Human Thoracic Response to Impact: Chestband Effects, the Strain-Deflection Relationship, and Small Females in Side Impact Crashes

DISSENTATION

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By

Benjamin Kelly Shurtz

Graduate Program in Mechanical Engineering

The Ohio State University

2017

Dissertation Committee:

Professor John H. Bolte, IV, Advisor

Professor Amanda M. Agnew

Professor Laura C. Boucher

Professor Rebecca B. Dupaix

Professor Yun-Seok Kang
Abstract

Motor vehicle crashes claim thousands of lives each year in the US, and injure millions more. The thorax is the region of the body at greatest risk for serious injury, and thus is of interest for increased protection. In order to improve systems providing occupant protection, a better understanding of the thorax is required, particularly for vulnerable occupants. The work of this dissertation is focused on increasing understanding of the thorax, and does so by examining instrumentation commonly used on the thorax, by introducing a novel analysis technique for understanding thoracic characteristics, and finally by presenting response and injury data for side impact loading.

The first study presented here provides an answer to the question, “Do chestbands alter thoracic response to impact?” This was accomplished by conducting a series of repeated impacts on two post-mortem human surrogates (PMHS), at the same impact velocity with 0, 1, and 2 chestbands. This was done for various impact speeds for a total of 22 impacts on the two subjects. ‘Response’ was divided into global response, defined as chest deflection and thoracic stiffness, and local response, defined as the individual rib strain. Results showed no significant difference in global or local response, thus providing support for the commonly held assumption that chestbands do not alter thoracic response to impact.
The second study introduces an analysis method, looking at rib strain as a function of chest deflection. An understanding of this relationship is intended to help bridge the gap between existing deflection-based injury criteria and strain-based injury prediction in finite element human body models. To this end, the strain-deflection (S-D) relationship was explored by rib level, fitting five different models to the data and constructing response corridors. It was additionally observed that the S-D relationship, or curve trajectory, tends to remain consistent across impacts on the same subject, even when those impacts are conducted at different velocities.

The final study of this work begins an examination of thoracic response and injuries occurring in small, fragile, elderly females involved in side impact vehicle crashes. The testing methodology is described, which includes a door intrusion and lateral underbody motion applied to a subject who is placed on a mass-production driver seat equipped with a side airbag, belted (with pretensioner), and interacts with a mass-production door liner. Rib fractures were the most common injury observed, with the first fractures occurring anteriorly on the struck side, followed by fractures anteriorly on the non-struck side and fractures posteriorly on the struck side. Spinal acceleration values, chest deflections, airbag pressures, and seatbelt tensions are reported. While this study does provide a valuable understanding of the injuries in the employed impact mode, it is intended that future tests similar to these may be conducted and that the combined dataset may be used to produce response corridors and a thoracic injury criterion specific to small, fragile females.
To a few of the many dear ones who love, support, and inspire me -

Kyla, Kelly, Chris, Joe, Boyd, and my kids
Acknowledgments

Thank you to Dr. Bolte for the consistent mentorship you have provided, for the many hours you have spent helping me along the journey. Thank you also to staff and students of the Injury Biomechanics Research Center who have contributed so much to the execution of my research studies, particularly Dr. Agnew, Dr. Kang, Michelle Murach, and David Stark. Finally, thank you to my wonderful wife, Kyla. You have motivated me and done a tremendous job of nurturing our family over the past years.
Vita

May 2005 .......................................................Orem High School

August 2013 ...................................................B.S./M.S Mechanical Engineering, Utah State University

2013-2014 ......................................................University Fellow, The Ohio State University

2014-2017 .....................................................National Science Foundation Graduate Research Fellow, The Ohio State University

Publications


Fields of Study

Major Field: Mechanical Engineering
# Table of Contents

Abstract ............................................................................................................................... ii

Acknowledgments............................................................................................................... v

Vita..................................................................................................................................... vi

Publications........................................................................................................................ vi

Fields of Study ................................................................................................................... vi

Table of Contents .............................................................................................................. vii

List of Tables ................................................................................................................... xiii

List of Figures ................................................................................................................... xv

Chapter 1: Introduction ....................................................................................................... 1

Abstract ........................................................................................................................... 1

Motivation ....................................................................................................................... 1

Side Impact Testing......................................................................................................... 2

Injury Criteria and Injury Assessment Reference Values .............................................. 5

Elderly, Fragile Females ............................................................................................... 8

Chestband Use............................................................................................................... 10
Chapter 3: Strain-Deflection (S-D) Relationship in the Human Thorax for Fixed-back Frontal Impacts

Abstract ......................................................................................................................... 37

Introduction ................................................................................................................... 38

Materials and Methods .................................................................................................. 39

Subject Selection ....................................................................................................... 40

Test Setup .................................................................................................................. 41

