BIOMECHANICAL PROPERTIES OF THE MALE AND FEMALE CHEST SUBJECTED TO FRONTAL AND LATERAL IMPACTS

Hideyuki Kimpara, Masami Iwamoto, Kazuo Miki
Toyota Central R&D Labs., Inc.

Jong B. Lee, Paul C. Begeman, King H. Yang, Albert I. King
Bioengineering Center, Wayne State University

ABSTRACT

The purpose of this study was to determine chest impact responses and injury thresholds due to gender differences based on a retrospective review of published data. Data from 83 cadaveric frontal and lateral blunt impacts to the chest and 96 isolated rib bending tests were selected to characterize chest biomechanical properties. Variables selected for analysis were relevant cadaveric information, test conditions, chest impact response and resulting chest injuries. It was found that chest stiffness was significantly higher in males than in females in frontal impact. Similarly, the cross-sectional area and bending stiffness of female ribs were significantly lower than those of males. More research is needed to determine injury thresholds for lateral impact due to gender differences.

Key words: Gender differences, Injury criteria, Chest stiffness, Rib strength

FATALITIES AMONG FEMALE DRIVERS increased approximately 16% from 1991 to 2001 compared to a 2% increase in male drivers during the same period in the United States (NHTSA 2001). Based on injury surveillance and laboratory data, it has been shown that females are more vulnerable than males, especially in the chest and lower extremity regions (Patrick and Andersson 1974, Mackay and Hassan 2000, and Lenard and Welsh 2001). With an increasing number of female drivers on the road today, there is great concern as to how female fatalities can be reduced. However, currently proposed injury tolerance and criteria for female occupants are not based on laboratory data obtained from female subjects. Rather, they are scaled from experimental data obtained largely from male cadavers (Eppinger et al. 1984, Mertz 1984, Mertz et al. 1989 and Irwin et al. 2002). However, these geometric and/or stress-related scaling methods have never been validated and geometric scaling alone may not take into consideration those differences in material property between males and females (Kuppa and Eppinger 1998).

Results from frontal sled tests, conducted by Patrick and Andersson (1974), to evaluate the efficacy of the three-point belt restraint system, show that only 8% of all subjects tested had rib fractures. However, among those with fractured ribs, the number of rib fractures in female cadavers was much higher than that in male cadavers. In frontal real-world automotive crashes, Mackay and Hassan (2000) found that females and the elderly are the two most vulnerable segments of the population that they have studied. For the same level of injury, the average tolerable delta-V for females was much lower than that for males. Roberts and Compton (1993) found that the delta-V causing a 50% probability of an injury of AIS (Abbreviated Injury Scale) 3+ in frontal unrestrained occupants, was 38 km/h for females and 44 km/h for males. Welsh and Lenard (2001) also reported similar trends when investigating MAIS 2+ injuries. They speculated that a more extensible seatbelt should be used to reduce the incidence of female chest injuries.

Several factors, including the mass and height of the subject, quality of bone, and seating position can affect injury outcome when studying gender differences. On the one hand, female occupants are generally lighter and have lower inertia, thus reducing the likelihood of injury. On the other hand, female drivers tend to sit in a more forward position due to their small stature. Manary et al. (1998) showed that small female drivers who sat closely to the steering wheel assembly might have more severe chest injuries due to a shorter ride-down distance. For postmenopausal females, reduced bone quality further increases their vulnerability.

Mathematical modeling techniques have also been used to better understand chest injury mechanisms (Huang et al. 1994, Lizee et al. 1998, Shah et al. 2001 and Iwamoto et al. 2002). Recently, Iwamoto et al. (2002) successfully reconstructed several injury scenarios using a whole-body finite element model of a 50th percentile male, which included representation of the head, spine, shoulder complex, ribcage, pelvis, upper and lower extremities and skin using two explicit codes (LS-DYNA and PAM-CRASH). Naturally, the material properties used in the model were those of a 50th percentile male and the model could not be used to study female injuries. At present, it is unknown if vulnerability of the female chest is due to its structural or material properties or a combination of both. Such information is needed to better understand differences between male and female chest injuries.

During impact, the ribcage provides crucial protection to vital internal organs. Because of this function, many static tests have been conducted on human ribs to determine its mechanical properties, such as, force and deflection, Young's modulus and fracture tolerance (Granik and Stein 1973, Got et al. 1975, Cesari et al. 1981 and Begeman et al. 1990). In dynamic investigations, it has been suggested that blunt impacts or pendulum-type tests are a better assessment of chest stiffness than that obtained from sled tests. This is because blunt impacts against a stationary subject do not need to account for its inertial effect. Consequently, many blunt chest impact tests were conducted and several force-deflection corridors were drawn (Nahum et al. 1970, Kroell et al. 1971, Stalnaker et al. 1972, Kroell et al. 1974, Cesari et al. 1981, Viano 1989, Talantikite et al. 1998 and Chung et al. 1999). In this study, male and female cadaveric subject data were extracted from aforementioned studies to evaluate chest biomechanical properties due to gender differences. These results can be useful in the development of new anthropomorphic test devices (ATDs) and mathematical models for small females.

METHODS

Frontal pendulum impact data were taken from cadaveric tests conducted by Nahum et al. (1970), Kroell et al. (1971), Stalnaker et al. (1972) and Kroell et al. (1974). Pneumatic impactors used all had the same diameter of 150 mm and were centered at approximately the mid-sternum level in all four studies. However, the mass of the impactor ranged from 1.6 to 23.6 kg and the impact velocities ranged from 4.0 to 14.5 m/s. The backs of the cadavers were unsupported in all tests, except for six subjects that were tested by Kroell et al. (1974). These were tested in the fixed-back configuration. Due to incomplete test results reported on Cadaver No. 11FF and 63FM (Kroell et al. 1971 and 1974), only 51 cases (40 males, 11 females) were available for frontal impact data analysis.

