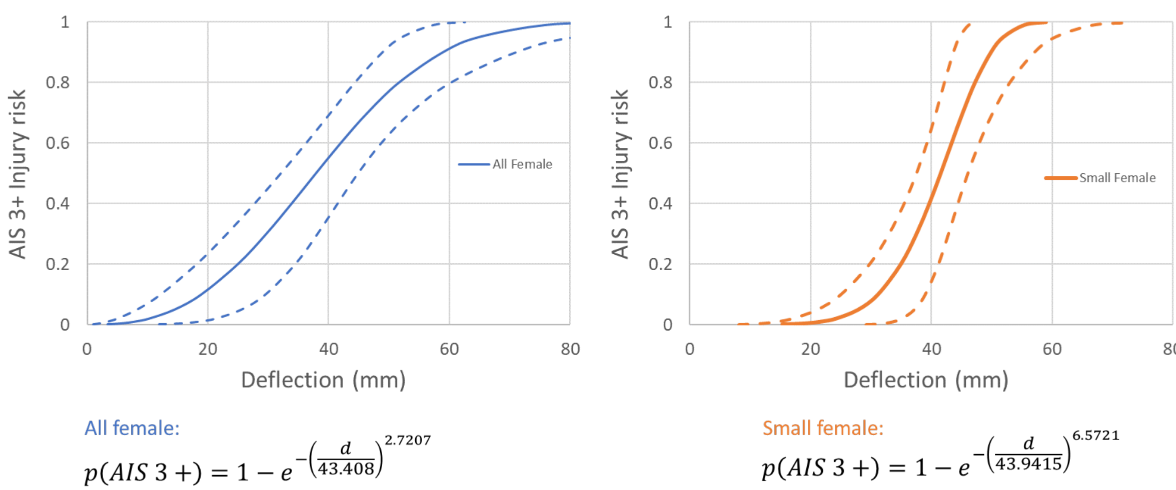


Figure 4. Female-specific PMHS-based injury risk function (left), compared with the small female injury risk function (right), developed with a Weibull distribution.

THOR-05F Injury Risk Function

Logistic Regression. Results from THOR-05F matched pair analysis demonstrated excellent discrimination according to AUROC. However, the significant p-value for H-L GOF test indicates the possibility of a poor model fit (**Table 3**). Like the PMHS-specific risk functions, age, mass and stature were not significant explanatory variables and therefore were not retained as covariates in the final models.

Table 3. Goodness of fit measures and model parameters for ATD-specific logistic regression analyses.

Dataset	Predictor*	N	-2 Log L	AUROC	H-L Pr<ChiSq	Intercept, β_0	Deflection Parameter, β_1
Small female	X-axis Deflection	37	37.15	0.83	0.017	-4.9134	0.1656
Small female	X-Y Resultant Deflection	37	36.88	0.83	0.019	-4.9522	0.1657
Small female	X-Y-Z Resultant Deflection	37	37.35	0.83	0.018	-4.7812	0.1562

*maximum of the 4 IR-TRACCs

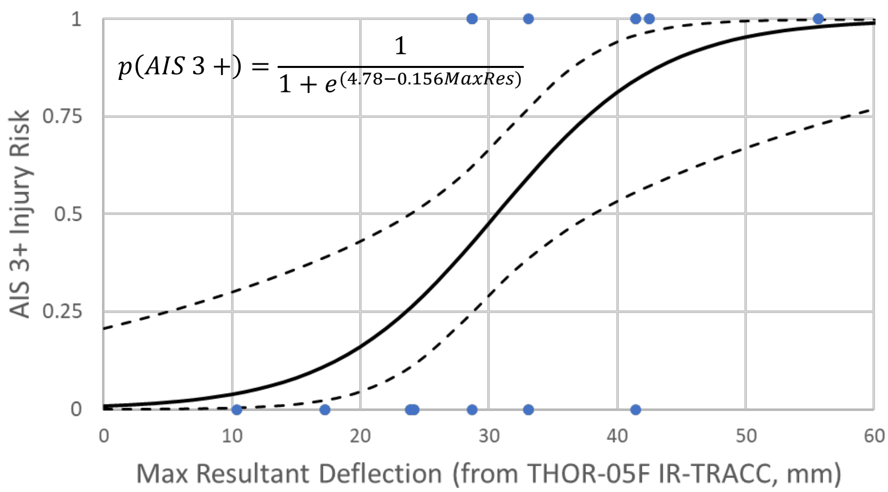


Figure 5. THOR-05F logistic regression with predictor Maximum Resultant Deflection, with 95% confidence intervals.