Instrumentation .......................................................................................................... 42

Test matrix ................................................................................................................. 43

Data Collection and Analysis .................................................................................... 44

Results ........................................................................................................................... 48

S-D Curve Shape ....................................................................................................... 48

Response Characterization ........................................................................................ 51

Discussion ..................................................................................................................... 56

S-D Curve Shape ....................................................................................................... 56

Comparison to Existing Data ..................................................................................... 58

Response Characterization ........................................................................................ 59

Strain as a Function of Deflection ............................................................................. 60

Limitations ................................................................................................................. 62
Chapter 4: Thoracic Response of Small, Osteopenic, Elderly Females in Side Impact Vehicular Crashes

Abstract

Introduction

Materials and Methods

Epidemiology Study

Subject Selection

Test Setup

Instrumentation

Data Collection and Analysis

Results

Test Input

Injuries

Occupant Acceleration

Chest Deflection

Seatbelt Force

Discussion
Acknowledgements ....................................................................................................... 90

Chapter 5: Summary and Conclusions.............................................................................. 91

Study 1: Chestband Effects ........................................................................................... 91

Study 2: The Strain-Deflection (S-D) Relationship in the Thorax ............................... 92

Study 3: Side Impact Response of Small Females........................................................ 93

References ......................................................................................................................... 96

Appendix A: Supplement to Chapter 2 ........................................................................... 105

Data Tables.................................................................................................................. 105

Selected Matlab Codes for Data Processing and Plotting ........................................... 107

Arranging the data ................................................................................................... 107

Data Processing ....................................................................................................... 107

Plotting..................................................................................................................... 115

Appendix B: Supplement to Chapter 3 ........................................................................... 123

Model Fits ................................................................................................................... 123

Model Parameter Tables.......................................................................................... 123

Plots ......................................................................................................................... 125

Selected Matlab Codes for Data Processing ............................................................... 127

Data Processing ....................................................................................................... 127

Plotting..................................................................................................................... 140
List of Tables

Table 1. Subject information........................................................................................................ 17
Table 2. Subject Information ..................................................................................................... 41
Table 3. Parameter values for models fit to the S-D response, by rib level. Shaded boxes indicate that they are the highest $r^2$ value for that rib level. ............................................. 53
Table 4. Subject information..................................................................................................... 69
Table 5. Summary of Vicon marker locations ........................................................................... 77
Table 6. Documented injuries in the two side impact tests.......................................................... 83
Table 7. Table of maximum acceleration values ........................................................................ 84
Table 8. Seatbelt tension values from both tests....................................................................... 87
Table 9. Global response summary............................................................................................ 105
Table 10. Local response summary .......................................................................................... 106
Table 11. Parameter values for the piecewise linear model (PL) by rib level......................... 123
Table 12. Parameter values for the exponential model for rib loading only (E1) by rib level................................................................................................................................. 124
Table 13. Parameter values for the exponential model for all thoracic loading (E2) by rib level................................................................................................................................. 124
Table 14. Parameter values for the power model (Po) by rib level ......................................... 124
Table 15. Strain gage locations on the ribs for test 1...................................................... 148
Table 16. Strain gage locations on the ribs for test 2...................................................... 149
Table 17. Orentation of each 6DX Pro motion block, relative to the subject................. 150
Table 18. Details of instruments used on PMHS 1............................................................ 150
Table 19. Details of instruments used on PMHS 2............................................................ 151
Table 20. Details of instruments used on the test setup.................................................. 151
Table 21. Naming scheme for strain gages on PMHS 1, as presented in Figure 98 and Figure 99 ......................................................................................................................... 180
Table 22. Naming scheme for strain gages on PMHS 2, as presented in Figure 100 and Figure 101 ....................................................................................................................... 191
List of Figures

Figure 1. Test setup including a 23 kg impactor ram, 90° back fixture, and PMHS with arms and forearms flexed at 90° (left). Position of the 2 chestbands on the PMHS (right).
.......................................................................................................................................................... 18

Figure 2: Instrumentation placed on each PMHS thorax prior to impact testing ............... 19

Figure 3: Flow of testing for the two test subjects. Each box represents an impact. Each * indicates a baseline impact within the test flow to verify that the system had not changed.
.......................................................................................................................................................... 20

Figure 4: Comparative analyses.................................................................................................... 22

Figure 5: Fractures in right ribs 3 and 4 from subject 1 and right rib 8 fracture from subject 2 (left). Each fracture is shown across the top, and each associated strain gage plot is shown across the bottom (right). ......................................................................................... 26

Figure 6. Chest deflection plots for impacts conducted on PMHS 1 at impact speeds of 0.8 m/s (left) and 1.5 m/s (right) ........................................................................................................... 26

Figure 7. Peak normalized deflection values for impacts on PMHS 1 at 0.8 m/s (top left), on PMHS 1 at 1.0 m/s (top right), on PMHS 2 at 1.0 m/s (bottom left), and PMHS 1 at 1.5 m/s (bottom right). Values shown for the baseline cases are the average of the first
four baseline impacts. The color of each difference bracket corresponds to the color of
the bar in Figure 8.

