A new method for developing structural and material clavicle response corridors for axial compression and three point bending loading

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ABSTRACT

A number of clavicle finite element (FE) models have been developed to study clavicle injuries in automotive side and frontal crashes. However, no loading response corridors exist in the literature for clavicle FE model validation. Therefore, the purpose of this study was to develop the clavicle response corridors for axial compression and three point bending, which were shown to represents the clavicle loading condition in side and frontal crashes respectively. Ten clavicles were loaded to failure in each of these two loading configurations at strain rates measured in sled tests. Both structural response (force VS deflection) and material response (force VS peak strain) corridors were developed for use in validating clavicle model loading response and injury prediction capacity. The method for creating both structural and material level corridors could be extended to develop corridors for other components of human body.

INTRODUCTION

Clavicle injuries are fairly common during automotive accidents. Over 9700 occupants restrained by a three-point-belt sustain clavicle fractures every year (Kemper, 2009). It was also reported that 66% of shoulder injuries during car lateral impacts are clavicle fractures (Frampton, 1997). The susceptibility of the clavicle to injury underscores its role as an important loading path during both frontal impact and side impact crashes (Melvin, 1998), since clavicle is loaded directly by shoulder belt in frontal impact and through shoulder in lateral impact crashes.

A number of FE models have been developed by researchers to study clavicle and shoulder injuries (Dalmases, 2008; Duprey, 2008; Duprey, 2010; Li, 2012). Although the biomechanical response of the clavicle has been characterized separately under both axial compression loading (Dalmases, 2008; Duprey, 2008) and three point bending (Kemper, 2009; Bolte, 2000), no clavicle response corridor exists in the literature for FE model validation.

Most of the corridors that exist in the literature were reported in terms of structural behavior, e.g., force-deflection (Lobdell, 1973; Kerrigan, 2003; Ivarsson, 2005). However, such a structural description has been shown to be often insufficient for the development of models which accurately predict fracture timing. Untaroiu et al. (2006) showed that, for example, it is possible to tune a FE model of the femur to match an experimental force-deflection response well with both an elastic-plastic and elastic-transversely isotropic material model; however, neither of these models were capable of predicting experimental bone surface strains, and the choice of material model can substantially affect the strain response prediction. Since strain threshold are often used to predict fracture in FE models, structural response validation is insufficient for fracture prediction. Thus, an FE model that can accurately predict structural response and surface strain provide for a much useful tool in injury risk modeling.

In this study, structural and material response corridors for axial compression and three-point bending of the clavicle to failure were developed to assist in FE model development and response validation. Component tests were used for the clavicle to ensure boundary condition represent clavicle response under belted shoulder loading in frontal and side impact sled. Ten clavicles were tested in each configuration. And the force-deflection and force-peak strain corridors were developed for each condition.

METHODS

1.1 Sled Test and clavicle loading condition identification

Side and frontal sled tests in this study were conducted to justify loading conditions for clavicle component level tests, 1) loading rate (strain rate), 2) loading directions (the neutral axis orientation). To characterize these loading conditions, a methodology based on bone surface strain measurement (Untariou, 2007) was used. Four uni-axial strain gages were installed around the perimeter of the clavicle cross-section at the location of maximum posterior concavity of the clavicle (Figure 1). This location was chosen because it is easily identifiable on the clavicle and failures most often occur in the middle third of the clavicle. The clavicle coordinate system (CS) was defined in this study (both sled test and component test) for convenience of expressing the neutral axis orientation (Figure 1c).

The side impact sled test was conducted at lateral impact speed of 4.3m/s using a rigid wall mounted to a massive 1700 kg rail mounted sled with a mid-sized male cadaver. The strain gages were installed on the clavicle of the impact side. The frontal impact sled test was conducted at an impact speed of 40km/h with a mid-sized male cadaver. The strain gages were installed on the clavicle which was loaded by three point seat belt. The general methodology for the side and frontal impact tests closely followed the methods utilized in previous experiments conducted at the University of Virginia (Lessley, 2010, Lopez-Valdes, 2010).

