DEVELOPMENT OF SIMULATION-BASED THORACIC INJURY PROBABILITY FUNCTION FOR ELDERLY FEMALE OCCUPANTS IN SIDE IMPACT

Hisaki Sugaya, **Takayuki Kawabuchi**, **Yukou Takahashi**,
Honda R&D Co., Ltd. Innovative Research Excellence, Tochigi, Japan

Craig Markusic, **Skye Malcolm**,
Honda Development & Manufacturing of America, LLC., Ohio, United States

Amanda Agnew, **Yun-Seok Kang**, **John Bolte IV**
Injury Biomechanics Research Center (IBRC), The Ohio State University, Ohio, United States

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ABSTRACT

Despite the high morbidity of elderly female car occupants in near side crashes, not many studies have been performed to predict the probability of injury to this population. A methodology to compensate for limitations in the amount of available biomechanical data is essential to derive an injury probability function for elderly females in near-side crashes. This study aims to establish a methodology to develop an injury probability function (IPF) by means of computational impact simulations using a human body model (HBM) that also includes variability in the material properties of human ribs. Focus was given to the prediction of rib fractures because of their high frequency in these near-side crash scenarios.

Variation in the material properties of ribs from the 5th percentile elderly female population were applied to a HBM developed in a past study by applying eight different stress-strain curves. The variability in the prediction of rib fracture was accounted for using a probabilistic approach derived from the literature. This altered HBM was then scaled to the size and mass of subjects used in experimental studies. The predicted thoracic deflection was validated against both isolated lateral thoracic impacts and side impact sled tests which included a side-airbag and a pretensioning seatbelt. The probability of three or more rib fractures predicted by the probabilistic approach was used to validate the altered HBM against the previous PMHS experiments. Additional sled test simulations were conducted with reduced energy by decreasing the impact velocity and also by varying the use of the airbag. IPF predicting the probability of rib fractures was developed using the logistic regression and compared between the original dataset based on the PMHS sled tests and the modified dataset created by the additional simulations conducted at reduced severity.

Chest deflection from the experimental thoracic impactor tests fell within the predicted range from the HBM simulations. In addition, chest deflection from the majority of the PMHS sled experiments that were simulated fell within the predicted range by the HBM. The probability of 3+ rib fractures was 100% for both the simulations and the experiments against realistic lateral sled tests. The IPF developed from the modified dataset predicted a significantly lower probability of rib fracture than that from the original dataset.

This study qualitatively evaluated the idea of predicting injury probability for a specific population by representing the variability in the material properties of ribs to an HBM, specifically a near-side impact load case for 5^{th} percentile elderly female occupants. The effect of the geometry, such as the shape of the rib cage and rib thickness, was not reproduced in this study. The method used to derive the IPFs could also be done for other load cases and populations.

INTRODUCTION

In the united states, approximately 2.28 million occupants were injured in car crashes in 2020 according to the accident analysis. [1] A previous study done by NHTSA analyzed the National Automotive Sampling System Crashworthiness Data System (NASS-CDS) and found that the percentage of drivers sustaining Maximum Abbreviated Injury Scale (AIS) 4+ injuries relative to the number of drivers involved in accidents is significantly higher for the elderly population of 65 years old and older than the age group between 25 and 44 years old, accounting for 1.85% and 0.76%, respectively. The percentage of the elderly population becomes even larger, specifically for left-side impacts without rollover, comprising the largest percentage of all crash modes [2]. This suggests that protection of elderly drivers involved in left-side impacts is crucial.

Further investigation of the side-impact elderly crash data from the previous study showed that elderly female occupants are more likely to suffer injuries than males, especially to the thoracic ribs. In near-side impacts, the probability of AIS 3+ injuries to the thorax and the ribs was significantly higher for females than for males within the elderly population.[3] This suggests that elderly female drivers in near-side impacts are a more susceptible group to thoracic injuries such as rib fractures than elderly male drivers. Therefore, this study focused on thoracic injuries sustained by elderly female occupants.