Figure 8: Effects of chestbands on thoracic deflection. Peak normalized deflection for
impacts on PMHS 1 at 0.8 m/s (left). Differences between peak deflections for impacts at
the same speed, comparing 0 chestbands with 1 chestband ($d_1-d_0$), 0 chestbands with 2
chestbands ($d_2-d_0$), and 1 chestband with 2 chestbands ($d_2-d_1$) (right). Error bars indicate
the 95% confidence interval.

Figure 9. Force-deflection plots for impacts conducted on PMHS 1 at impact speeds of
0.8 m/s (left) and 1.5 m/s (right).

Figure 10. Thoracic stiffness values for impacts on PMHS 1 at 0.8 m/s (top left), on
PMHS 1 at 1.0 m/s (top right), on PMHS 2 at 1.0 m/s (bottom left), and PMHS 1 at 1.5
m/s (bottom right). Values shown for the baseline cases are the average of the first four
baseline impacts. The color of each difference bracket corresponds to the color of the bar
in Figure 11.

Figure 11: Effects of chestbands on thoracic stiffness. Stiffness values for impacts on
PMHS 1 at 0.8 m/s (left). Differences between thoracic stiffness for impacts at the same
speed, comparing 0 chestbands with 1 chestband ($k_1-k_0$), 0 chestbands with 2 chestbands
($k_2-k_0$), and 1 chestband with 2 chestbands ($k_2-k_1$) (right). Error bars indicate the 95%
confidence interval.

Figure 12: Peak strain values in the right 3rd rib during impacts with zero chestbands and
one chestband (left). Average change in peak strain for ribs in contact with a chestband
(right). Ribs level 3-4 are shown on the left, comparing impacts with one chestband vs.
zero chestbands. Ribs level 6-7 are shown on the right, comparing impacts with two chestbands vs. one chestband. Error bars represent a 95% confidence interval for the average strain difference. .................................................................................................. 32

Figure 13: Test setup including a 23 kg impactor ram, 90° back fixture, and PMHS with arms and forearms flexed at 90° (left). The test setup with added ram stoppers (right). The red box identifies the stoppers. .................................................................................................. 42

Figure 14: Instrumentation placed on each PMHS thorax prior to impact testing ........ 43

Figure 15: Flow of testing for each PMHS, beginning at low impact velocity and gradually increasing ......................................................................................................................... 44

Figure 16: Representative S-D curves from the L3 rib on PMHS 1. S-D curve for 1m/s and 1.5m/s impact speeds (left) and for all impacts on PMHS 1 (right). ......................... 49

Figure 17: Variation in S-D curve shape. Complete S-D curves from L3 for PMHS 1 and PMHS 2 (left). S-D curves for L3 during thoracic loading only, for PMHS 1 and PMHS 2 (right). ........................................................................................................................................ 49

Figure 18: S-D curves for PMHS 1 during thoracic loading for all impacts on all rib levels (left). S-D curves for R4 during thoracic loading for all impacts on all subjects (right). ............................................................................................................................... 50

Figure 19: Complete S-D curve (left). S-D curve for thoracic loading only (center). S-D curve for 5% deflection to peak deflection during loading (right). ........................................... 51

Figure 20: S-D curve for L3 during one impact on PMHS 1, accompanied by fitted models (left). S-D curve for L3 during one impact on PMHS 2, accompanied by fitted models (right)................................................................................................................... 52
Figure 21: S-D curves for 3\textsuperscript{rd} level ribs during all impacts on all subjects, accompanied by fitted models (left). S-D curves for 5\textsuperscript{th} level ribs during all impacts on all subjects, accompanied by fitted models (right). ................................................................. 52

Figure 22: PMHS S-D curves for 3\textsuperscript{rd} level ribs (left). S-D response corridor for 3\textsuperscript{rd} level ribs (center). PMHS S-D curves and response corridor for 3\textsuperscript{rd} level ribs (right).............. 54

Figure 23: PMHS S-D curves for 4\textsuperscript{th} level ribs (left). S-D response corridor for 4\textsuperscript{th} level ribs (center). PMHS S-D curves and response corridor for 4\textsuperscript{th} level ribs (right)............. 54

Figure 24: PMHS S-D curves for 5\textsuperscript{th} level ribs (left). S-D response corridor for 5\textsuperscript{th} level ribs (center). PMHS S-D curves and response corridor for 5\textsuperscript{th} level ribs (right)............... 54