Datasets available for lateral pendulum impact analysis were much smaller. A survey of the literature found data for only 26 males and six females (Cesari et al. 1981, Viano 1989, Talantikite et al. 1998 and Chung et al. 1999). In these studies, pneumatic impactors were used by Cesari et al. (1981), Talantikite et al. (1998) and Chung et al. (1999) while Viano (1989) used a pneumatically driven pendulum impactor. The impactors used in all tests were aligned at the level of the xiphoid process. The mass of the impactor used by Cesari et al. (1981) and Viano (1989) was 23.4 kg compared to either 12 or 16 kg used by Talantikite et al. (1998) and 50 kg used by Chung et al. (1999). Although six cadavers were tested in the study reported by Chung et al. (1999), two were tested with padding and were thus excluded from this study. Chung et al. (1999) measured chest deflection from the lateral side of 6th rib using a 40-channel chestband, while the deflection measurement was based on film analysis in the study reported by Viano (1989) and Talantikite et al. (1998). Occasionally, chest deflection and force data were not tabulated in the original report and required digitization from the chest force-deflection curves or time histories to extract the needed information. Moreover, Cesari et al. (1981) did not report cadaveric response data such as the chest deflection and chest force. Lastly, information on subject height, chest force, viscous tolerance, chest stiffness, number of rib fractures, or chest injury was sporadically missing from these studies. Hence, the data quality and quantity available for lateral impact analysis were worse than those used in frontal impact.

Data were analyzed for the following variables: test conditions, subject age and anthropometry, chest impact response and resulting chest injury. The test conditions analyzed include the impactor mass, impact velocity, energy and momentum. Analysis was also done based on the height, weight, gender, age, and chest depth and chest width of the test subject. Chest response, parameters analyzed included the maximum chest deflection (D_{max}), chest compression ratio (C_{max}), maximum chest force (F_{max}), stiffness of the chest and viscous tolerance ($(VC)_{max}$).

Additionally, the number of rib fractures and AIS were used as injury variables when the probability of injury was analyzed using test variables, such as, subject age and anthropometry and impact response variables. The logistic regression method described by Menard (1995) and linear regression method described by Zar (1984) were used. Cadaveric injury severity was based on the number and location of rib fractures, as specified by the Association for the Advancement of Automotive Medicine (AAAM), AIS version 1990 with 1998 updates. An AIS 3 injury represents four or more rib fractures on one side of the chest and three or less rib fractures on the other side. An AIS 4 injury was defined by four or more rib fractures on each side of the chest. Additionally, a binary system was used to distinguish any tests with or without seven or more rib fractures, AIS 3+ and 4+ injuries for logistic regression analysis. Kent et al. (2001) showed that seven or more rib fractures constitute a good indicator for flail chest injury. Commercially available software, STATISTICA (StatSoft, Inc., Tulsa, OK), was used for all statistical analyses.

Rib material properties data were based on the three-point bending test setup shown in Figure 1. Data from a series of 73 quasi-static three-point rib bending tests reported by Koh (2000) and another series of 23 test results, using the same test protocol, compiled during the course of this study were used for analysis. The ribs used were the 6th and 7th ribs between the rear axillary line and the mid-clavicular line from 70 male and 26 female cadavers. An anti-bacterial saline solution spray was used during the test to keep the specimen moist while an Instron machine (Model 1321, Canton, MA) was used to load the specimen at a rate of 0.169 mm/s. A band saw was used to cut the rib after the test to determine its cross-sectional properties (Figure 2).

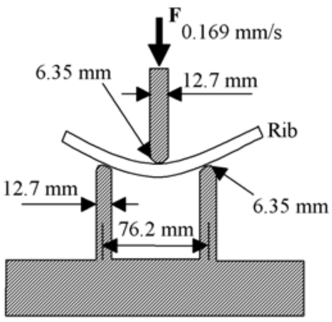


Figure 1 – Three-point bending test configuration of the ribs used by Koh (2000)

Figure 2 – A typical cross-sectional view of the rib used to calculate the cross-sectional area and moment of inertia

RESULTS

RELEVANT INFORMATION ON CADAVERS SUBJECTED TO PENDULUM IMPACTS: In the frontal impact group, the average age of the male and female subjects was 63.8 ± 13.9 and 63.7 ± 14.7 years, respectively. There was no statistical difference between males and females in the average age for the frontal impact group. However, in the lateral impact group, the average age for males (66.7 ± 9.8) was significantly ($p < 0.045$) lower than that for females (76.7 ± 13.0). The average height for the male and female cadavers used was 1.77 ± 0.068 and 1.62 ± 0.092 m in frontal impact and 1.71 ± 0.081 and 1.57 ± 0.081 m in lateral impact, respectively. In the frontal impact group, the male and female cadavers weighed 66.9 ± 12.5 and 52.3 ± 14.7 kg respectively while the respective weights were 72.0 ± 15.9 and 51.0 ± 19.0 kg for the lateral impact group. Statistically, the male cadavers used were taller and heavier than the female cadavers used in both the frontal and lateral impact groups. Similarly, the chest depth and width were larger in males compared to females. In the frontal impact group, the chest depth for males and females were 227 ± 23 and 206 ± 22 mm, respectively. The respective chest widths were 313 ± 22 and 273 ± 30 mm for male and female cadavers used in lateral impact.