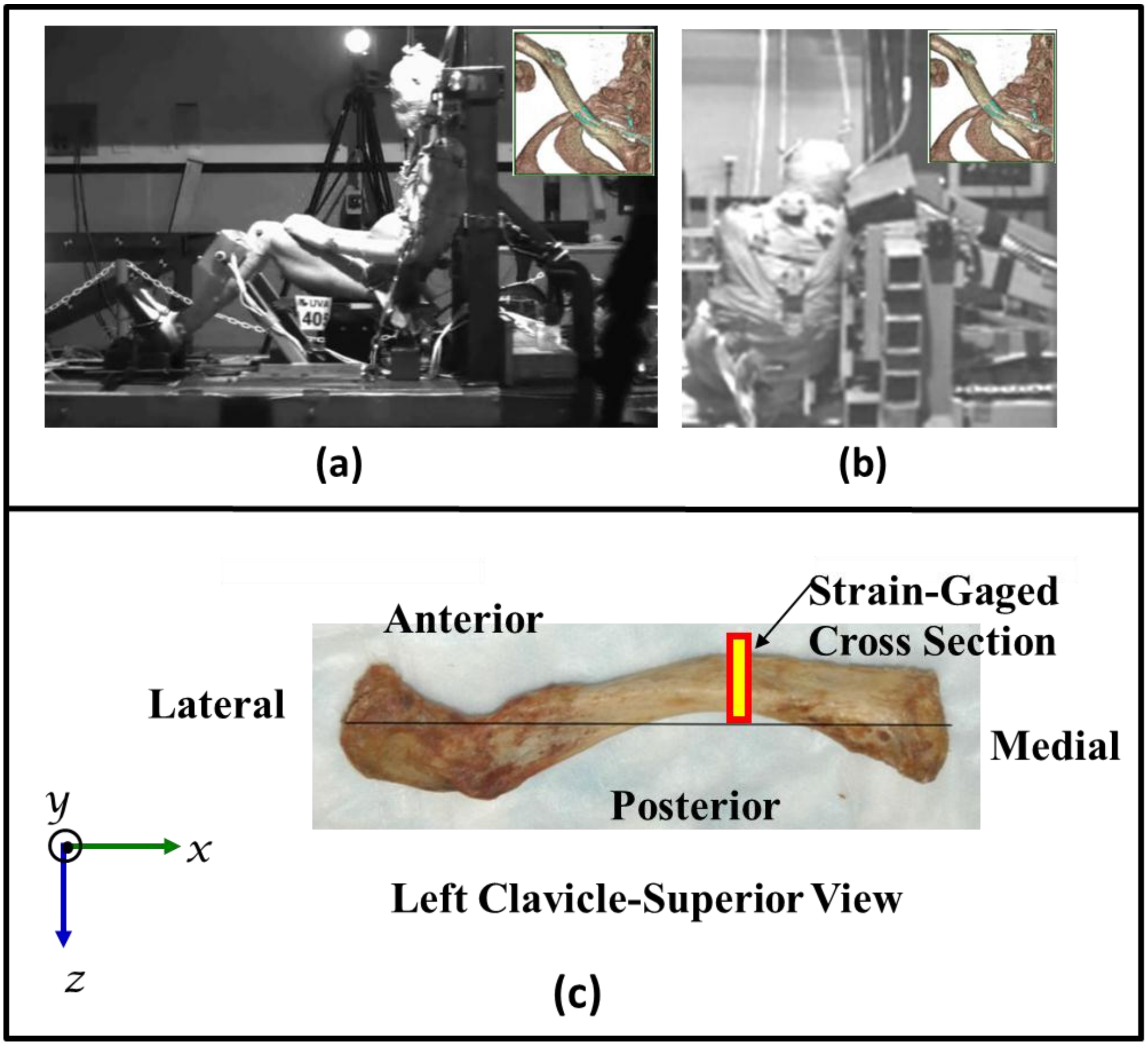

Figure 1: (a) frontal impact sled test setup with 4 strain gage adhered in the right side (b) side impact sled test setup with 4 strain gage adhered in the right side(impact side). (c) Clavicle coordinate system definition: 1) clavicle major plane defines the x-z plane, 2) x-axis pointing from clavicle lateral to medial side, 3) z-axis points from anterior to posterior, 4) y-axis points from inferior to superior

The clavicle strain rate in sled was calculated from the strain gage data. The location of the neutral axial was determined at each time point by assuming a linear strain profile across the cross-section, assuming a linear beam approximation of the clavicle (Untariou, 2007) as shown in Figure 2. Points of zero strain were calculated by linearly interpolating the strain values between the locations of each strain gauge across the clavicle cross-section. The CT scans were used to identify the strain gage locations. A line of best fit was passed through these points of zero strain to approximate the neutral axis (Figure 2).