Figure 25: PMHS S-D curves for 6\textsuperscript{th} level ribs (left). S-D response corridor for 6\textsuperscript{th} level ribs (center). PMHS S-D curves and response corridor for 6\textsuperscript{th} level ribs (right)............. 55

Figure 26: PMHS S-D curves for 7\textsuperscript{th} level ribs (left). S-D response corridor for 7\textsuperscript{th} level ribs (center). PMHS S-D curves and response corridor for 7\textsuperscript{th} level ribs (right)............ 55

Figure 27: PMHS S-D curves for 8\textsuperscript{th} level ribs (left). S-D response corridor for 8\textsuperscript{th} level ribs (center). PMHS S-D curves and response corridor for 8\textsuperscript{th} level ribs (right).............. 55

Figure 28: Example of a 4-part thoracic loading S-D curve shape (left). Example of a 2-part thoracic loading S-D shape (right)................................................................................ 57

Figure 29: Free-body diagram of the external forces acting on the thorax and how those forces affect the lateral aspect of the rib. ................................................................. 57

Figure 30: Comparison of data from previous studies to data from this study for 4\textsuperscript{th} level ribs (left) and 5\textsuperscript{th} level ribs (right). ................................................................. 59
Figure 31: Comparison of F-D curves (left) and S-D curves (right) for three impacts on PMHS 1.......................................................... 61

Figure 32. Risk of AIS 3+ injury to vehicle occupants engaged in near-side impact, grouped by male (left) and female (right) from Ramachandra et al. (2017) ....................... 67

Figure 33. HYGE sled track which simulated the motion of the impacted vehicle (left), and ASIS which produced a door intrusion (right)................................................................. 70

Figure 34. Pre-test positioning of the occupant ................................................. 71

Figure 35. Schematic of subject instrumentation............................................. 73

Figure 36. Strain gages installed on the subject’s ribs. The gage on the right has been secured but not yet sealed. The gage on the left has been secured and sealed. .............. 74

Figure 37. 6DX Pro motion block containing 3 accelerometers and 3 angular rate sensors (left). 6DX Pro mounted to the T1 vertebra, posterior view (right). .......................... 75

Figure 38. 59-channel Humanetics chestband (top). Contour reconstruction prior to impact (left). Contour reconstruction at peak lateral deflection (right) ....................... 76

Figure 39. 6aω tetrahedron, placed on the occupant head.................................. 77

Figure 40. The four high speed camera views employed in this study: frontal onboard (top left), frontal offboard (top right), overhead (bottom left), and oblique offboard (bottom right).......................................................... 79

Figure 41. Velocity of the sled for test 1 and test 2 (left) and relative intrusion velocity of the door with respect to the occupant (right)......................................................... 80

Figure 42. Airbag pressure readings for two ports on test 1 and test 2....................... 81
Figure 43. Strain measured during test 2 on the left 7th rib (left) and the left 3rd rib (right). Fracture timing was identified from these as the sudden, sharp change in strain............ 82

Figure 44. Acceleration vs. time during impact for the manubrium and T4 vertebra in the lateral direction (top) and A/P direction (bottom) in test 1 (left) and test 2 (right) ........ 85

Figure 45. Percent lateral chest deflection for the axillary and xiphoid level chestbands on both tests, accompanied by approximate A/P deflection from the manubrium to the T4 vertebra ............................................................................................................................. 86

Figure 46. S-D curves from rib levels 3-8 for all impacts on all PMHS, plotted by rib level, and shown with four models fit to the data................................................................. 126

Figure 47. Schematic of subject instrumentation for test 1 ............................................. 148

Figure 48. Schematic of subject instrumentation for test 2 ............................................. 149

Figure 49. Vicon marker locations on the subject and the test structure ..................... 152

Figure 50. Overview of left side rib fractures................................................................. 153

Figure 51. Left second rib ............................................................................................ 154

Figure 52. Left third rib ............................................................................................... 154

Figure 53. Left fourth rib ............................................................................................ 155

Figure 54. Left ribs 2-4, pleural surface ....................................................................... 155

Figure 55. Left sixth rib ............................................................................................... 156

Figure 56. Overview of right side showing location of R4 injury ................................. 156

Figure 57. Right fourth rib cutaneous ......................................................................... 157

Figure 58. Right fourth rib pleural ................................................................................ 157