In a previous study focused on elderly female biomechanical response, whole single rib bending tests were performed, showing that the force at a fracture of female ribs was significantly lower than those of male ribs [4], which could point to the elderly female being more fragile than the elderly male. Due to the growing importance for the protection of elderly female occupants in near-side impacts, several studies have investigated this impact configuration. At the full-scale level, Wood et al. [5] developed a thoracic injury probability function (IPF) for elderly female in side impacts using a rigid wall and elderly post-mortem human surrogates (PMHS), with six female and two male subjects. Based on the thoracic IPF, a normalized half deflection (NHD) value of 0.23 was proposed for a 50% probability of AIS3+ thoracic injury. A more recent study by Shurtz et al. [6] and Bolte et al. [7] conducted side impact sled tests utilizing a mass productionbased restraint system with ten elderly female PMHS and a Delta-V of approximately 28 km/h. These sled tests produced NHDs from 0.05 – 0.13 and AIS 3+ thoracic injuries for eight of the ten subjects that reached AIS 3+. These studies reveal differences in the relationship between NHD and the occurrence of AIS3+ thoracic injury. One possible explanation for this is the influence of different boundary conditions. However, there has not been a study of applying the IPF using vehicle boundary conditions. Therefore, the objective of this study was to investigate a method to develop an IPF for thoracic injury to elderly female occupants given real-world vehicle boundary conditions.

In order to accurately predict injury probability in realistic crash scenarios, especially when focusing on specific crash conditions, a method that complements the limited number of PMHS experimental data is needed. Due to the small number of samples, it is difficult to predict individual variation solely based on experimental results. In this study, a methodology to complement the limitations by means of computer simulation was used. The body size of PMHS can be matched from subject data, however, material properties are not known for each rib from each individual subjects. In this study, these unknown material properties were modeled by including variation across a number of physical material property coupon tests. The purpose of this study was to investigate a method to improve the IPF for thoracic injury to elderly female occupants using crash simulation with a human body model that applied variations to the material properties of human rib cortical bone tissue, which comprises the major component of the stiffness of the thoracic cage.

METHOD

The methods used to improve the thoracic IPF for this crash scenario began by developing the HBM to include experimental cortical bone properties. Once the model was updated it was validated against both impactor and sled tests with real-world boundary conditions. Finally, the model was then used to create the new thoracic IPF.

Development of a Variability Human Body Model (vHBM)

The HBM used in this study was an inhouse HBM developed by Sugaya et al. [8] representing an elderly female with the size of 5^{th} % American female (AF) using LS-DYNA R7.1.2. This study developed a variability human body model (vHBM) that reflects variability in the material property of rib cortical bone using MATERIAL TYPE 124 (*MAT_PLASTICITY_COMPRESSION_TENSION).[9] The variability of the material property was reproduced by giving variation to the modulus of elasticity, yield stress, and slope in the plastic region determined from rib bone material data of eight female ribs over 61 years old described by Katzenberger et al. [10] and

Kemper et al. [11]. The fracture probability of each of the “true” ribs, the first seven which attach to the sternum, was calculated using maximum strain values from the literature as shown in appendix A. As shown in Figure 1, the relationship between the fracture strain and the fracture probability (fracture probability equation) was developed using the survival method. Using the fracture probability equation, the probability of fracture to 3 or more ribs was calculated using the probabilistic analysis by Forman et al. [12] using a generalized form of a binomial probability model Pr(X) with equation (1).

$$\Pr(X) = \sum_{i=1}^{\binom{N}{X}} \left(\prod_{k \in C_i} p_j \right) \left(\prod_{k \in C_i} (1 - p_k) \right) \qquad Equation\ (1)$$

where Pj is the fracture probability at the j th site (rib)
N is the number of potential fracture sites (number of ribs)
Ci is a vector containing the ith combination of X site indices
$\bar{Ci}$ is a vector containing the set-exclusive-or values between the index vector [1…N] and the combination vector