CHEST RESPONSES VERSUS CADAVERIC ANTHROPOMETRICS: Based on a linear regression analysis, there was no significant correlation between the chest impact response data (D_{max}, C_{max}, F_{max} and chest stiffness) and cadaveric age, height or weight ($p > 0.05$, $r^2 < 0.2$) for both frontal and lateral impacts. Figure 3 shows a comparison of chest stiffness between males and females due to blunt impact in the frontal and lateral directions. In frontal impact, the average stiffness for males was 476 ± 324 and 267 ± 150 kN/m for females. Based on a Student's t-test, the male chest was significantly stiffer than the female chest (p = 0.045). In lateral impact, while the average chest stiffness (186 ± 158 kN/m) was still higher in males, it is not statistically different from female chest stiffness (144 ± 49 kN/m). It should be noted that only four female subjects were available for lateral impact analysis because no stiffness data were provided for two of the six females tested.

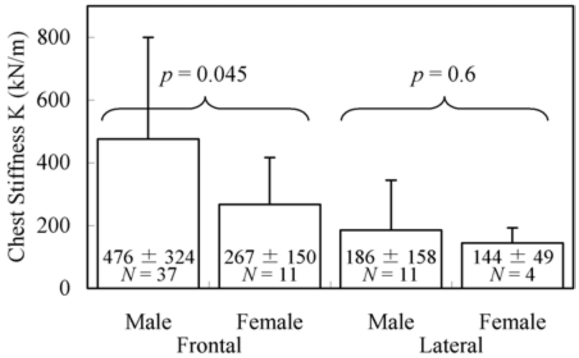
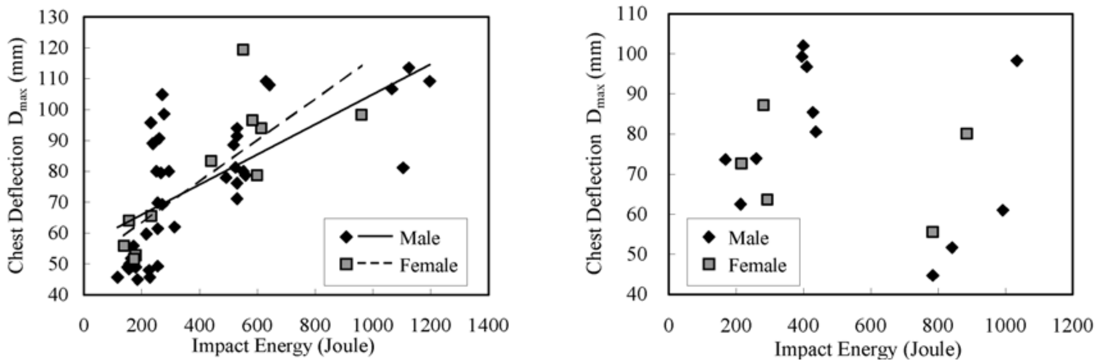


Figure 3 – Average value and standard deviation of chest stiffness due to blunt impact,
Left: male versus female response in frontal impact,
Right: male versus female response in lateral impact

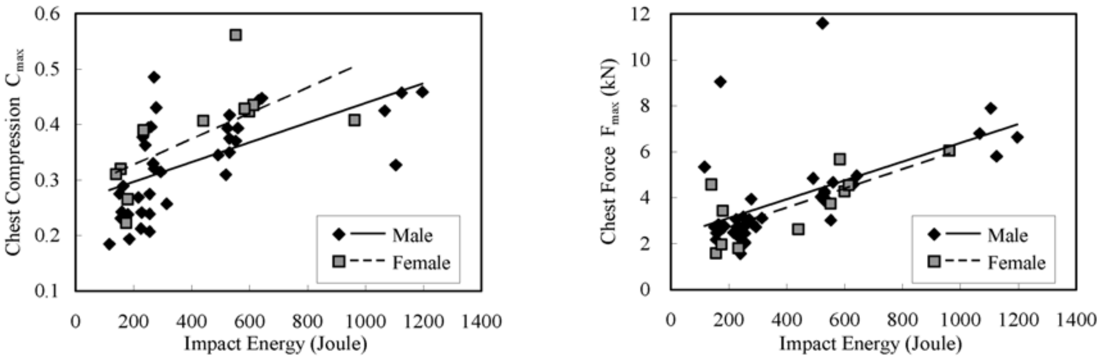
CHEST RESPONSE VERSUS INPUT TEST CONDITIONS: Figure 4 illustrates D_{max} as a function of the impact energy in frontal and lateral impacts. The analysis is limited to the impact energy range of 200 to 1200 joules and extrapolation of the regression lines beyond the range shown is not recommended. In frontal impact, the maximum chest deflection increased as the impact energy increased. For both males (p = 0.000004, r^2 = 0.43) and females (p = 0.003, r^2 = 0.65) D_{max} was somewhat linearly correlated to impact energy. In frontal impact, the slope for females was 0.067 mm/Joule. It was steeper than that for males (0.049 mm/Joule) indicating that larger chest deflections were observed in females when subjected to the same impact energy, especially for high-energy impacts. In lateral impact, D_{max} did not correlate linearly with the impact energy (p = 0.4, r^2 = 0.06 for males and p = 0.7, r^2 = 0.04 for females). Thus, linear regression lines were not provided in Figure 4(b).



(a) Frontal impact (b) Lateral impact

Figure 4 – The maximum chest deflection (D_{max}) as a function of impact energy in frontal and lateral blunt impact

Figure 5 shows linear correlation of C_{max} and F_{max} with impact energy in frontal impact. Both C_{max} (male: p = 0.00005, r^2 = 0.36 and female: p = 0.03, r^2 = 0.44) and F_{max} (male: p = 0.0002, r^2 = 0.32 and female: p = 0.01, r^2 = 0.54) increased significantly as impact energy increased. For C_{max} versus impact energy, both the slope and intercept for females were slightly higher indicating that the chest compression ratio is higher in females, probably due to the fact the female chest depth is smaller than males. In lateral impact, only F_{max} in males correlated linearly against the impact energy (p = 0.000006, r^2 = 0.58). Other chest response parameters were not linearly correlated with impact energy.