Figure 59. Sternum........................................................................................................ 158
Figure 60. Left radius ................................................................. 158
Figure 61. Left ulna ................................................................. 158
Figure 62. Overview of left side posterior rib fractures ......... 159
Figure 63. Left fourth rib posterior cutaneous ...................... 159
Figure 64. Left fifth rib posterior cutaneous ......................... 160
Figure 65. Left sixth rib posterior cutaneous ......................... 160
Figure 66. Left seventh rib posterior cutaneous ................. 161
Figure 67. Left eighth rib posterior cutaneous ...................... 161
Figure 68. Overview of left side anterior rib fractures ....... 162
Figure 69. Left third rib anterior cutaneous, two fractures ... 162
Figure 70. Left fourth rib anterior cutaneous ....................... 163
Figure 71. Left fifth rib anterior cutaneous ......................... 163
Figure 72. Left sixth rib anterior cutaneous ......................... 164
Figure 73. Left seventh rib anterior cutaneous ................. 164
Figure 74. Left ribs 3-5, fractures on 3-5 anterior and 4-5 posterior ............ 165
Figure 75. Left sixth rib pleural, anterior and posterior fractures .................. 165
Figure 76. Left ribs 7-8 pleural, fractures on 7 anterior and 7-8 posterior ........ 166
Figure 77. Overview of right side anterior rib fractures ........ 166
Figure 78. Right third rib anterior cutaneous ....................... 167
Figure 79. Right third rib anterior pleural ......................... 167
Figure 80. Right fourth rib anterior cutaneous .................... 168
Figure 81. Right fourth rib anterior pleural ....................... 168
Figure 82. Right fifth rib anterior cutaneous ................................................................. 169
Figure 83. Right fifth rib anterior pleural ..................................................................... 169
Figure 84. Right sixth rib anterior cutaneous .............................................................. 170
Figure 85. Right sixth rib anterior pleural ................................................................. 170
Figure 86. Right seventh rib anterior cutaneous ......................................................... 171
Figure 87. Right seventh rib anterior pleural ............................................................. 171
Figure 88. Left clavicle distal fracture ......................................................................... 172
Figure 89. Left fibula proximal fracture ................................................................. 173
Figure 90. Spleen laceration .................................................................................... 174
Figure 91. Velocity of the sled for test 1 and test 2 .................................................. 175
Figure 92. Acceleration and velocity of ASIS cylinder 1 for test 1 and test 2 ......... 176
Figure 93. Intrusion distance of the door relative to the sled for test 1 and test 2 (left).
Difference in door intrusion distance between the two tests (right). ...................... 176
Figure 94. Velocity of the sled and of the occupant thorax for test 1 and test 2 ....... 177
Figure 95. Door intrusion rate relative to the sled and relative to the occupant for test 1
and test 2 ......................................................................................................................... 178
Figure 96. Airbag pressure readings for both ports on test 1 and test 2 ................. 179
Figure 97. Seatbelt load cell data for test 1 (left) and test 2 (right) ......................... 179
Figure 98. Strain plots for PMHS 1 (26 plots)............................................................ 181
Figure 99. Strain rate plots for PMHS 1 (26 plots).................................................... 186
Figure 100. Strain plots for PMHS 2 (29 plots)......................................................... 192
Figure 101. Strain rate plots for PMHS 2 (29 plots).................................................. 197
Chapter 1: Introduction

Abstract

This chapter introduces the background which motivates the studies contained in this dissertation. Also included in this chapter is a review of literature which is pertinent to the injury biomechanics studies presented. The studies contained in this dissertation each have different areas of focus, including testing, instrumentation, analysis, and application. Correspondingly, background in each of those areas is contained within this introductory chapter.

Motivation

Fatal and injurious automotive collisions occur at a rate of 1.7 million per year in the United States, and accounted for 32,675 deaths in 2014 (NHTSA 2016). Approximately 20% of the collisions and deaths are cases of side impact, while about 55% are from frontal (NHTSA 2016). Because frontal collisions are the most common, they have been a focus of research and development in vehicular safety systems for several decades (Kroell et al. 1971, Kroell et al. 1974, Horsch et al. 1991, Cesari et al. 1994, Kent et al. 2003a, Kent et al. 2005a, Poulard et al. 2013). As a result of such focus, safety systems have improved in their ability to protect against frontal collisions, as
indicated by a steadily increasing trend in the annual percentage of lives saved due to these systems (NHTSA 2015).

In more recent years, there has been an increasing interest in improving vehicle safety performance for side impact conditions. In 1990, FMVSS 214 (the federal regulation for side impact safety) was expanded to require car companies to pass a dynamic safety test, which was fully implemented by 1997 (NHTSA 2015). In response to the expanded safety regulations, advancements such as the side airbag and inflatable curtain, as well as improved structural design of the vehicle, have been introduced to increase occupant protection in side impacts. However, efficacy studies and technology refinement for these systems are still needed in order to ensure that the technologies save as many people as possible. (Yoganandan et al. 2007).