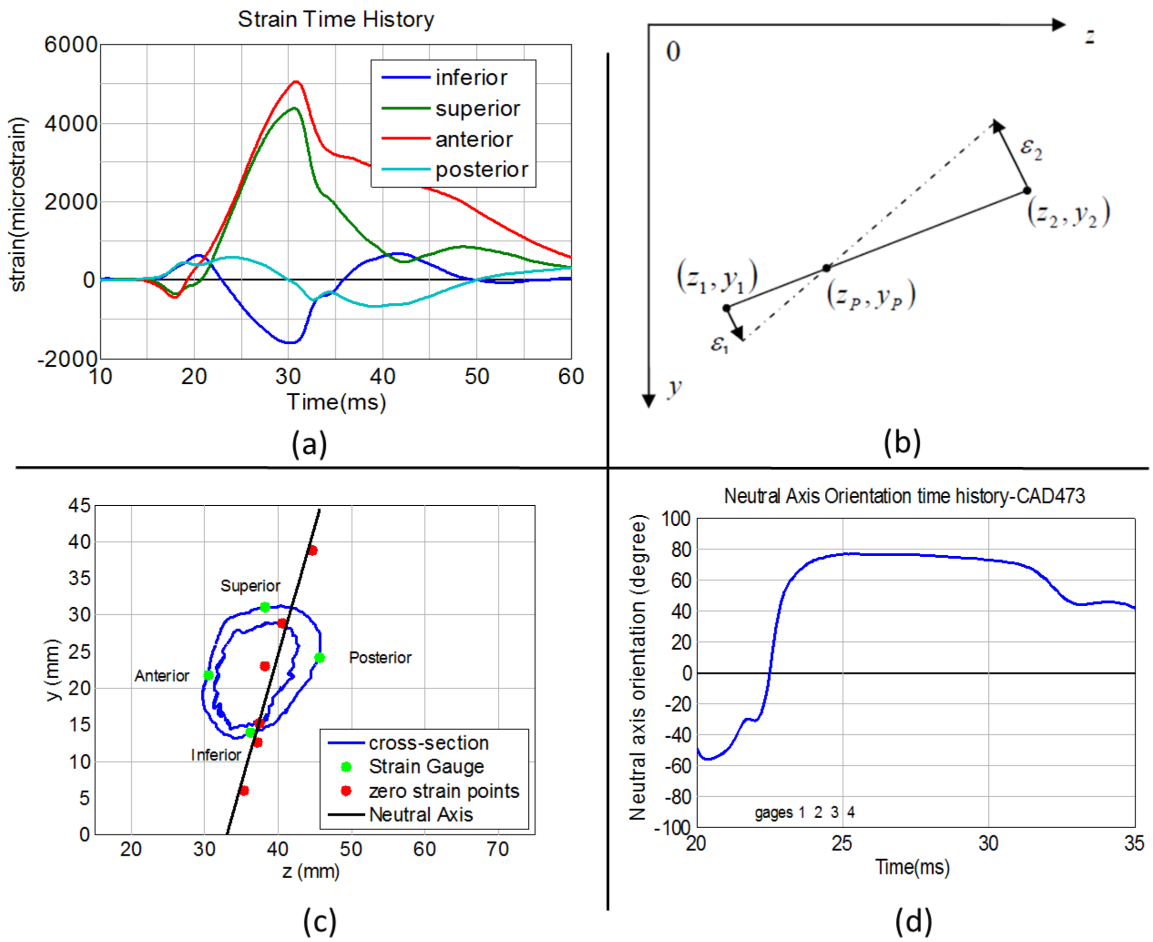

Figure 2: Clavicle Neutral Axis Orientation calculation: a) strain time history data, strain rate was calculated f; b) determine zero strain point; c) fit neutral axis d) neutral axis orientation time history in side impact sled test (CAD473), the neutral axis angle was reported as average angle during the major loading periods in the tests (in this case it is from 22ms to 30ms)

In side impact sled test, the clavicle was loaded at strain rate on the order of 5%/s to 40%/s, with clavicle neutral axis orientation at around 76 degrees in y-z plane of the clavicle coordinate system (Figure 2). Similarly, in the frontal impact sled test, the clavicle was loaded at strain rate on the order of 10%/s to 40%/s, with clavicle neutral axis orientation at around 71 degree (Table 2). These clavicle loading conditions were then used to guide the design of the loading condition for clavicle component level test shown in the following section.

1.2 Clavicle Component Test

Specimen Preparation. Twenty clavicle specimens extracted from 12 post-mortem human surrogates (PMHS) were tested for the component level test (Table 1). After thawing the specimens, all soft tissues were removed. Each clavicle was then measured to determine the length of the clavicle in the medial-lateral direction (Table 1). Each clavicle extremity was potted in a square-shaped aluminum mold with a polyurethane resin. The bone was rotated until the transverse plane of the clavicle was aligned with one face of the potting mold (to ensure that the anterior, superior, posterior, and inferior aspects of the bone were aligned with the mold edges), and the loading is applied within the clavicle major plane(x-z plane) (Figure 3a). This will ensure the component level tests to be able to replicate similar loading conditions as the sled test according to our component tests pilot design.

Table 1: Clavicle Specimen Information

Specimen ID	**PMHS Information**					**Clavicle Length**	**Test Configuration**
	Aspect	**Gender**	**Age (year)**	**Height (m)**	**Weight (kg)**		
217	Left	Male	64	1.78	93.4	153	Axial
218	Right	Male	63	1.74	76.2	164	Axial
218	Left	Male	63	1.74	76.2	174	Axial
357	Left	Male	75	1.65	77	156	Bending
363	Right	Male	60	1.72	75	148	Axial
363	Left	Male	60	1.72	75	163	Axial
364	Right	Female	63	1.72	117.9	152	Axial
367	Left	Male	57	1.79	59	182	Bending
400	Right	Male	53	1.82	145	157	Axial
400	Left	Male	53	1.82	145	150	Axial
405	Right	Male	70	1.81	87	165	Bending
405	Left	Male	70	1.81	87	157	Bending
411	Left	Male	76	1.78	70	186	Bending
411	Right	Male	76	1.78	70	180	Bending
453	Right	Male	58	1.8	192.8	155	Bending
453	Left	Male	58	1.8	192.8	156	Bending
454	Right	Male	55	1.72	63.5	154	Axial
454	Left	Male	55	1.72	63.5	154	Axial
456	Right	Male	47	1.62	72.6	154	Bending
456	Left	Male	47	1.62	72.6	152	Bending

Similarly, four uni-axial strain gages were adhered around the perimeter of the clavicle cross-section at the location of maximum posterior concavity of the clavicle. One gage was positioned on each of the four anatomical aspects of the bone—anterior, superior, posterior, inferior—with the sensitive axis of the gage aligned with the longitudinal axis of the bone (Figure 3.a). Medium-resolution (~0.25 mm in-plane resolution, 0.625 mm slice thickness) CT scans was then taken of each specimen after the preparation process was completed.

Test Fixture, Instrumentation, Test Procedure. A total of 20 tests were performed on the 20 clavicle specimens. Half of the specimens were failed in axial compression and the other half of the specimens were failed in 3-point bending.