(a) C_{max} vs. Impact energy (b) F_{max} vs. Impact energy

Figure 5 – The maximum chest compression ratio (C_{max}) and maximum chest force (F_{max}) as a function of impact energy in frontal blunt impact

Upon inspection of the impact energies used in various experimental studies in frontal impact, they can be divided into three groups: low (approximately 200 Joules), middle (approximately 600 Joules) and high (approximately 1,000 Joules). There were only four males and one female in the high impact energy group and it was thus not possible to perform a Student's t-test on the data. Chest response data for the other two groups are shown in Table 1. From the p values, it can be seen that there was a significant gender difference for C_{max} (p = 0.03) in the middle impact energy group. Comparison of other parameters showed no statistical differences. In lateral impact, impact energies can be divided into two groups: low (approximately 300 Joules) and high (approximately 900 Joules). No significant gender difference in chest responses was observed.

Table 1 – Average and standard deviation of chest response for males and females in frontal impact

Low impact energy	Male		Female		p	Female/Male
	N	Average ± S.D.	N	Average ± S.D.		
D_{max} (mm)	25	66.7 ± 19.5	5	58.0 ± 6.4	0.34	86.9 %
C_{max} (%)	25	29.6 ± 8.1	5	30.2 ± 6.3	0.88	102.0 %
F_{max} (kN)	24	3.05 ± 1.47	5	2.67 ± 1.29	0.60	87.6 %

Middle impact energy	Male		Female		p	Female/Male
	N	Average ± S.D.	N	Average ± S.D.		
D_{max} (mm)	11	87.0 ± 12.7	5	94.4 ± 15.8	0.33	108.5 %
C_{max} (%)	11	38.8 ± 4.3	5	45.1 ± 6.3	**0.03**	116.3 %
F_{max} (kN)	11	4.91 ± 2.28	5	4.17 ± 1.11	0.50	84.8 %

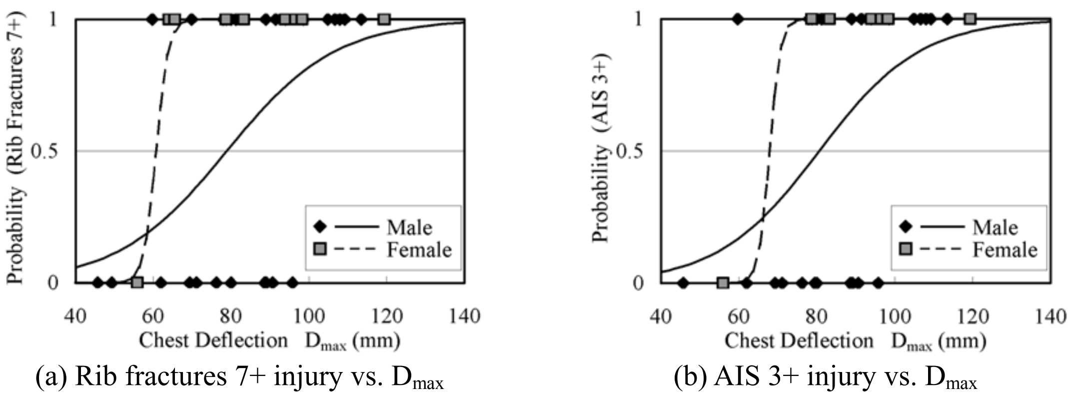
CHEST INJURIES VERSUS IMPACT RESPONSES: Table 2 shows the results of logistic regressions for AIS 3+ and AIS 4+ injuries as well as chest injuries with seven or more rib fractures against injury predictors D_{max}, C_{max}, F_{max} and $(VC)_{max}$. If we randomly choose a minimum chi-squared value of 5 to select the parameters for both male and female injury prediction, we could predict AIS 3+ injuries using D_{max} and C_{max} and injuries with seven or more rib fractures using D_{max} for frontal impact. There were insufficient data to determine which response parameters could be used to predict these injuries for lateral impact.

Table 2 – Cross-reference of chest injuries by chest responses

Chest Responses	Chest Injuries	Sex	Frontal Impact N	Frontal Impact Chi-square	Frontal Impact p	Lateral Impact N	Lateral Impact Chi-square	Lateral Impact p
D_{max}	Rib fractures 7+	M	30	8.3	**0.004**	12	1.9	0.2
		F	9	5.9	**0.02**		N/A	
	AIS 3+	M	28	7.9	**0.005**	12	0.7	0.4
		F	7	5.7	**0.02**		N/A	
	AIS 4+	M	28	9.0	**0.003**	12	6.8	**0.009**
		F	7	1.4	0.2	5	0.0	0.9
C_{max}	Rib fractures 7+	M	30	7.0	**0.008**	12	0.8	0.4
		F	9	4.7	**0.03**		N/A	
	AIS 3+	M	28	7.2	**0.007**	12	0.3	0.6
		F	7	5.7	**0.02**		N/A	
	AIS 4+	M	28	8.1	**0.004**	12	2.5	0.1
		F	7	3.7	0.056	5	0.7	0.4
F_{max}	Rib fractures 7+	M	30	1.8	0.2	26	2.4	0.1
		F	9	0.3	0.6		N/A	
	AIS 3+	M	28	1.9	0.2	26	5.5	**0.02**
		F	7	0.0	0.9		N/A	
	AIS 4+	M	28	1.7	0.2	26	4.3	**0.04**
		F	7	0.0	0.9	6	0.0	0.9
$(VC)_{max}$	Rib fractures 7+	M	28	9.1	**0.003**	12	0.6	0.5
		F	7	5.7	**0.02**		N/A	
	AIS 3+	M	28	9.1	**0.003**	12	0.3	0.6
		F	7	5.7	**0.02**		N/A	
	AIS 4+	M	28	9.2	**0.002**	12	1.0	0.3
		F	7	0.4	0.5	5	0.3	0.6