Side Impact Testing

In order to improve safety system design, data must be collected about human response to applicable impact conditions, using post-mortem human surrogates (PMHS). Several test types have been utilized previously, and are described along with their advantages by Yoganandan et al. (2007). Full-scale vehicle tests are the most realistic, but are large, complex, and expensive to conduct. Studies therefore generally simulate selected aspects of a side impact scenario. Free-fall drop tests and sled tests both have the subject interact with a wall, thus maintaining full-body interaction and response, but reduce complexity and cost of using an actual vehicle. Since subjects are seated for sled tests, these tests most closely replicate an actual vehicle crash. A further step down in complexity involves localized loading of body regions using a pendulum or ram
impactor, providing region-specific response characteristics. Finally, component tests involving only a single bone, limb, or body region further reduce the complexity of the system being examined and provide specific response characteristics for the components tested. Because full-scale vehicle tests and sled tests are the most realistic overall loading conditions, they are the most desirable for development of injury measures in vehicle safety testing (Eppinger 1999).

Sled testing has been utilized to understand human tolerance for several decades (Stapp 1957, Melvin 1976, Marcus 1983, Morgan 1994, Shaw 2009, Donlon 2015). In 1976, Melvin et al. conducted a series of side impact sled tests utilizing seven PMHS, employing combinations of 7, 9, and 12 m/s impact velocities, with a padded or unpadded rigid wall. Cavanaugh et al. (1990) expanded the work by conducting 12 side impact sled tests utilizing combinations of 6.7 m/s and 9 m/s into a stiffly padded, softly padded, or unpadded rigid wall, with and without a 6” pelvic offset. It was found that compression and velocity times compression were the best of the predictors of thoracic injury which were evaluated. In 1993, Cavanaugh et al. built on their previous work by adding 5 PMHS sled tests into a padded wall. Conclusions for the extended dataset were similar to the original conclusions from 1990. They also analyzed a combined dataset from the National Highway Traffic Safety Administration (NHTSA) and found that acceleration-based criteria performed better for predicting injury on the large dataset than on their own subset.

Similar to the studies by Cavanaugh et al. (1990, 1993), Pintar et al. (1997) conducted a series of 26 PMHS sled tests in combinations of 24 km/h and 32 km/h (6.7
m/s and 9 m/s) into rigid, padded, and pelvic offset wall cases. This study, however, added chestbands to the instrumentation setup, which was the first time chestbands had been used in side impact. They observed that the padded wall condition resulted in lower accelerations, forces, and deflections than the rigid wall condition. In addition to evaluating several existing injury criteria, a new criterion was presented which is the product of thoracic trauma index and maximum chest compression (TTI*C) with a threshold value of 58, corresponding to a 50% probability of AIS4+ injury.

Yet another expansion of the side impact data under similar conditions was presented in 2003 by Kuppa et al., providing the results of 42 PMHS sled tests conducted at the Medical College of Wisconsin. The tests were conducted at combinations of 24 and 32 km/h (6.7 and 9 m/s) into rigid and padded walls. Several injury criteria were evaluated and it was found that maximum normalized average half thorax deflection was the best predictor of injury. Another 16 tests with the ES-2re were done to provide anthropomorphic test device (ATD) injury assessment reference values (IARV).

Although the previously established methodology for side impact sled tests has proven useful in numerous studies, Yoganandan et al. (2012a) introduced a slightly different methodology which has accompanying benefits and drawbacks. In place of the traditional fixed wall used for sled tests, a modular wall was implemented. An advantage of a modular wall is that it can be adjusted such that the input load interacts with the subject the same way every time, despite the subject to subject variation which exists in PMHS testing. In that same year, Yoganandan et al. (2012b) presented 15 PMHS
impacts, 5 of which were in pure lateral impact at 6.7 m/s. Thoracic deflections were calculated from chestband data and were compared to deflections from oblique impacts.

In each of the side impact studies cited, subject response to impact was recorded and reported (Melvin et al. 1976, Cavanaugh et al. 1990, Cavanaugh et al. 1993, Pintar et al. 1997, Kuppa et al. 2003, Yoganandan et al. 2012b). Response corridors are useful as biofidelity targets in ATD design. Response data was used in some instances to develop injury criteria and IARVs (Cavanaugh et al. 1990, Cavanaugh et al. 1993, Pintar et al. 1997, Kuppa et al. 2003). Injury criteria and IARVs are of value in predicting injury for vehicle occupants.

Injury Criteria and Injury Assessment Reference Values

Injury predictive models, also called injury risk curves, and injury criteria use measured response data to predict the probability of injury, and have been employed for several decades to test (and ultimately improve) vehicle safety systems (Robbins et al. 1979, Eppinger et al. 1999, Kuppa et al. 2003, Petitjean et al. 2003, Yoganandan et al. 2007, Marjoux et al. 2008). The first thoracic injury criterion developed was done by Kroell et al. (1971), and their subsequent work (Kroell et al. 1974) predicts AIS=3 injury at a chest deflection equal to 34% of the chest depth. The methods for risk curve generation have been standardized for the field of impact biomechanics by the International Organisation for Standardisation (ISO/TC22/SC12/WG6), and were outlined by Audrey Petitjean et al. in a 2012 publication.