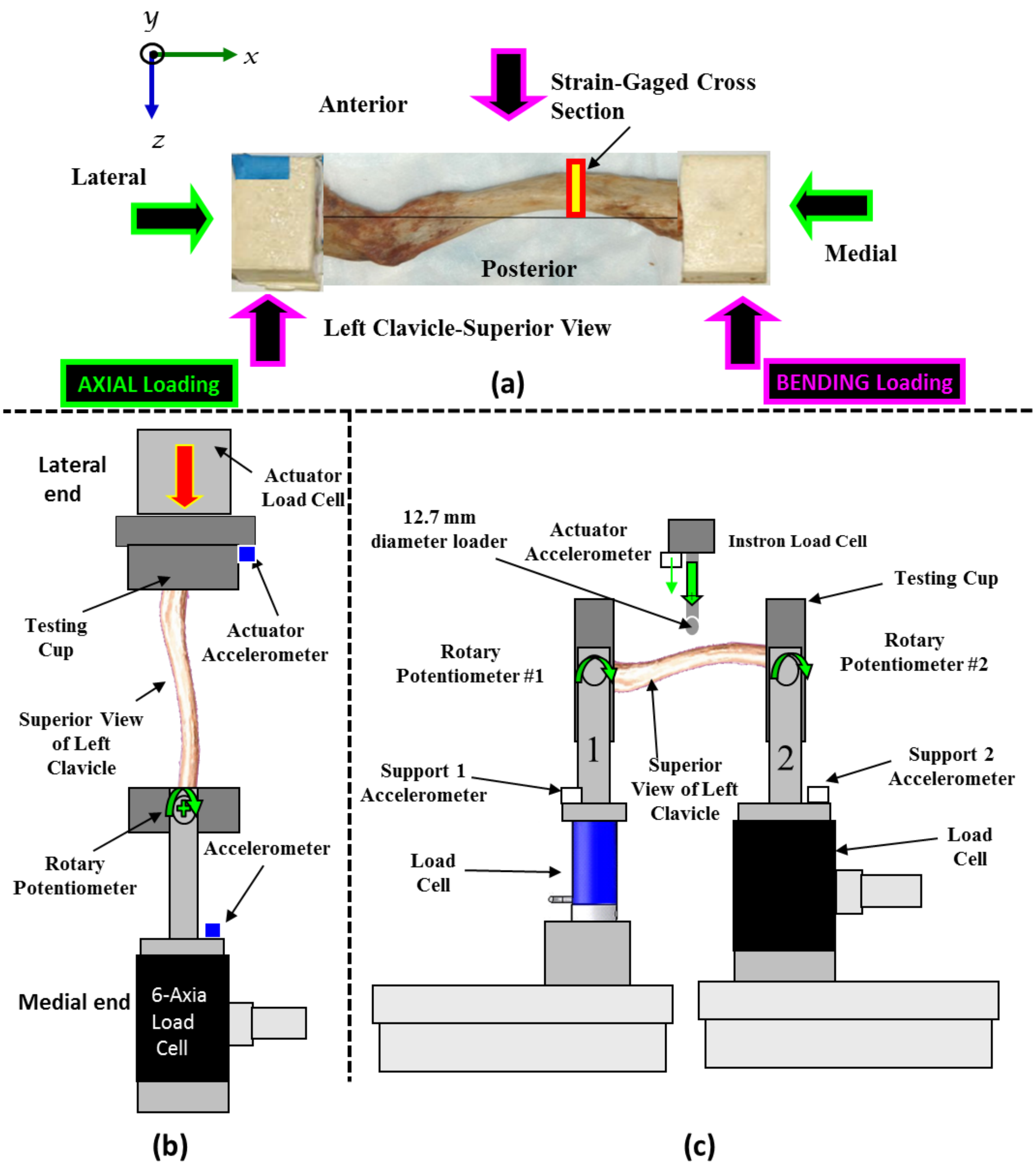

Figure 3: (a) Clavicle Potting method in component level test and its loading schematics under axial and three point bending condition (b) Axial test fixture schematic (c) Bending test fixture schematic

The axial test fixture provided a pinned boundary condition at the medial end of the specimen and a fixed (cantilever) boundary condition at the lateral end (Figure 3b). The medial end was attached to a metal cup which was permitted to rotate about the superior-inferior axis only. The lateral end was clamped to the piston of a servo-hydraulic testing machine to prevent rotation. A 6-axis load cell and a rotational potentiometer were located on the medial end assembly to measure reaction force and rotation of the end. A uni-axial load cell was installed between the actuator and lateral potting block. The actuator was displaced at 100 mm/sec to a maximum displacement of 30 mm to ensure gross failure of the specimen and to achieve similar clavicle loading rate as in the side impact sled.

For the bending tests, each end of the clavicle was supported by a similar pinned assembly which permitted rotation about the superior-inferior axis (Figure 3c). No other rotation or translation of the ends was permitted; note that this boundary condition allows for three-point bending where the compressive/tensile forces are not release. A 12.7mm-diameter cylindrical section of aluminum loaded the clavicle midway along its length to failure; this loader was attached to the Instron piston. 6-axis load cells measured the reaction force at each end, and rotational potentiometers measured the rotation of each end. The loader was displaced at 100 mm/sec up to at least 60 mm to ensure gross failure of the specimen and to achieve similar clavicle loading rate as in the frontal impact sled.