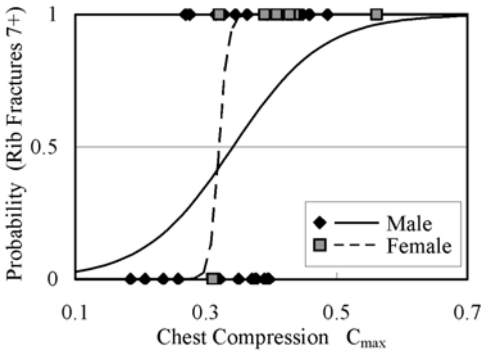
While chi-squared values were still high for $(VC)_{max}$ as an injury predictor, negative logistic curves were found in the plots of $(VC)_{max}$ versus seven or more rib fractures or AIS 3+ injuries for females. This indicates a higher probability of sustaining seven or more rib fractures or AIS 3+ injuries with a lower $(VC)_{max}$. Because this conclusion is intuitively wrong, $(VC)_{max}$ is not considered as a good injury predictor.

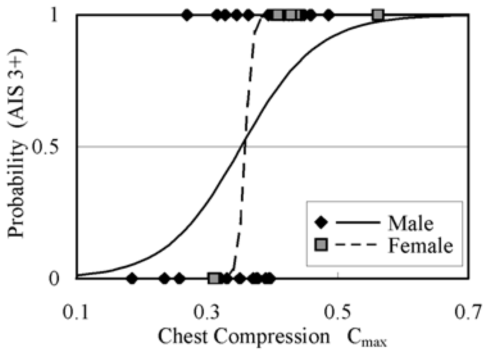
Figures 6(a) and 7(a) show logistic plots of the probability of sustaining an injury with seven or more rib fractures in frontal impact as a function of D_{max} and C_{max}, respectively. For a 50% probability of sustaining an injury with seven or more rib fractures, the values for D_{max} and C_{max} were 79 mm and 34% for males and 61 mm and 32% for females, respectively. Figures 6(b) and 7(b) show the logistic plots of the probability of sustaining AIS 3+ injuries in frontal impact as a function of D_{max} and C_{max}. For a 50% probability of sustaining an AIS 3+ injury, the values for D_{max} and C_{max} were 81 mm and 35% for males and 68 mm and 36% for females, respectively.



(a) Rib fractures 7+ injury vs. D_{max} (b) AIS 3+ injury vs. D_{max}

Figure 6 – Logistic plots of chest injury probability due to D_{max} in frontal impact





(a) Rib fractures 7+ injury vs. C_{max} (b) AIS 3+ injury vs. C_{max}

Figure 7 – Logistic plots of chest injury probability due to C_{max} in frontal impact

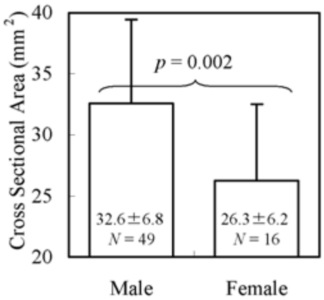
CADAVERIC ANTHROPOMETRICAL DATA USED IN RIB BENDING TEST: The average age for male and female cadavers used in rib bending tests was 59.2 ± 9.8 and 58.3 ± 11.9 years, respectively. There is no statistical difference. The average height and weight for males were 1.73 ± 0.079 m and 69.9 ± 14.8 kg. The males were statically taller and heavier than females whose height and weight were1.59 ± 0.075 m and 58.9 ± 11.0 kg respectively.

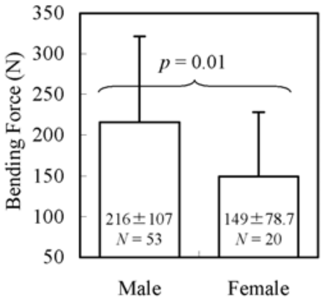
RIB STRUCTURAL AND MATERIAL PROPERTY IN ISOLATED RIB BENDING TEST: Based on a linear regression analysis, data obtained from isolated rib bending test did not correlate statistically with age, height, weight, chest depth and chest width of both the male and female cadavers tested ($p > 0.05$, $r^2 < 0.3$).

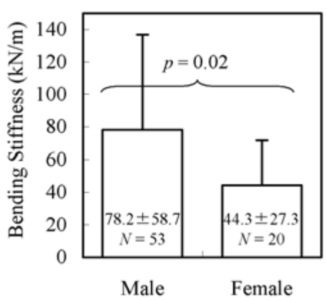
Table 3 compares the differences between male and female specimens in terms of the cross-sectional area, maximum bending force, maximum bending stiffness, Young's modulus and bone mineral density of the ribs. The cross-sectional area for females was approximately 81% of that of males. Based on Student's t-tests, the cross-sectional area ($p = 0.002$), bending force ($p = 0.01$) and bending stiffness ($p = 0.02$), were significantly higher in males compared to females (Figure 8). However, no significant differences can be found in Young's modulus and bone mineral density. These data indicate that while the structural properties of male ribs are significantly higher than female ribs, no significant differences are observed for the material properties.