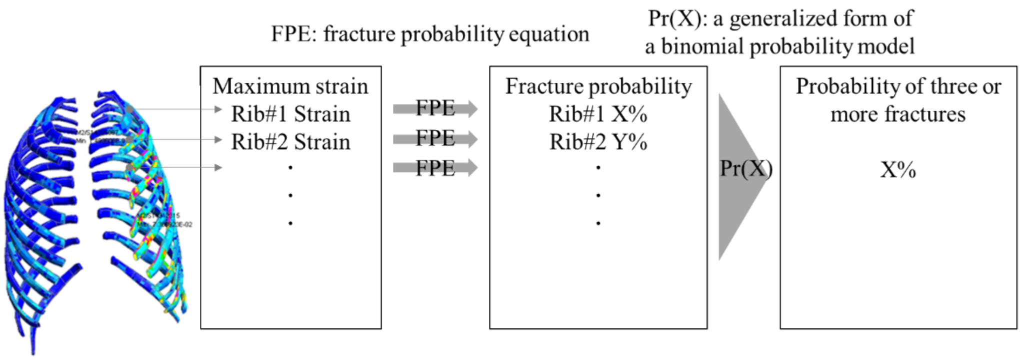

Figure 1: Probabilistic analysis

Evaluation of vHBM against thorax impactor tests

The vHBM was evaluated to compare the chest deflection in the thorax cylindrical impactor tests conducted by Talanikite et al. [13]. The vHBM was 3D scaled to two different subject body sizes (L02, L03) used in the experiment. The vHBM weight was also altered to match the mass of the two PMHS by adjusting the visceral density. The cylindrical impactor had a 15 cm diameter, a mass of 16 kg, and impacted the thorax of the subjects at a velocity of 6 m/s. The impact location to the vHBM was centered laterally on Rib 5 to match the experimental tests. Thoracic deflection was calculated from the impactor displacement relative to T8 and NHD was calculated by dividing the chest deflection by the chest width of the vHBM. Finally, the NHD from the simulated impacts was compared with the experimental results.

Evaluation of vHBM against realistic lateral sled tests

The vHBM was also evaluated using the sled tests with vehicle boundary conditions conducted by Shurtz et al. [6] and Bolte et al. [7]. As with the cylindrical impactor tests, the vHBM was used to reproduce the body size and mass of four of the PMHS used in the sled experiments by 3D scaling. Figure 2 shows the simulation model representing the vehicle-based sled tests, which included a mass-production seat, a three-point restraint with pretensioner, an intruding door liner, and an airbag. The ΔV applied to the simulated sled was the same as in the experiment at 28 km/h. The seatbelt pretensioner and airbag ignition timing were both set at 6 msec as in the physical experiment. The head block was modeled to mimic a foam block utilized in the lateral sled tests to represent a simplified side curtain airbag. The urethane foam had a strength of 0.15Mpa at 20% compression.

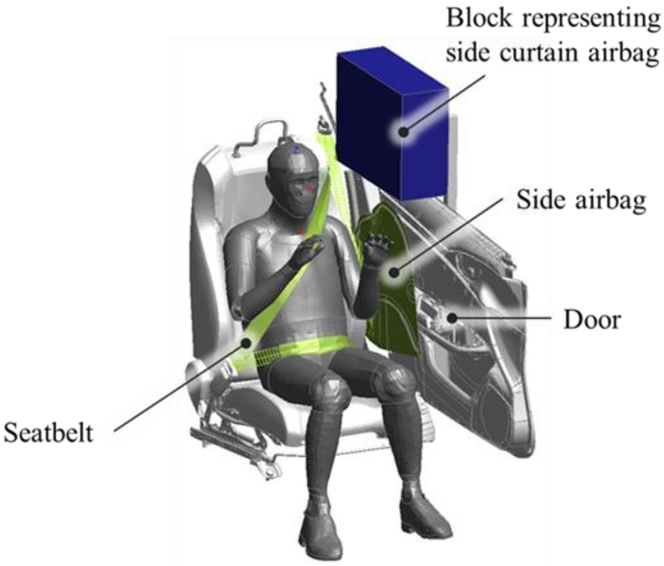

Figure 2: Configuration of vHBM simulation of realistic lateral sled tests

For this simulation NHD was measured at 50% of the ribs #5 and #6 at the mid-axillary line location similar to that in the experiment. The maximum principal strain on the rib cortical bone was calculated for each of the ribs 1-10 on the impact side. Using these maximum strains and the previously developed fracture probability equations, the probability of three or more fractures was calculated using the probabilistic analysis proposed by Forman et al. [12]. The upper and lower value of the NHD and the probability of rib fracture obtained from the simulation results were compared with the experimental data to verify the reproducibility of the injuries recorded in the PMHS sled tests.