Once various risk curves have been produced, one must be selected as the best model to use for an injury criterion. There are several different indices used in practice to
assess the quality of risk curves, including the C-statistic, Akaike Information Criterion (AIC), and Bayesian Information Criterion (BIC) (Bamber 1975, Akaike 1972, Schwarz 1978). Petitjean et al. (2012) suggest using a quality index to verify model validity based on the size of the confidence interval, then to identify the best model based on the AIC. Once a model has been selected, the injury criterion is identified as the value of the independent variable at a specified probability of injury. Various injury probability thresholds have been used previously, including 25% risk of AIS5+ injury (Viano et al. 1989), 5% risk of AIS4+ injury (Mertz 1984), 50% risk of AIS4+ (Pintar et al. 1997), 25% risk of AIS3+ injury (Horsch 1991, Kuppa et al. 2003), and 50% risk of AIS3+ injury (Neathery et al. 1975, Kleinberger 1998).

In 1979, Robbins et al. ran a series of impact tests on 18 PMHS and evaluated several potential injury criteria including LURQ, LSV15, RURV19, and BLUR, and found the BLUR (B-parameter for left upper rib) criterion to be the best of those evaluated. Some other previously determined thoracic injury criteria for the 50\textsuperscript{th} percentile male are a chest deflection of 63 mm (Eppinger et al. 1999), chest acceleration of 60g (Eppinger et al. 1999), viscous criterion (VC) of 1.47 m/s (Viano et al. 1989), combined thoracic index (CTI) of 1 (Kleinberger 1998), average half chest deflection in side impact of 22% (Kuppa et al. 2003), and the thoracic trauma index (TTI) of approximately 90g, depending on the vehicle type (Yoganandan et al. 2007). Several different values for chest compression injury threshold in frontal and side impacts have been reported, including 30% (Tarriere et al. 1979, Pintar et al. 1997), 34% (Kroell et al. 1997).
1974), 35% (half-chest compression) (Stalnaker et al. 1979), 37% (Kuppa et al. 2003), and 38% (Viano et al. 1989).

The ability to predict vehicle occupant injuries based on measured response data becomes of greatest value when ATDs can be used instead of humans to provide the response measurements for injury prediction. If an ATD is biofidelic, the response of the ATD will match a human response, and thus the injury criteria will be the same for both. Otherwise, a relationship must be established relating ATD response to human response, as discussed by Horsch et al. (1991).

In order to establish the response relationship, an ATD is subjected to the same loading conditions as the PMHS, and response data is again collected, as was done by Mertz et al. (1991). A transfer function is then determined which provides PMHS response as a function of ATD response. The value of the ATD measurement which corresponds to the threshold value of the PMHS injury criterion serves as the IARV. These IARVs are the ATD threshold values for human injury.

The first IARV was introduced by Mertz in 1984, indicating a 65mm chest deflection threshold value for the Hybrid-III 50th. Horsch et al. (1991), based on a comparison to field data, suggested a 40mm chest deflection IARV for belt loading on the Hybrid-III, corresponding to 25% risk of AIS3 injury. IARVs for ATDs other than the 50th male have been previously determined by applying a scaling factor to the 50th male IARV (Mertz et al. 1997, Yoganandan et al. 2014). It would be most ideal, however, to use actual data from a given demographic group to derive the associated IARVs.
Elderly, Fragile Females

Similarly with IARVs, safety systems in general have historically been designed for the 50th percentile male. This approach is logical as it is catering to the needs of the average person. Vehicle occupant demographics, however, are rapidly changing. With medical advancements of the past century, average life expectancy has nearly doubled (Oskvig 1999), and is projected to continue to rise (Ortman et al. 2014). The effects of increased lifespan on population demographics have been amplified by the aging of the baby boomer generation as they have been entering retirement age and adding to the elderly population (Colby et al. 2014).

Worldwide, the older population has been growing faster than the younger population, a trend which is projected to continue over the next 35 years (He et al. 2016). Because of the growing elderly population, there are more elderly occupants in vehicles than there have been previously. This recognition has prompted NHTSA to specifically consider the elderly in all aspects of traffic safety, including vehicle design (NHTSA 2013). Furthermore, Hill et al. (2006) found that older females have the greatest risk for severe injury in frontal, side, and rear collisions when compared to other demographic groups. The need to design for vulnerable occupants has a tremendous impact on the design of safety systems because they are more frail than healthy young and middle-aged adults.