Table 3 – Bending test results of the ribs obtained by Koh (2000) and from this study

t-test (Male versus Female)	Male *N*	Male Average ± S.D.	Female *N*	Female Average ± S.D.	Female/Male
Cross-sectional Area (mm²)	49	32.6 ± 6.8	16	26.3 ± 6.2	80.6 %
Max Bending Force (N)	53	216 ± 107	20	149 ± 78.7	69.1 %
Bending Stiffness (kN/m)	53	78.2 ± 58.7	20	44.3 ± 27.3	56.7 %
Young's Modulus (G Pa)	53	7.21 ± 5.94	20	7.57 ± 5.44	105.4 %
Bone Mineral Density (%)	53	42.2 ± 9.3	20	45.9 ± 9.4	108.8 %







(a) Cross-sectional area (b) Bending force (c) Bending stiffness

Figure 8 – Comparison of male and female of rib bending properties

DISCUSSION

This retrospective study analyzed data from 83 cadaveric pendulum-type impacts: 40 males and 11 females in frontal impact and 26 males and six females in lateral impact. Because female subjects represented only 20% of tested cadavers, we believe more female subject tests are needed for gender differences to be evaluated fully. One drawback of using published pendulum test results obtained from different sources for data analysis is that different test protocols were used. To minimize the effect of this deficiency, linear regression against impact energy was used prior to comparison of biomechanical responses between genders. Nevertheless, findings derived from this study can be used to better understand similarities and differences in biomechanical properties between males and females.

In this retrospective study, the age distribution of the donors is shown in Figure 9. As can be seen in this figure, the age of a majority of the test subjects was from the 40’s to the 80’s, a range which may not be totally representative of the driving population. Thus, although our findings indicated that there were no statistical correlations between the impact responses of the chest and rib bending strength against age, these findings may be related to the fact that mainly elderly subjects were tested. We believe that recent advances in medical technology are responsible for this increase in life expectancy. There are a number of studies, which showed age dependent material properties of the human bone. However, these studies have focused on the long bones such as the femur, humerus, tibia and radius (Yamada 1970, Hayes 1976 and Zioupos and Currey 1998). The only age dependent study on human ribs we found was reported by Stein and Granik (1976). While this study reported that the breaking load, bending strength and cross-sectional area decreased as the age of the test subjects increased, all 218 specimens were obtained from 79 male cadavers. Consequently, the results cannot be used to test the hypothesis that the strength of the female rib was lower than that of males.

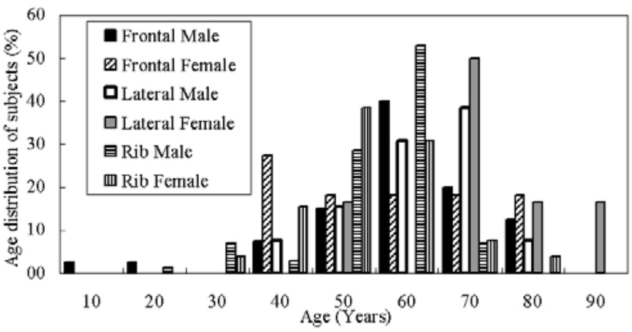


Figure 9 – Age distribution for the test subjects used in this retrospective study

The female chest was significantly more compliant than the male chest in frontal impact. While the difference was not statistically significant, male chest stiffness was also higher in lateral impact. Additionally, chest injuries, in terms of the number of rib fractures, tended to be less severe in males than in females when impacts of the same energy were considered. However, even though the average impact responses in terms of C_{max} and D_{max} were higher and in terms of F_{max} were lower in female subjects, the gender differences were not statistically significant. The only exception was the C_{max} in the 600 Joules impact energy group due to frontal impact. In this impact energy group, C_{max} in male subjects averaged 38.8% compared to 45.1% among female subjects (p = 0.03).

The above findings could probably be better explained by results from three-point bending tests of isolated ribs taken from 70 male and 26 female age equivalent cadavers (Table 3). In these tests using an identical test protocol, we found that the average stiffness for males was 43% higher than that for females. Additionally, the cross-sectional area of female ribs was approximately 19% smaller than male ribs (p = 0.002). However, the Young’s modulus, calculated from three-point bending tests and bone mineral density, measured from the ash content, showed no difference between males and females. We believe the low bending stiffness observed in the female chests was due to a lower area moment of inertia of the ribs, which have a smaller cross-sectional area.

The equal stress-equal velocity scaling procedure proposed by Eppinger et al. (1984) was used to scale all data to a 46.2 kg person, a representation of the fifth percentile female subject. The basic scaling factor, lambda (λ), is defined in Equation (1):

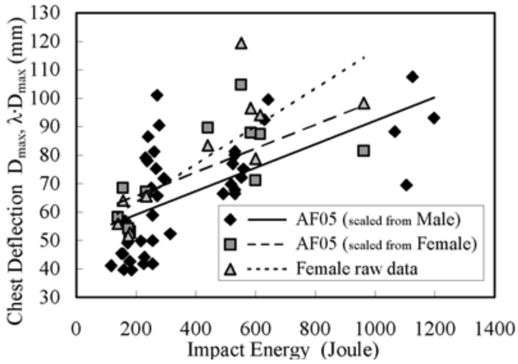
$$\lambda = \sqrt[3]{M_{af05} / M_{cadaver}} \quad (1)$$

Where M_{af05} and $M_{cadaver}$ represent the mass of a fifth percentile female and of the test subject, respectively. To determine the 5th percentile female chest deflection we use the product of λ and D_{max}. To determine the 5th percentile female chest force, we use the product of λ^2 and F_{max}.