Survival Analysis. The resulting Weibull risk function is shown in **Figure 6** compared with the PMHS-specific risk functions. The peak deflections of the THOR-05F tended to underpredict the peak deflections experienced by the PMHS, demonstrated by the leftward shift in the ATD risk function.

Some other differences were that the PMHS typically experienced the greatest deflection at the sternum, while the THOR-05F experienced the greatest deflection at the lower IR-TRACC on the inboard/buckle side. This may have been due to the shape and flexibility of the PMHS specimens, which in general tended to fold around the belt in a way that was not replicated by the ATD. Also, while initial ATD belt position was targeted to match the PMHS, the belt still rested differently on the thorax of different surrogates. On the PMHS, in many cases, the belt was not even in contact with the lower inboard region, whereas it was flush with the ATD (and again, this tended to be the location of highest deflection in the ATD).

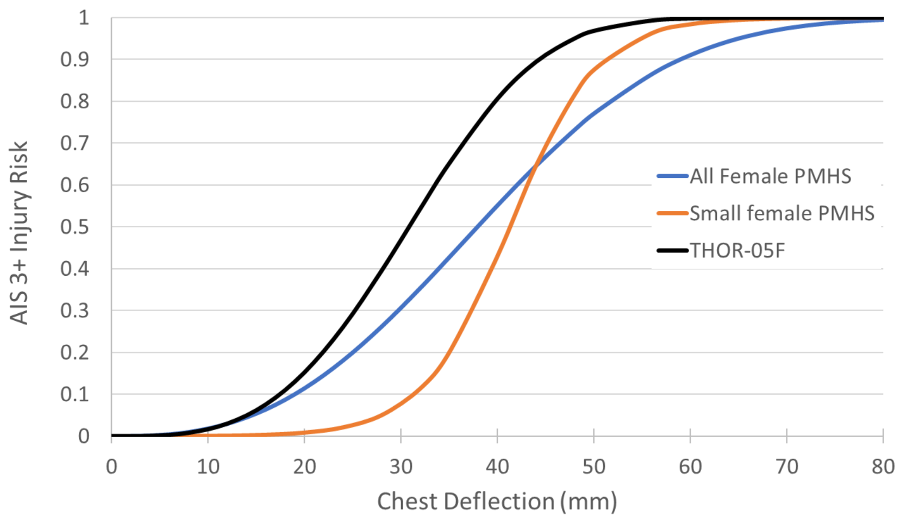
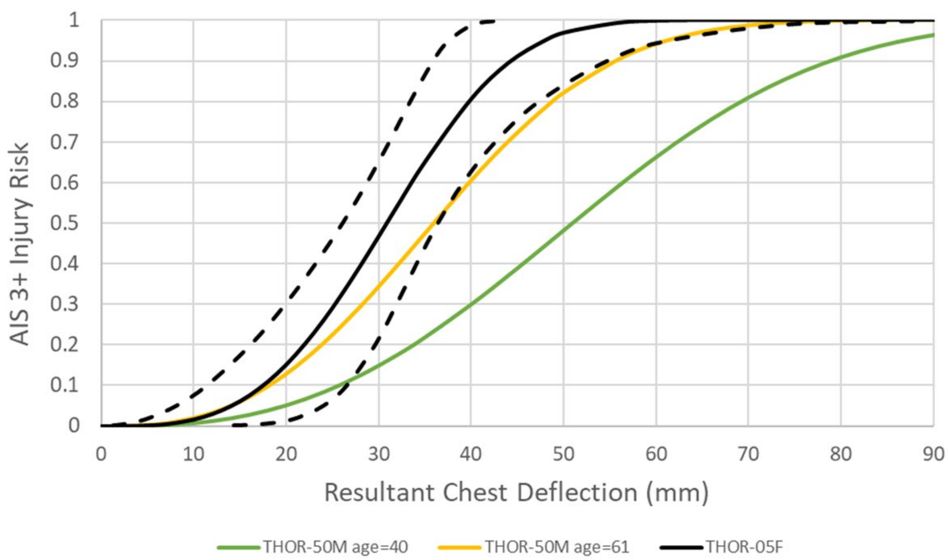


Figure 6. THOR-05F risk function (Weibull distribution) compared with PMHS-specific risk functions.