Development of the injury prediction function (IPF) with additional simulations.

Since all of the experimental PMHS and simulation models reached AIS 3+, additional simulations were needed to identify cases where the number of rib fractures were reduced. Therefore, additional simulations were conducted with the simulated sled velocity at both 16 km/h and 24 km/h and also simulated with and without the airbag. All of the simulations were then combined to develop an IPF. The reduced values of ΔV correspond to published ΔVs with the highest frequency of AIS 2 and AIS 3 thoracic injury in accident data analysis for elderly female occupants in lateral crashes [14].

A total of 192 cases were simulated using 32 types of vHBMs (8 types of materials x 4 body sizes) in 6 different loading conditions (3 ΔVs, with and without airbag) to collect the data for an IPF. From the results of these simulations, the NHD at the mid-axillary line location for ribs #1 to #10 were measured. In addition, the maximum principal strain of each rib was measured and the probability of three or more fractures was calculated in each simulation case in the same way that was used for the evaluation of vHBM against the PMHS sled tests. The maximum NHD and the probabilistic analysis was plotted for the probability of three or more rib fractures, and the curve was fitted using logistic regression to develop the IPF with R software [15].

RESULTS

Development of Variability Human Body Model (vHBM)
Figure 3 shows the eight stress-strain curves for the material properties applied to vHBM. MAT124 PLASTICITY_COMPRESSION_TENSION in LS-DYNA was used for the cortical bone of the ribs. The range of the yield stress, elastic modulus and slope in the plastic region were 24-79 MPa, 7-15 GPa and 1.6-3.1 GPa, respectively (Table1). The material properties from subject 231 was the lower limit defined in this study.

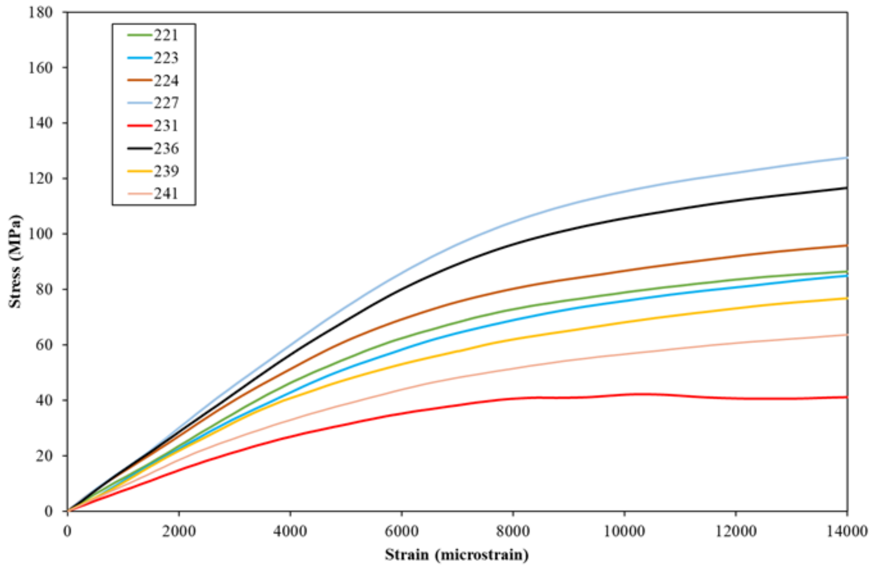

Figure 3: Rib cortical material for vHBM

Table 1: Rib cortical bone material properties

	221	**223**	**224**	**227**	**231**	**236**	**239**	**241**
Yield strain (10^{-6}):	4643	4643	4643	5313	3411	5852	3822	3260
Yield stress (MPa):	52	52	52	78	24	79	40	28
Elastic Modulus (GPa):	12	12	12	15	7	14	11	9
Slope in plastic region	2.8	2.8	2.8	3.1	1.6	2.7	2.8	1.9