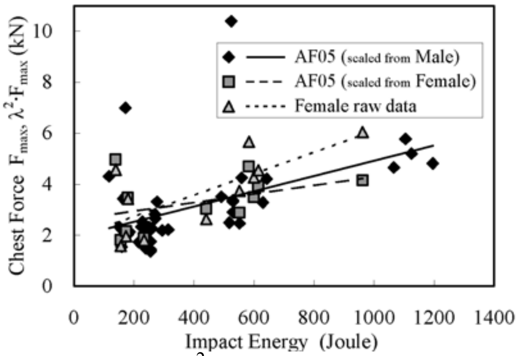
FRONTAL IMPACT SCALING: Figure 10 shows normalized maximum chest deflection ($\lambda \cdot D_{max}$) and force ($\lambda^2 \cdot F_{max}$) versus impact energy in frontal impact, scaled to the 5th percentile female from all male subjects tested (diamond) and all female subjects tested (square). A linear regression was used to correlate resulting 5th female representation scaled from male subjects (solid line) and from female subjects (dashed line). Additionally, the raw data of D_{max} and F_{max} obtained from all female subjects (triangle) and respective linear regressions (dotted line) are shown on the same figure for reference.

If the equal stress-equal velocity scale law correctly predicted 5th percentile female responses, then the three regression lines should be close to each other. Otherwise, it indicates that besides the weight differences, other disparities may separate males from females. Based on the linear regression of $\lambda \cdot D_{max}$ versus the impact energy, the slopes were very similar when comparing scaled results using all male data and all female data. However, there was an offset of 6 mm in $\lambda \cdot D_{max}$ between these two regression lines. The slope obtained from linear regression of the female raw data was steeper than that obtained from the two scaled lines. When considering D_{max} versus impact energy as shown in Figure 4(a), results from linear regression of D_{max} for the low and middle impact energy groups for males and females were approximately the same. However, the slightly higher slope in females resulted in a larger difference when the impact energy increased.

For the $\lambda^2 \cdot F_{max}$, it was observed the slope of the linear regression between $\lambda^2 \cdot F_{max}$ and impact energy was the greatest for the raw female data, followed by that obtained from all male scaled data then all female scaled results. The $\lambda^2 \cdot F_{max}$, scaled from all female data, was greater than that scaled from all male data for the low impact energy group, however, the $\lambda^2 \cdot F_{max}$ scaled from all female data was less than that scaled from all male data for the high impact energy group. In contrast, the slope and intercept of F_{max} versus impact energy for both genders as shown in Figure 5(b) were very similar.



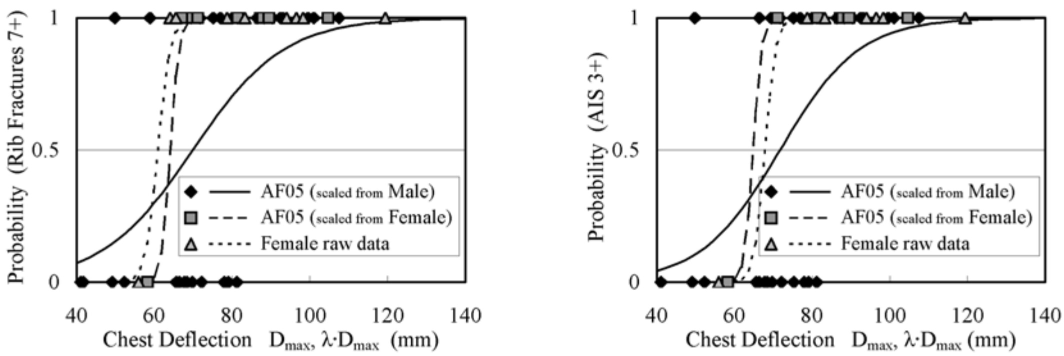
(a) D_{max} and $\lambda \cdot D_{max}$ vs. Impact energy



(b) F_{max} and $\lambda^2 \cdot F_{max}$ vs. Impact energy

Figure 10 – Plots of normalized chest responses against impact energy in frontal impact

INJURY PREDICTORS: Using scaled and raw female data, the probability of sustaining an injury with seven or more rib fractures and AIS 3+ injuries in frontal impact is shown in Figures 11(a) and 11(b), respectively. $\lambda \cdot D_{max}$ denotes chest deflection for a 5th percentile female, scaled from all male (solid line) and all female (dashed line) subjects tested. These curves are compared with the logistic regression curve for raw female data, plotted as a dotted line on the same figure. For a 50% probability of sustaining an injury with seven or more rib fractures, the values for $\lambda \cdot D_{max}$ were 69.9 and 64.1 mm when scaled from all male results and from all female results, respectively. The corresponding value for raw female data was 61 mm, as shown in Figure 6 above. Similarly, for a 50% probability of sustaining an AIS 3+ injury, the respective values were 71.7 and 64.8 mm and the corresponding value for raw female data was 68 mm (Figure 7). The difference in $\lambda \cdot D_{max}$ scaled from all male data and from raw female data was approximately 13% for seven or more rib fractures and 5% for AIS 3+ injuries. Although the discrepancy is small, it should be noted that the logistic curves are widely divergent between the scaled male data and the raw female data.



(a) Rib fractures 7+ injury vs. D_{max} and $\lambda \cdot D_{max}$ (b) AIS 3+ injury vs. D_{max} and $\lambda \cdot D_{max}$

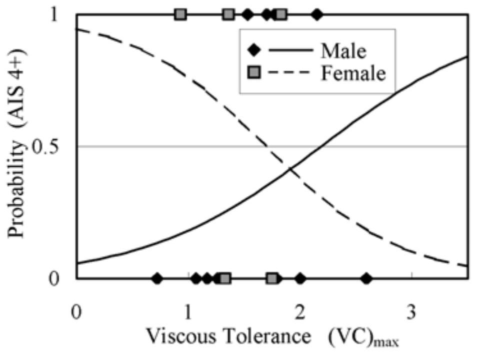
Figure 11 – Logistic plots of injury probability due to normalized chest deflection in frontal impact

The aforementioned findings were obtained by lumping all available impacts for logistic regression, regardless of the impact energy. These data seem to suggest D_{max} is capable of separating male responses from female responses. For a 50% probability of sustaining seven or more rib fractures, it was 79 and 61 mm for males and females, respectively. Similarly, for a 50% probability of sustaining AIS 3+ injuries, it was 81 and 68 mm for males and females, respectively. On the other hand, when three impact energy groups were considered separately, we found D_{max} was not statistically different between males and females.