Finally, the THOR-05F risk function was compared with the published risk function for the 50th male THOR-50M ATD (Craig et al., 2020). The THOR-50M risk function included age as a covariate, due to the finding that age was significant for the sample of tests. As can be seen in **Figure 7**, a given chest deflection produced a similar level of risk in both the THOR-05F function (based on small female data) and the THOR-50M risk function (based on mid-sized male data) when evaluated at age 61. This demonstrates that it will be critical to evaluate the role of age in the female data in the future.



THOR-05F: $p(AIS\,3+) = 1 - e^{-\left(\frac{MaxRes}{34.457}\right)^{3.313}}$

Figure 7. THOR-05F risk function (Weibull distribution, with 95% confidence intervals) compared with THOR-50M risk function at two distinct ages (40 years and 61 years).

Discussion

While there are many methods in the literature for developing injury risk functions, the risk curves in this study were developed using a process outlined by Hasija et al. (2011), in which logistic regression was first used to differentiate between non-correlated and well-correlated datasets. For a well-correlated dataset with overlapping left and right censored injury and non-injury data, Hasija et al. (2011) demonstrated that both logistic regression and survival analysis (with Weibull, log-logistic or log-normal) produce nearly identical risk functions. McMurry et al. (2015) described a similar approach, whereby a logistic regression is fit first, followed by a Weibull distribution to extrapolate to smaller risks. McMurry et al. (2015) noted that if the Weibull and logistic fits differ significantly, the logistic regression should be taken as more reliable in the middle of the data, and the Weibull should not be used. This approach was used in the current study, and both logistic regression and survival analysis were evaluated.

For a given deflection (up to about 45 mm), the “all female” risk functions predict higher AIS 3+ injury risk than the “small female” risk function. Inclusion of bigger female specimens to the dataset was expected to lower risk for a given deflection, because bigger specimens would be expected to require more deflection to cause injury. This may have occurred because the “small female” dataset was much more homogenous in both size and restraint condition, with the majority of tests being “gold standard” style tests with force-limited belts and knee bolsters restraining the lower extremity, but no airbag.

An influence analysis demonstrated that there were three observations in the “all female” dataset that may be considered overly influential (based on DFBETAS diagnostic$>2/\sqrt{n}$). There was also one observation in the small female dataset that would be considered influential, using the same criterion. These four possibly influential specimens sustained injury at low values of chest deflection. One of these specimens, who was also one of the heaviest at 97 kg, was originally excluded by Eppinger due to head contact with the sun visor during the sled test, which resulted in high spinal accelerations. Since the current effort was focused on chest deflections (rather than accelerations), this specimen was included in the current study. For the other three possibly influential specimens, there was no apparent physical or biomechanical reason to warrant exclusion. As such, all specimens were retained in the current study.

Age was not a significant predictor of injury in the current study. This was surprising, given extensive prior literature concluding age increases chest injury risk (Hanna and Hershman, 2009; Stitzel et al., 2010). The specimens tended to be older and relatively homogeneous in age (mean age for all female specimens: 68±14 years; mean age for small female specimens: 72±13 years), which likely contributed to the lack of significance. The resulting risk functions should therefore be interpreted cautiously if applied to populations younger than included in the current study.

Finally, note that THOR-05F matched pair data was not available for all the PMHS data in the expanded “all female” dataset. Since some of the prior data used was conducted in the early 1990’s, obtaining identical fixtures and restraint systems with which to test the THOR-05F would likely be impossible.

CONCLUSIONS

This study developed preliminary female-specific injury risk functions for both PMHS and THOR-05F. A key finding was that age was not a significant predictor of injury for the current sample, likely due to the older age of most specimens. This work found that the proposed risk functions matched the available data well. However, gaps were identified in the available data. Specifically, the ATD-specific risk function will benefit from additional data collection in realistic restraint conditions and from younger aged subjects.

ACKNOWLEDGEMENTS

Testing was conducted by the University of Virginia and the Medical College of Wisconsin.