Data Analysis. For the axial loading tests, only the force in the direction of loading was considered. For the bending tests, the applied bending moment was calculated by averaging the products of proximal and distal moment arms with the vertical shear forces from loadcell1 and loadcell2 (Figure 3), assuming the contribution from the force in horizontal direction is insignificant , considering that the moment arm for the horizontal force is very small. An effective stiffness K was calculated as the slope of the linear curve fitted in the displacement and force response between the onset of loading and the time of fracture. In order to verify the loading condition of the component test, the strain rate and neutral axis orientation was calculated for each test from the 4 strain gage data with the same method and clavicle coordinate system definition as the sled test (Figure 1, 2).

To develop force-strain based response corridors, the peak strain along the strain gauge cross-section will be calculated, as the peak strain gives more useful information to verify the injury prediction capability of a FE model. To calculate peak strain, the point that is farthest from the neutral axis line was identified and the peak longitudinal strain on the strain gauge cross section can be calculated (Untaroiu, 2007). It should be noted that the peak strain location in the strain gauge cross-section varies with increasing displacement of the loader.

Data Scaling and Corridor Development. To minimize the variations in subject response due to individual geometry and material properties, the mechanical response data (force, deflection, strain) were first scaled to the response of a standard subject. Assuming the specimens are geometrically similar, the mechanical responses were scaled to a reference size subject responses using a scale factor $\lambda_L = \frac{L_{ref}}{L}$ based on the length of clavicle specimen ($L_{ref}$is the clavicle length of a standard 50th male measured from the GHBMC model $L_{ref} = 150$mm). The scaling factor for strain is 1 because strain is dimensionless metric.

$$F_{scaled} = {\lambda_L}^2 F_{measured}$$

$$Disp_{scaled} = \lambda_L Disp_{measured}$$

$$Strain_{scaled} = Strain_{measured}$$

With these scaled response data, both elliptical-based (Ash, 2012) and rectangular-based (Lessley, 2004) corridor development method were used in this study to build the corridors. In this study, force-deflection and force-peak strain corridors were developed for both the axial compression and three-point bending tests.

RESULTS

Reliable data for reaction force, reaction moments, rotations, applied displacement, and strain were obtained for all 20 tests, and summarized in Table 2, 3.

In the clavicle component tests, the axial compression tests have strain rate on the order of 5%/s to 15%/s, and neutral axis orientation of 72.6±8.3 degrees, the three point bending tests have strain rate on the order of 10%/s to 15%/s, and neutral axis orientation of 78.7±4.3 degrees. These results agree well with the sled test conditions (Table 2).

Table 2: Neutral Axis Orientation Comparison between Component tests and Sled Test (N/A indicate the specimen was not successfully fractured in the experiment)

	Specimen No.	**Test Type**	**Neutral Axis Angle(degrees)**	**Specimen No.**	**Test Type**	**Neutral Axis Angle(degrees)**
Clavicle Component Test	217L	Axial	85.6	357L	Bending	74.4
	218L	Axial	72.4	367L	Bending	N/A
	218R	Axial	75.3	405L	Bending	78.9
	363L	Axial	57.3	405R	Bending	73.6
	363R	Axial	N/A	411L	Bending	76.6
	364R	Axial	N/A	411R	Bending	78.4
	400L	Axial	72.4	453L	Bending	86.5
	400R	Axial	70.6	453R	Bending	82.8
	454L	Axial	N/A	456L	Bending	78.4
	454R	Axial	74.5	456R	Bending	N/A
	Aver		72.6	Aver		78.7
	STD		8.3	STD		4.3
Sled Test	CAD473	Side Impact	76	CAD422	Frontal Impact	71.4

The average stiffness was 440±164 N/mm for the axial loading tests, and 199±38 N/mm for the three point bending tests. The fracture force of the axial loading tests was 2966±800N, while the fracture force of three point bending tests was 1053±231 N (Table 3).

Table 3: Summary for component clavicle failure tests (N/A indicate the specimen was not successfully fractured in the experiment)

Axial Compression Loading				**Three Point Bending**			
Clavicle	***Stiffness*** (N/mm)	D_{frac} (mm)	F_{frac} (N)	**Clavicle**	***Stiffness*** (N/mm)	D_{frac} (mm)	F_{frac} (N)
217L	852.7	4.28	3138	357L	159.1	5.25	701
218L	500.5	5.09	2368	367L	168.3	4.9613	691
218R	641.9	5.234	2295	405L	218.6	5.836	1085
363L	444.5	6.56	2183	405R	197.2	6.804	1144
363R	449.3	5.924	2468	411L	161.8	7.9	1062
364R	384.7	13	4391	411R	172.8	6.89	917
400L	240	N/A	N/A	453L	240.6	7.005	1346
400R	396.8	10.82	4104	453R	275.8	4.233	1043
454L	502.9	7.34	3238	456L	208.9	7.783	1361
454R	436.7	11	2781	456R	185	7.275	1180
AVERAGE	485.0	7.7	2966	AVERAGE	198.8	6.39	1053
STDEV	164.5	3.3	800	STDEV	37.9	1.25	231

The structural level and material level corridors for the axial and three point bending tests were presented in Figure 4, 5, 6, 7. The red curve is the corridor by ellipse-based method, while the green curve is by rectangular-based method.