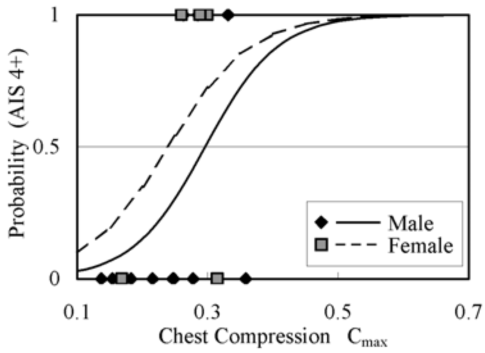
The slope obtained from linear regression of C_{max} versus impact energy for females ($p = 0.03$, $r^2 = 0.44$) was approximately 31% steeper than that for males ($p = 0.00005$, $r^2 = 0.36$). This indicates that a higher chest compression ratio was observed in females compared to males when subjected to the same impact energy (Figure 5a). C_{max} for females was 2% ($p = 0.88$) and 16.3% ($p = 0.03$) greater than that for males in the low and middle impact energy groups, respectively (Table 1). The high impact energy group was not compared due to the small number of specimens available. While there was a significant difference in C_{max} between males and females ($p = 0.03$) for the middle impact energy group, we found almost no difference in C_{max} for the prediction of a 50% probability of sustaining seven or more rib fractures or AIS 3+ injuries (Figure 7). For a 50% probability of sustaining seven or more rib fractures, C_{max} was 34% and 32% for males and females, respectively. Similarly, for a 50% probability of sustaining AIS 3+ injuries, C_{max} was 35% and 36% for males and females, respectively.

LATERAL IMPACT: In lateral impact, linear relationships between response variables (D_{max}, C_{max}, F_{max}, $\lambda \cdot D_{max}$ and $\lambda^2 \cdot F_{max}$) and impact energy were found to be statistically not significant, probably due to the small number of cases available. More cadaveric pendulum impact data are needed for a better understanding of lateral impacts to the chest.

Viano (1989) proposed the use of $(VC)_{max}$ and C_{max} as measures of chest injury tolerance for lateral impact. For a 25% probability of sustaining an AIS 4+ injury, the proposed injury thresholds for $(VC)_{max}$ and C_{max} were 1.47 m/s and 38.4%, respectively. Figure 12 shows the logistic plots of the probability of sustaining AIS 4+ injuries in lateral impact as a function of $(VC)_{max}$ and C_{max} obtained from this study. The tolerance in terms of $(VC)_{max}$ and C_{max} for a 25% probability of sustaining an AIS 4+ injury was 1.32 m/s and 23.5% for males, both lower than reported by Viano (1989). However, the logistic curve obtained for females for AIS 4+ injuries in terms of $(VC)_{max}$ showed a negative correlation (Figure 12a). This result is intuitively incorrect and more research is needed regarding the use of $(VC)_{max}$ as an injury predictor in female lateral impact.



(a) AIS 4+ injury vs. $(VC)_{max}$



(b) AIS 4+ injury vs. C_{max}

Figure 12 – Logistic plots of AIS 4+ injury probability due to chest responses in lateral impact

In this study, only 17 female cadavers (11 cases in frontal and six cases in lateral impacts) were available to analyze chest biomechanical properties. Lenard and Welsh (2001) estimated that the probability of sustaining AIS 2 chest injuries for female occupants was much higher than that for male occupants in frontal impact. However, we could not duplicate that analysis because only one female case (Cadaver No. 30FF, Kroell et al. 1974) sustained an AIS 2 injury with three rib fractures, while the rest of the female cadavers sustained AIS 3+ injuries with seven or more rib fractures. Therefore, more female low injury severity data are needed for an in-depth analysis of the differences in injury response and injury threshold between males and females.

CONCLUSIONS

Several conclusions can be drawn from this study based on a retrospective analysis of 83 frontal and lateral blunt cadaveric impacts and 96 isolated rib bending tests. The variables analyzed include test condition, cadaveric anthropometric data, chest impact response and resulting chest injury.

1. Female chest stiffness (267 ± 150 kN/m) was considerably lower than that of the male (476 ± 324 kN/m) in frontal impact, probably due to the smaller cross-sectional area of female ribs.
2. There was no significant gender difference in Young's modulus and bone mineral density based on isolated rib bending tests. However, the cross-sectional area, maximum bending force and stiffness of female ribs were approximately 19, 30 and 43% lower than those of male ribs, respectively.
3. Based on a linear regression analysis, data obtained from isolated rib bending tests did not correlate statistically the age, height, weight, chest depth and width of the cadavers tested for both males and females. It should be noted that no correlation was found between impact responses of the chest and age. This may be related to the fact that only middle age to elderly cadavers were used in the experimental studies selected for this retrospective analysis.
4. The maximum chest deflection, compression ratio and maximum force somehow correlated linearly with impact energy for both males and females in frontal impact. This linear relationship will be useful in the development of a 5th percentile female numerical model and ATDs.
5. The slopes of maximum chest deflection and compression ratio versus impact energy for females are 37 and 31% steeper than those for males, respectively. In general, the maximum deflection and compression ratio for females are considerably higher than those for males when subjected to the same impact energy.
6. The use of the equal stress-equal velocity scaling law to predict 5th percentile female responses are not appropriate because this normalization method does not consider gender differences.

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