REFERENCES

BOLTON, J.R., KENT, R.W., CRANDALL, J.R. (2000) Passenger airbag impact and injury response using a Hybrid III test dummy and human surrogates. NHTSA Biomechanics Database (Report b8372).

BOLTON, J.R., KENT, R.W., CRANDALL, J.R. (2006) Passenger airbag impact and injury response using a Hybrid III test dummy and human surrogates. NHTSA Biomechanics Database (Report b8384).

CRAIG, M., PARENT, D., LEE, E., RUDD, R., TAKHOUNTS, E., HASIJA, V. (2020). Injury Criteria for the THOR 50th Male ATD. Washington, DC: National Highway Traffic Safety Administration.

CRANDALL, J. (2016). Small Female/Older Occupant Thoracic Biofidelity: Gold Standard Buck Condition 2.1: 2 kN Force Limited Belt, 30 km/h Frontal, Tests UVA0370-0374. NHTSA Biomechanics Database (Report b12083-1).

CRANDALL, J. (2018). Small Female/Older Occupant Thoracic Biofidelity: Gold Standard Buck Frontal Condition: Low (4g peak, 10 km/h) and Intermediate (6g peak, 20 km/h), Tests UVA0470-0474. NHTSA Biomechanics Database (Report b12810-1).

EPPINGER, R., SUN, E., BANDAK, F., HAFFNER, M., KHAEWPONG, N., MALTESE, M., KUPPA, S., NGUYEN, T., TAKHOUNTS, E., TANNOUS, R., ZHANG, A., SAUL, R. (1999). Development of improved injury criteria for the assessment of advanced automotive restraint systems–II. Washington, DC: National Highway Traffic Safety Administration.

FORMAN J., POPLIN G.S., SHAW C.G., MCMURRY T.L., SCHMIDT K., ASH J., SUNNEVANG C. (2019). Automobile injury trends in the contemporary fleet: Belted occupants in frontal collisions, Traffic Injury Prevention, 20(6), pp.607-612

HANNA R., HERSHMAN L. (2009). Evaluation of thoracic injuries among older motor vehicle occupants. (Report No. DOT HS 811 101) Washington, DC: National Highway Traffic Safety Administration.

HASIJA, V., TAKHOUNTS, E.G. AND RIDELLA, S.A. (2011). Evaluation of statistical methods for generating injury risk curves. In: Proceedings of the 22nd International Technical Conference on the Enhanced Safety of Vehicles (No. 11-0331).

HUMM, J.R., YOGANANDAN, N., DRIESSLEIN, K.G. AND PINTAR, F.A. (2018). Three-dimensional kinematic corridors of the head, spine, and pelvis for small female driver seat occupants in near-and far-side oblique frontal impacts. Traffic injury prevention, 19(sup2), pp.S64-S69.

KAHANE, C. J. (2013). Injury vulnerability and effectiveness of occupant protection technologies for older occupants and women (Report No. DOT HS 811 766). Washington, DC: National Highway Traffic Safety Administration.

MCMURRY, T.L. AND POPLIN, G.S. (2015). Statistical considerations in the development of injury risk functions. Traffic injury prevention, 16(6): 618-626

NHTSA (2022). Biomechanics Test Database. https://www.nhtsa.gov/research-data/research-testing-databases#/biomechanics

PARENTEAU, C.S., ZUBY, D., BROLIN, K., SVENSSON, M.Y., PALMERTZ, C. AND WANG, S.C. (2013). Restrained male and female occupants in frontal crashes: Are we different? Proceedings of the 2013 IRCOBI Conference. Paper #IRC-13-98.

SHAW, G., LESSLEY, D., ASH, J., POPLIN, J., MCMURRY, T., SOCHOR, M. AND CRANDALL, J. (2017). Small female rib cage fracture in frontal sled tests. Traffic injury prevention, 18(1), pp.77-82.

STITZEL JD, KILGO PD, WEAVER AA, MARTIN RS, LOFTIS KL, MEREDITH JW. (2010). Age thresholds for increased mortality or predominant crash induced thoracic injuries. Ann Adv Automot Med., 54:41-50.