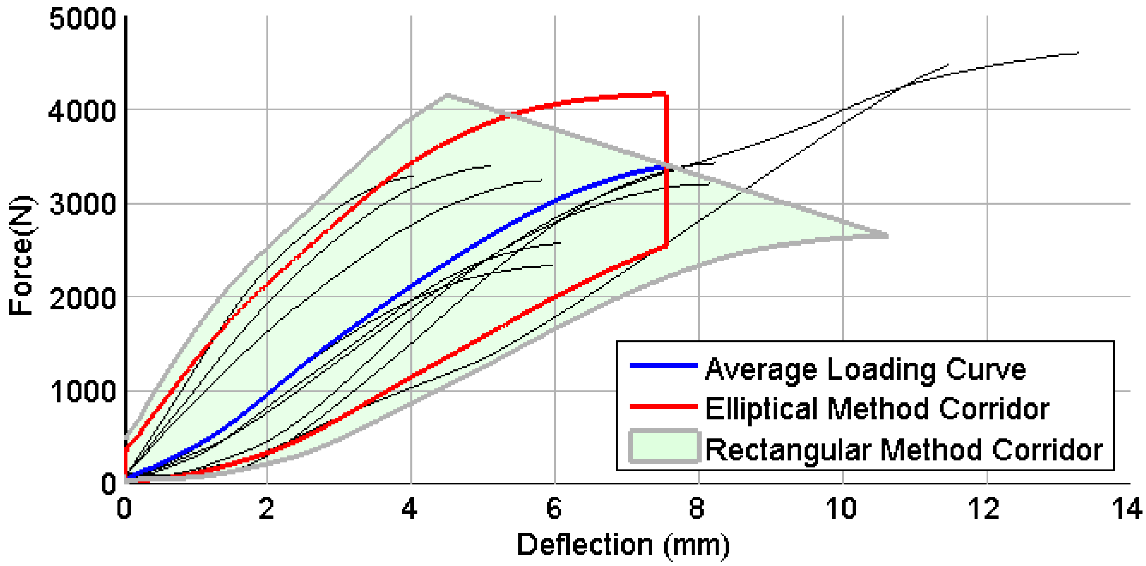

Figure 4: Clavicle force vs deflection response corridor for axial compression test.

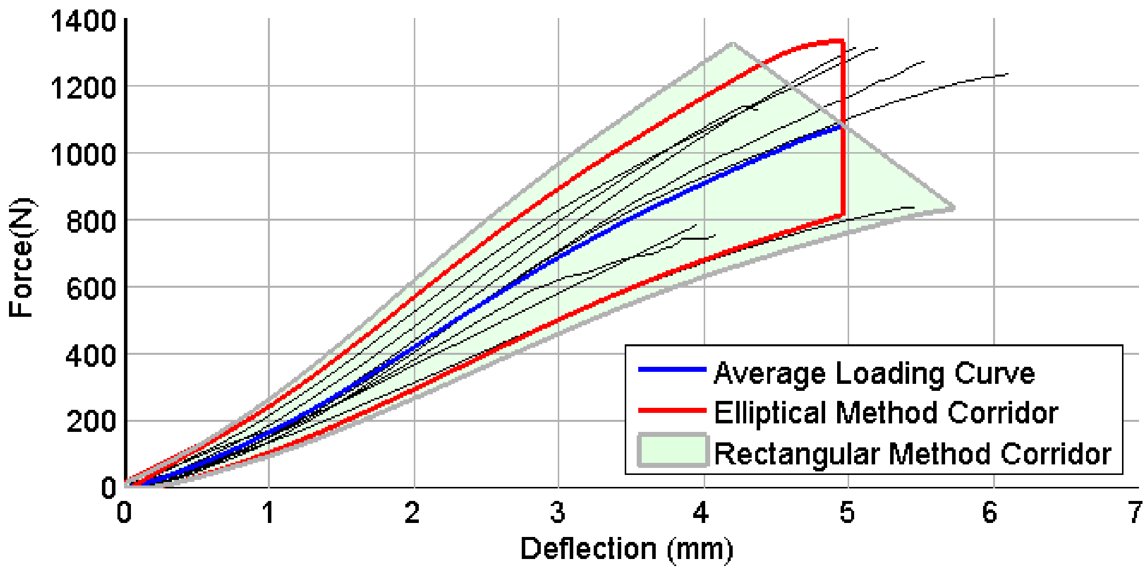

Figure 5: Clavicle moment vs deflection response corridor for three point bending test.