The fracture probability equation was determined by fitting the test data using a survival analysis with Weibull distribution as shown in equation (2). Data were selected for ribs 1-7 from the literature with the age of 61 and above. The literature revealed that 50% of fracture probability was reached at 2.1% of strain. This fracture probability equation was applied to vHBM.

$$Fracture\ probability\ equation = 1 - exp(-\left(\frac{Strain}{2.430}\right)^{2.667}) \qquad Equation\ (2)$$

Evaluation of vHBM against thorax impactor tests
Two simulations of the thorax impactor tests were conducted for the evaluation of vHBM. Chest deflection results are shown in Table 2. The maximum thoracic deflection differed with different cortical bone material parameters. The range of the maximum deflection in the LCT02 and LCT03 simulations were 0.28-0.31 and 0.22-0.27,

respectively. The change in the material parameters resulted in the change in the maximum deflection of approximately 15% for both subjects.

Table 2: Chest deflection of impactor simulation and experiment results

		LCT02	LCT03
Simulation	**221**	0.28	0.25
	223	0.28	0.24
	224	0.28	0.23
	227	0.27	0.23
	231	0.31	0.27
	236	0.28	0.23
	239	0.28	0.23
	241	0.29	0.22
	Range	0.27-0.31	0.22-0.27
Experiment		0.31	0.26

Evaluation of vHBM against sled tests

Injury reproducibility was verified under the PMHS lateral sled test condition with vehicle boundary conditions. In Table 3, NHD values are shown for both the simulation and experimental results. The range of deflection was 0.08-0.10, 0.11-0.13, 0.09-0.11 and 0.08-0.10 for Subject 1, 2, 3 and 5, respectively. The change in the material parameters resulted in the change in NHD by around 20% for all subjects. All but one of the simulations predicted 100% probability of AIS 3+.

Table 3: NHD of Sled simulation and experiment results

		Subject 1		Subject 2		Subject 3		Subject 5	
		NHD	**Probability of AIS3+**	**NHD**	**Probability of AIS3+**	**NHD**	**Probability of AIS3+**	**NHD**	**Probability of AIS3+**
Simulation	**221**	0.10	100%	0.11	100%	0.10	100%	0.09	100%
	223	0.10	100%	0.11	100%	0.10	100%	0.09	100%
	224	0.09	100%	0.11	100%	0.10	100%	0.09	100%
	227	0.08	100%	0.11	100%	0.09	100%	0.08	99%
	231	0.10	100%	0.13	100%	0.11	100%	0.10	100%
	236	0.10	100%	0.11	100%	0.10	100%	0.09	100%
	239	0.10	100%	0.12	100%	0.10	100%	0.09	100%
	241	0.10	100%	0.12	100%	0.11	100%	0.10	100%
	Range	0.08-0.10	100%	0.11-0.13	100%	0.09-0.11	100%	0.08-0.10	99%
Experiment		0.08	AIS3	0.13	AIS3	0.05	AIS3	0.09	AIS3

Development of the IPF with additional simulations.

The probability of three or more rib fractures and the maximum NHD results were plotted for all of the 192 simulations. The increase in NHD tended to increase the probability of three or more rib fractures as shown in Figure 4. The increase in NHD from 0.05 to 0.12 resulted in increase in fracture probability from approximately 20% and 80%, respectively. The IPF was formulated in Equation (3) by using logistic regression

$$Probability\ of\ AIS3+= \frac{e(-3.339 + 37.955 * NHD)}{1 + e(-3.339 + 37.955 * NHD)} \qquad Equation\ (3)$$

where NHD is maximum normalized half deflection.