WANG, Z.J., LEE, E., BOLTE, J., BELOW, J. LOEBER, B., RAMACHANDRA, R., GREENLEES, B., GUCK, D. (2018). Biofidelity evaluation of THOR 5th percentile female ATD. In: Proceedings of the 2018 IRCOBI Conference. Paper #18-88.

APPENDIX

Lab/ Study	TSTREF[†]	Condition	Angle	ΔV (km/h)	Belt	Bag	Age [yr]	Stature [cm]	Mass [kg]	AIS 3+	PMHS max_CB*	PMHS max_xy Res.**	THOR-05F Max, Res.	THOR-05F TSTREF
UVA	UVAS0209	GS, Frontal	0°	30	3PT+FL	No	75	149	37	Yes	.	35.7	28.7	UVAS0586
UVA	UVAS0210	GS, Frontal	0°	30	3PT+FL	No	95	155	31	Yes	.	62.6	28.7	UVAS0587
UVA	UVAS0211	GS, Frontal	0°	30	3PT+FL	No	57	162	40	Yes	.	55.3	28.7	UVAS0588
UVA	UVAS0212	GS, Frontal	0°	30	3PT+FL	No	88	164	54	Yes	.	38.5	28.7	
UVA	UVAS0213	GS, Frontal	0°	30	3PT+FL	No	65	152	47	Yes	.	48.0	28.7	
UVA	UVAS0370	GS, Frontal	0°	30	3PT+FL	No	72	154	40	No	.	45.6	28.7	
UVA	UVAS0371	GS, Frontal	0°	30	3PT+FL	No	89	165	44	Yes	.	45.8	28.7	
UVA	UVAS0372	GS, Frontal	0°	30	3PT+FL	No	58	151	28	No	.	32.6	28.7	
UVA	UVAS0373	GS, Frontal	0°	30	3PT+FL	No	72	163	56	Yes	.	53.3	28.7	
UVA	UVAS0374	GS, Frontal	0°	30	3PT+FL	No	69	160	47	Yes	.	46.7	28.7	
UVA	UVAS0470	GS, Frontal	0°	10	3PT+FL	No	48	152	41	No	.	24.5	10.4	UVAS0591
UVA	UVAS0471	GS, Frontal	0°	10	3PT+FL	No	60	155	48	No	.	33.7	10.4	UVAS0592 UVAS0593
UVA	UVAS0472	GS, Frontal	0°	20	3PT+FL	No	64	164	60	No	.	32.1	17.2	UVAS0589
UVA	UVAS0473	GS, Frontal	0°	20	3PT+FL	No	60	156	40	No	.	27.4	17.2	UVAS0590
UVA	UVAS0474	GS, Frontal	0°	20	3PT+FL	No	54	159	41	No	.	39.3	17.2	UVAS0591
MCW	NSFSC0122	GS3, Near-side	-30°	30	3PT+FL	No	62	154.9	48.1	Yes	.	62.2	41.5	NSFSD0151
MCW	NSFSC0123	GS3, Near-side	-30°	30	3PT+FL	No	57	160	44.4	Yes	.	45	41.5	NSFSD0152
MCW	NSFSC0124	GS3, Near-side	-30°	30	3PT+FL	No	69	161.8	42.6	No	.	33.9	41.5	NSFSD0153
MCW	NSFSC0127	GS3, Near-side	-30°	30	3PT+FL	No	89	157.4	40.8	Yes	.	57.8	41.5	
MCW	NSFSC0128	GS3, Near-side	-30°	30	3PT+FL	No	75	167.6	60.3	No	.	39.7	41.5	
MCW	NSFSC0120	GS3, Far-side	30°	30	3PT+FL	No	59	155	53.4	No	.	42.2	33.1	NSFSD0145
MCW	NSFSC0121	GS3, Far-side	30°	30	3PT+FL	No	78	152.4	54.5	No	.	35.2	33.1	NSFSD0146
MCW	NSFSC0125	GS3, Far-side	30°	30	3PT+FL	No	83	154.9	46.7	Yes	.	28.3	33.1	NSFSD0147
MCW	NSFSC0126	GS3, Far-side	30°	30	3PT+FL	No	65	149.9	39.5	No	.	30.6	33.1	
MCW	NSFSC0129	GS3, Far-side	30°	30	3PT+FL	No	79	149.9	43.1	Yes	.	46.3	33.1	
MCW	NSFSC0130	GS3, Near-side	-30°	15	3PT+FL	No	92	162.6	47.7	No	.	29.8	23.9	NSFSD0148
MCW	NSFSC0132	GS3, Near-side	-30°	15	3PT+FL	No	70	147.3	46.4	No	.	43.7	23.9	NSFSD0149
MCW	NSFSC0134	GS3, Near-side	-30°	15	3PT+FL	No	83	157	37.3	No	.	23.6	23.9	NSFSD0150