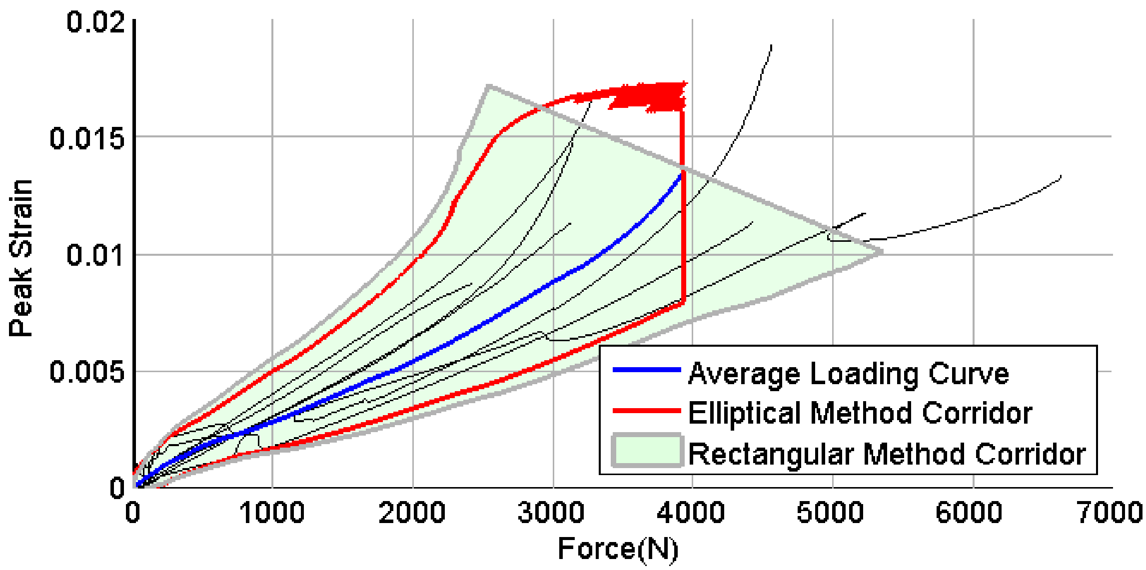

Figure 2: Clavicle peak strain vs force response corridor for axial compression test

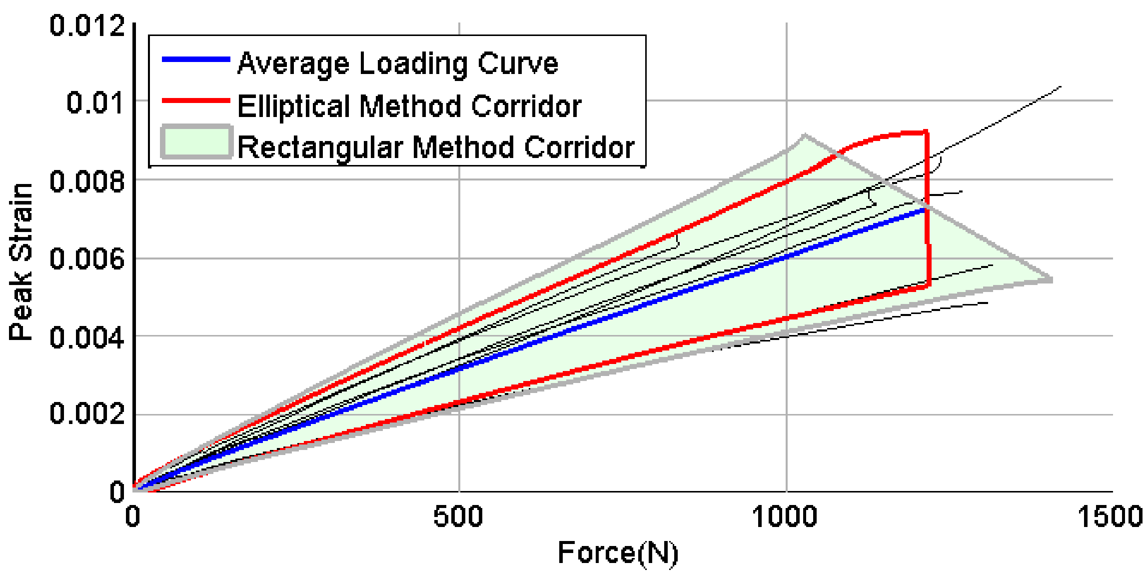

Figure 3: Clavicle peak strain vs force response corridor for three point bending test

DISCUSSION

While the biomechanical response of the clavicle has been characterized separately under axial compression (Dalmases, 2008, Duprey, 2008) and three point bending (Kemper, 2009, Bolte, 2000), none of this studies have justified their choice of loading conditions. In the current study, by carefully designing to replicate the clavicle loading condition that experienced in a typical side or frontal impact, the clavicle component level tests give us a higher confidence on its validity.

The average stiffness for axial loading tests (439.5±164N/mm) was lower than that in the Dalmase`s study (786±258N/mm). The average bending stiffness for three point bending test (199±38 N/mm) was higher than the stiffness measured in Kemper`s study (127±43N/mm). This may be due to the age of the PMHS used in this study (61 ± 8.7years old) is lower than Kemper`s study (72.7 ± 15 years old).

The fracture force (2966+800N) in the axial compression tests is much higher than the results from Dalmases et al. (2008) and Duprey et. al (2008). However, the loading rate in Dalmases`s study is significantly lower than this study (0.63 mm/s vs 100 mm/s). And Duprey et. al.(2008) , use specimens which are much older than this study (Duprey used subjects aged 78±12 years), and a pronounced different boundary condition. The Duprey`s study used a ball-and socket joint on the two clavicle ends, allowing for rotation about all three axes rather than the single axis used in the present study. The fracture force (1053±231 N) in the three point bending test is higher than the fracture force in Kemper`s three point bending tests (644±216 N), which again maybe because of the age difference.

Although response corridors for FE model validation have been established for several other parts of the human body, such as the thorax (Lobdell, 1973), the lower extremity (Kerrigan, 2003; Ivarsson, 2005), all of these corridors are structural response corridors (force vs. deflection). The material-level (eg. strain) corridors developed in the current study can provide higher confidence when validating a FE model, and therefore give a higher ability to predict injury.