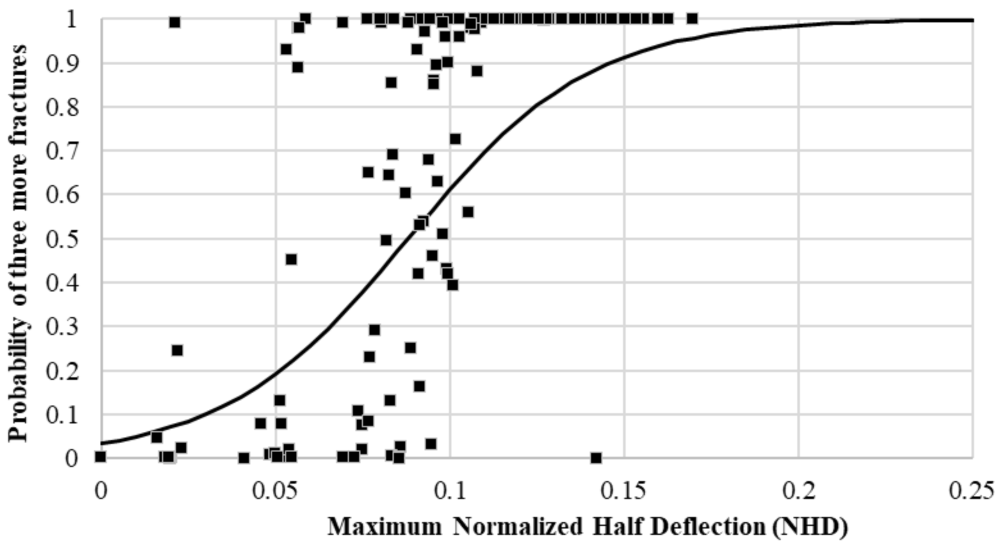

Figure 4: Probability of three or more fractured ribs

DISCUSSION & LIMITATION

The method of HBM
The experimental PMHS impactor and sled tests were reproduced by the vHBM simulations imparting individual variation in the material property of the cortical bone of the ribs. The experimental results fell within the range of the deflection obtained from the vHBM simulations that incorporated individual variability of the material property of the rib cortical bone, suggesting that the variability defined for the vHBM is a reasonable estimation of actual human variation. One exception was that the test results from one of the experimental PMHS subjects was not within the range of the variability predicted by the vHBM simulations. This may be due to the lack of consideration of other sources of variability, such as the thickness of the ribs or the geometry of the thoracic cage, which may be insufficient to reproduce variability in the material property of human bodies as indicated by Sugaya et al. [8] and Kang at al. [4]. Therefore, it may be necessary to further improve the reproducibility of individual variation in the future by reproducing other relevant sources of human variation.

Validity of IPF
Comparison of the IPF developed in this study with others in the literature showed an increased probability of three or more fractures. In addition, a comparison of the thoracic deflection from the PMHS sled tests and the fracture probability predicted by the parametric probability function showed that the IPF developed in this study was the closest to the IPF based on NHD and injury data from Bolte et al. [7] as shown in Figure 5. As a result, this probability function is likely to be reasonable under realistic vehicle boundary conditions.