MCW	NSFSC0136	GS3, Far-side	30°	15	3PT+FL	No	85	154.9	57.2	No	.	34.4	24.2	NSFSD0142
MCW	NSFSC0138	GS3, Far-side	30°	15	3PT+FL	No	86	162.1	49.4	No	.	28.4	24.2	NSFSD0143
MCW	NSFSC0140	GS3, Far-side	30°	15	3PT+FL	No	58	160.5	37.7	No	.	17.2	24.2	NSFSD0144
MCW	NSFSC0137	Driver-Seat	0°	48	3PT	Yes	85	154.9	57.2	Yes	60.1	.	42.5	NSFSD0157
MCW	NSFSC0139	Driver-Seat	0°	48	3PT	Yes	86	162.1	49.4	Yes	69.1	.	42.5	NSFSD0158
MCW	NSFSC0141	Driver-Seat	0°	48	3PT	Yes	58	160.5	37.7	Yes	65.4	.	42.5	NSFSD0160
MCW	NSFSC0131	Rear-Seat	0°	48	3PT	No	92	162.6	47.7	Yes	71.8	.	55.7	NSFSD0174
MCW	NSFSC0133	Rear-Seat	0°	48	3PT	No	70	147.3	46.4	Yes	66.7	.	55.7	NSFSD0175
MCW	NSFSC0135	Rear-Seat	0°	48	3PT	No	83	157	37.3	Yes	62.4	.	55.7	NSFSD0176
Eppinger	ASTS53	2PT/KNE	0°	34.9	2PT	No	61	152.6	61	Yes	72.2	.	Not tested	
Eppinger	ASTS174	3PT/KNE	0°	25.9	3PT	No	57	167	61	Yes	68.6	.	Not tested	
Eppinger	ASTS259	2PT/KNE	0°	56.4	2PT	No	64	163	77	Yes	32.8	.	Not tested	
Eppinger	ASTS294	3PT/KNE	0°	56.8	3PT	No	68	148.1	55	Yes	71.1	.	Not tested	
Eppinger	ASTS305	3PT/ABG	0°	59.4	3PT	Yes	66	160.9	58	Yes	75.2	.	Not tested	
Eppinger	9310 DOT	3PT/KNE	0°	48	3PT	No	52	168	68	No	60	.	Not tested	
Eppinger	9311 DOT	ABG/3PT	0°	48	3PT	Yes	47	169	76	No	52.8	.	Not tested	
Eppinger	RC107R	3PT	0°	48.3	3PT	No	63	170.2	77	Yes	91.7	.	Not tested	
Eppinger	RC110V	3PT	0°	48.3	3PT	No	63	160	61	Yes	77	.	Not tested	
Eppinger	RC112F	ABG/LAP	0°	48.3	Lap	Yes	67	163.8	50	Yes	24.3	.	Not tested	
Eppinger	RC115H	ABG/3PT	0°	48.3	3PT	Yes	67	150	57	Yes	72.6	.	Not tested	
Eppinger	RC118U	ABG/KNE	0°	46.5	None	Yes	29	170.2	41	No	40.5	.	Not tested	
Eppinger	RC122S	3PT	0°	23.7	3PT	No	81	157	60	Yes	50.4	.	Not tested	
Eppinger	RC123G	3PT	0°	23.7	3PT	No	67	165	68	No	44.2	.	Not tested	
Eppinger	RC125Z	ABG/KNE	0°	43.8	None	Yes	75	180.3	85	Yes	73.6	.	Not tested	
Eppinger	RC126W	ABG/KNE	0°	34.7	None	Yes	64	167.6	54	Yes	66.6	.	Not tested	
Eppinger	RC128L	ABG/3PT	0°	29.9	3PT	Yes	67	153.7	46	No	57.8	.	Not tested	
Eppinger	ASTS104	2PT/KNE	0°	32.3	2PT	No	66	179	104	Yes	113.9	.	Not tested	
Eppinger	ASTS113	2PT/KNE	0°	47.3	2PT	No	24	158.7	57	Yes	81.2	.	Not tested	
Eppinger	ASTS94	ABG/KNE	0°	49.6	None	Yes	66	155.7	62	Yes	45.6	.	Not tested	
Eppinger	ASTS96	ABG/KNE	0°	34	None	Yes	58	158.7	97	Yes	18.9	.	Not tested	
Bolton	UVA578	AB/3PT+FL	0°	48	3PT+FL	Yes	69	155	53	Yes	52	.	Not tested	
Bolton	UVA579	AB/3PT+FL	0°	48	3PT+FL	Yes	72	156	59	Yes	88	.	Not tested	
Bolton	UVA667	AB/3PT	0°	48	3PT	Yes	59	161	79	Yes	95	.	Not tested	
Bolton	UVA668	AB/3PT	0°	48	3PT	Yes	54	162	55.3	Yes	91	.	Not tested	