CONCLUSIONS

20 clavicle dynamic axial compression and three-point bending failure tests with representative loading condition of side and frontal impact sled test were performed. The mechanical response data (eg. force, displacement) were reported in the study. In addition, force vs. deflection and force vs. peak strain corridors were developed for these two loading configurations. The results of this study are useful for clavicle FE model loading response validation. In addition, the force vs. peak strain corridor development method could also be extended to develop corridors for other components of the human body.

REFERENCES

BOLTE, J.H., HINES, M.H., McFADDEN, J.D., SAUL, R.A. (2000). Shoulder Response Characteristics and Injury Due to Lateral Glenohumeral Joint Impacts. Proc. 44th Stapp Car Crash Conference, Paper No. 00S-11, 261-280.

ASH.JH, LESSLEY.DJ, FORMAN. JL, ZHANG.Q, SHAW.CG, CRANDALL. JR(2012). Whole-Body Kinematics: Response Corridors for Restrained PMHS in Frontal Impacts. International Conference on the Biomechanics of Impact .

BOLTE, J., HINES, M., MCFADDEN, J., & SAUL, R. (2000). Shoulder response characteristics and injury due to lateral glenohumeral joint impacts. Stapp Car Crash Journal, 44, 261–280.

DUPREY S, BRUYERE K, VERIEST JP. (2008) Influence of Geometrical Personalization on the Simulation of Clavicle Fractures. Journal of Biomechanics Vol.41

DUPREY S, BRUYERE K, VERRIEST, JP(2010) Clavicle Fracture Prediction: Simulation of Shoulder Lateral Impacts With Geometrically Personalized Finite Elements Models. The Journal of Trauma, Injury, Infection, and critical Care. Volume 68(1).

FRAMPTON, R.J., MORRIS, A.P., THOMAS, P.,BODIWALA, G.G. (1997). An overview of upper extremity injuries to car occupants in UK vehicles crashes. Proc IRCOBI Conference, 37--52.

B. Johan Ivarsson, Jason R. Kerrigan, David J. Lessley, D. Chris Drinkwater, Check Y. Kam, Drew B. Murphy, Jeff R. Crandall, and Richard W. Kent(2005) Dynamic Response Corridors of the Human Thigh and Leg in Non-Midpoint Three-Point Bending. Paper 2005-01-0305, Society of Automotive Engineers.

KEMPER A, STITZEL J, GABLER C, DUMA S. (2009) Biomechanical Response of the Human Clavicle: The Effects of Loading Direction on Bending Properties. Journal of Applied Biomechanics, 2009, 25, 165-174

KERRIGAN, J, BHALLA, J, MADELEY, N, CRANDALL, J, DENG, B. (2003) Response Corridors for the Human Leg in 3-Point Lateral Bending. The 7th US National Congress on Computational Mechanics.

LESSLEY D, CRANDALL J, SHAW G, KENT R, FUNK J (2004) Normalization Technique for Developing Corridors from Individual Subject Responses. Paper 2004-01-0288, Society of Automotive Engineers.

LESSLEY, DJ, SHAW, CG, PARENT, DP, ARREGUI-DALMASES, C, KINDIG, M, RILEY, P, PURTSEZOV, S, SOCHOR, M, GOCHENOUR, T, BOLTON, JR, SUBIT, D, CRANDALL, JR, TAKAYAMA, S, ONO, K, KAMIJI, K, YASUKI, T. (2010) Whole-body response to pure lateral impact. Stapp Car Crash Journal, 53.

ZUOPING LI, MATTHEW W. KINDIG, JASON R. KERRIGAN, RICHARD W. KENT & JEFF R. CRANDALL (2012): Development and validation of a subject-specific finite element model of a human clavicle, Computer Methods in Biomechanics and Biomedical Engineering, DOI:10.1080/10255842.2011.641122

LÓPEZ-VALDÉS, FJ, LAU, AG, LAMP, J, RILEY, PO, LESSLEY, DJ, DAMON, AM, KINDIG, MW, KENT, RW, BALASUBRAMANIAN, S, SEACRIST, T, MALTESE, MR, ARBOGAST, KB, HIGUCHI, K, TANJI, H. (2010) Analysis of Spinal Motion and Loads During Frontal Impacts. Comparison between PMHS and ATD. Annals of Advances in Automotive Medicine (AAAM), 54.

LOBDELL, T.E., KROELL, C.K. SCHNEIDER, D.C. AND HERING, W.E. (1973) Impact Response of the Human Thorax. in Human Impact Response: Measurement and Simulation; Proceedings, William F. King and Harold J. Mertz (eds.), pp. 201-245. Plenum Press, New York, NY.

MELVIN, J., BARON, K., LITTLE, W., GIDEON, T.W.,PIERCE, J. (1998). Biomechanical analysis of Indy race car crashes. Proceeding 42nd STAPP Car Crash Conference, p337.d

UNTAROIU DC, KERRIGAN.JR, CRANDALL.JR(2006) Material Identification using Successive Response Surface Methodology, with Application to a Human Femur subjected to Three-Point Bending Loading. Paper 2006-01-0063, Society of Automotive Engineers.

UNTAROIU DC, KERRIGAN JR, KAM, C, CRANDALL JR, YAMAZAKI, K, FUKUYAMA, K, KAMIJI, K, YASUKI, TSUYOSHI(2007) Correlation of Strain and Loads Measured in the Long Bones with Observed Kinematics of the Lower Limb during Vehicle-Pedestrian Impacts. Stapp Car Crash Journal, Vol. 51 (October 2007)