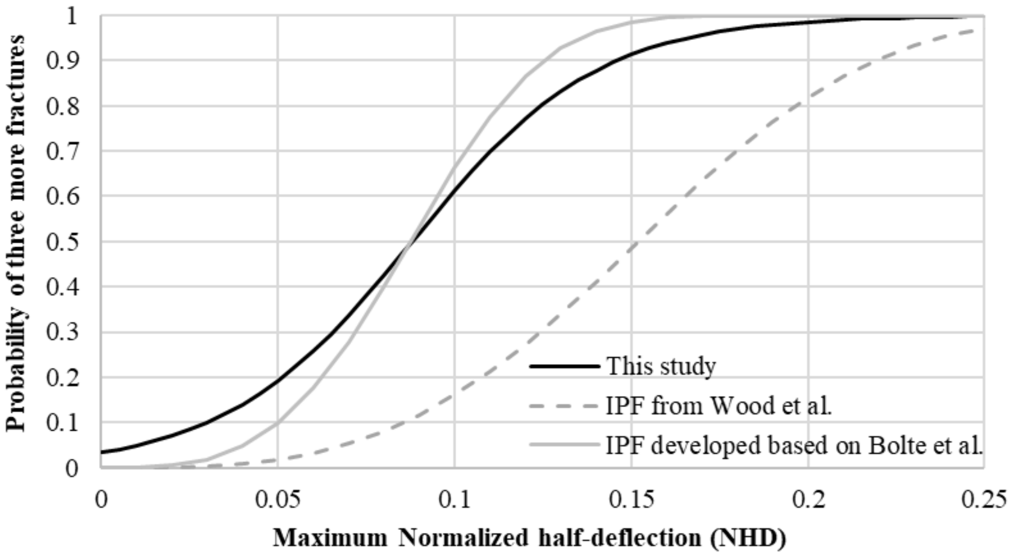

Figure 5: Probability of three or more fractured ribs comparing with literature

In the present IPF calculated by replicating the sled tests by Shurtz et al. [6] and Bolte et al. [7], differences in loading configurations may have influenced increased injury probability: the number of fractures increased in the elderly female due to pretensioning, or combined loading, as shown by Kawabuchi et al. [15]. The anterior-posterior deflection of the chest due to the activation of the pretensioner may have increased the strain in the ribs, and thus the influence of the seat belt, which was not seen in the impactor condition, may have been one of the factors contributing to the increased injury probability. It is possible that the combined loading of the lateral load from the airbags and the anterior-posterior load from the seatbelt may have increased the probability of injury. This suggests that injury probability depends on the loading configuration. Therefore, it is necessary to further improve the accuracy of the injury probability function by adding additional load cases in the future.

CONCLUSION

The vHBM was developed by applying material properties of rib cortical bone from a series elderly female coupon tests. The vHBM was able to predict chest deflections for both impactor and sled test configurations. An IPF was developed using the vHBM to represent the human variation under the boundary conditions of actual vehicles. The new IPF compared closely to the injury probability curve from the PMHS sled tests.

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APPENDIX A

TEST	ID	RIB #	Sex	Age	Fracture strain(ustrain)	strain(%)
Kemper et al.	Cad1-3L	3	F	64	36064	3.61
Kemper et al.	Cad1-3P	3	F	64	20789	2.08
Kemper et al.	Cad4-3A	3	F	61	35332	3.53
Kemper et al.	Cad4-3L	3	F	61	31069	3.11
Kemper et al.	Cad4-3P	3	F	61	25762	2.58
Kemper et al.	Cad1-4L	4	F	64	22208	2.22
Kemper et al.	Cad4-4A	4	F	61	36077	3.61
Kemper et al.	Cad4-4L	4	F	61	27386	2.74
Kemper et al.	Cad4-4P	4	F	61	16482	1.65
Kemper et al.	Cad1-5A	5	F	64	18404	1.84
Kemper et al.	Cad1-5L	5	F	64	11271	1.13
Kemper et al.	Cad4-5A	5	F	61	29876	2.99
Kemper et al.	Cad4-5L	5	F	61	21804	2.18
Kemper et al.	Cad1-6A	6	F	64	13471	1.35
Kemper et al.	Cad1-6L	6	F	64	27903	2.79
Kemper et al.	Cad4-6L	6	F	61	13519	1.35
Kemper et al.	Cad4-6P	6	F	61	26274	2.63
Kemper et al.	Cad1-7A	7	F	64	5217	0.52
Kemper et al.	Cad4-7A	7	F	61	45858	4.59
Kemper et al.	Cad4-7L	7	F	61	18873	1.89
Katzenberger et al.	261	6	F	93	10638	1.06
Katzenberger et al.	180	6	F	69	14499	1.45
Katzenberger et al.	103	6	F	75	9509	0.95
Katzenberger et al.	367	6	F	87	18196	1.82
Katzenberger et al.	363	6	F	87	14932	1.49
Katzenberger et al.	352	6	F	90	13110	1.31
Katzenberger et al.	221	6	F	74	19518	1.95
Katzenberger et al.	223	6	F	82	17353	1.74
Katzenberger et al.	224	6	F	76	24528	2.45
Katzenberger et al.	227	6	F	66	16364	1.64
Katzenberger et al.	231	6	F	92	14283	1.43
Katzenberger et al.	236	6	F	84	26115	2.61
Katzenberger et al.	239	6	F	70	19265	1.93
Katzenberger et al.	241	6	F	99	27825	2.78