[†]TSTREF indicates Test Reference Number in NHTSA Biomechanics Database (https://www.nhtsa.gov/research-data/research-testing-databases#/biomechanics)

*Maximum deflection from chestband (CB)
**Maximum x-y resultant deflection, from VICON motion tracking

All Authors' full name, address, and e-mail

1. Ellen Lee
   National Highway Traffic Safety Administration
   1200 New Jersey Ave., SE, Washington DC 20590
   (202) 366-1435
   Ellen.lee@dot.gov

2. Matthew Craig
   National Highway Traffic Safety Administration
   1200 New Jersey Ave., SE, Washington DC 20590
   (202) 366-4720
   Matthew.craig@dot.gov

Question Asked	**Answer Given**
Where did the 8mm adjustment for soft tissue come from?	Because the chestband measures external deflection, these data were adjusted by subtracting 8 mm to account for soft tissue. This method has been used previously by NHTSA in developing ATD risk curves (Eppinger et al. 1999). Additional adjustment approaches may be investigated in the future. Eppinger, R., Sun, E., Bandak, F., Haffner, M., Khaewpong, N., Maltese, M., Kuppa, S., Nguyen, T., Takhounts, E., Tannous, R., Zhang, A., Saul, R., 1999. Development of improved injury criteria for the assessment of advanced automotive restraint systems–II. Washington, DC: National Highway Traffic Safety Administration.
Why is there a risk at zero chest deflection?	While there are many methods in the literature for developing injury risk functions, the risk curves in this study were developed using a process outlined by Hasija et al. (2011), in which logistic regression was first used to differentiate between non-correlated and well-correlated datasets. For a well-correlated dataset with overlapping left and right censored injury and non-injury data, Hasija et al. (2011) demonstrated that both logistic regression and survival analysis (with Weibull, log-logistic or log-normal) produce nearly identical risk functions, particularly in the middle of the data. Logistic regression has the "drawback" of producing a non-zero risk at a zero stimulus, while survival analysis has the advantage of producing a risk function that presents zero risk with zero stimulus. Survival analysis also allows accurate treatment of specimens tested more than once. For these reasons, we presented both logistic regression and survival analysis-based risk functions. Hasija, V., Takhounts, E.G. and Ridella, S.A., 2011. Evaluation of statistical methods for generating injury risk curves. In: Proceedings of the 22nd International Technical Conference on the Enhanced Safety of Vehicles (No. 11-0331).
Hi there, thanks for the nice talk. Ellen, do you plan on doing more experiments with younger female PMHS to evaluate the age influence on the risk curves?	Yes. NHTSA recently kicked off a new task order to continue collecting data on the female thorax response in sled tests. We are specifically targeting younger aged PMHS in order to examine the age influence on the risk function. Of course, we are always limited by the available specimens.
For Ellen: was bone quality (BMD) of the PMHS selected for testing used as a criterion for inclusion?	Yes. For the majority of the tests, specimens categorized as osteoporotic (according to BMD) were excluded. In one limited test series, we obtained both "healthy" and "non-healthy" (i.e. osteoporotic) specimens to compare responses between the two groups. Responses generally were not significantly different and therefore, all specimens were combined for subsequent analyses.