With the shift in design focus, a shift is also required in research and data collection, studying fragility and frailty in the elderly (NHTSA 2013). An understanding of the biomechanical response of elderly, fragile, female human subjects is essential in
order to design safety systems which accommodate such occupants. Some work was done by Kent et al. (2003a, 2003b, 2005b) to study the effects of aging on occupant thoracic stiffness and injury criteria in frontal impact.

A few studies have also examined the response of small females. Crandall et al. (1998) conducted 7 PMHS frontal impact tests to check the 5th percentile female Hybrid-III biofidelity. Yoganandan et al. (2005) reported response corridors for small females in side impact from 27 sled tests, but did so by scaling the data from subjects which were not representative of small females. Baudrit et al. (2014) studied the impact response of 6 small female PMHS in lateral and oblique ram impacts in order to compare to mid-size male response. Shaw et al. (2017) conducted frontal sled tests on 5 small, elderly female PMHS restrained by a custom 3-point belt and reported rib fracture patterns. A limitation to the combined set of previous work is that the studies included mostly subjects of healthy bone mineral density. Thus, fragile subjects were not being examined. One exception was the study by Shaw et al. (2017), in which 3 of their subjects were osteoporotic and the other 2 subjects were osteopenic. In that study, serious injuries were observed at a relatively low severity crash scenario, which did not correspond to trends observed in epidemiology studies. Another shortcoming of the combined set of previous work is that while the response of small females was studied, injury criteria were not developed to represent the small females. As a result of these deficiencies, there exists a need to acquire biomechanical response data and develop injury criteria for elderly, fragile females, especially in side impact. The present work represents a next step in biomechanical data collection toward injury criteria development.
Chestband Use

The study of fragile PMHSs requires special caution, as injury is more easily caused during handling, preparation, and use. One consideration during study design for the present work is whether chestbands can or should be used to measure chest contour throughout impact. A chestband, also called an External Peripheral Instrument for Deformation Measurement (EPIDM), is a strip of steel with a series of strain gages attached to it, all encased in polyurethane (Eppinger 1989). Chestbands are wrapped tightly around the thorax, and the strain gage measurements are used to measure the shape of the chestband (which is presumably the same shape as the thorax).

Since the introduction of the chestband in 1989, and up to the current day, it has been used in various studies to represent the contour of the thorax (both PMHS and ATD) during impact, from which chest deflection is calculated (Eppinger 1989, Cesari et al. 1994, Pintar et al. 1997, Yoganandan et al. 2002, Crandall et al. 2006, Rhule et al. 2011, Yoganandan et al. 2012b, Shaw et al. 2014). Several studies have validated the accuracy of measurements from chestband contours (Eppinger 1989, Cesari et al. 1994, Pintar et al. 1996, Bass et al. 2000). In the study by Bass et al. (2000), the measurement errors were specifically studied and quantified.

The contours measured by the chestband can be used to calculate chest deflection, for which multiple methodologies exist. In frontal impact, it is logical to look at the change in distance between the sternum and spine or the A/P translation of some other anterior chestband gage location with the spine gage being anchored (Cesari et al. 1994). For pure lateral impacts and motions, a similar approach calculating the change in
distance between the lateral-most gages is logical, but Pintar et al. (1996) found that this may not be an optimal method. Pintar et al. (1997) subsequently used two distances to compute chest deflection – the lateral aspects (25% - 75% chest circumference) and slightly anterior of lateral (30% - 70% chest circumference). For oblique impacts, the determination of chest deflection becomes more complex. Yoganandan et al. (2013) presented a spine-sternum method, a bilateral method, and a spine-box method of computing chest deflection and recommended the bilateral method as the best one.

Despite the utility of chestbands for collecting chest deflection data, they may not be the best choice in every situation. There existed a concern that by tightly wrapping a chestband, or especially multiple chestbands, around the thorax of a fragile PMHS, that the thoracic response may be altered, thus confounding the data. No information could be found in literature which indicates whether chestbands have any effect on thoracic response to impact. As such, the present work addresses this concern.

Research Goals and Accomplishments

The goals of the present work were to fill the identified knowledge gaps in chestband effects and thoracic response, and to produce new data regarding biomechanical response of elderly female PMHS in side impact. Each chapter contributes toward these goals. Chapter 2 presents a study assessing effects of chestbands on thoracic response. In order to effectively analyze the data for the chestband effects study, a new analysis method examining strain as a function of chest deflection was developed and is presented in chapter 3. Chapter 4 provides response data from small females in side impact which may subsequently contribute toward the development of new injury criteria.
and injury assessment reference values. Finally, chapter 5 brings everything together as it summarizes the highlights and conclusions from chapters 2-4.
Chapter 2: Effect of Chestbands on the Global and Local Response of the Human Thorax to Frontal Impact

Abstract

The purpose of this study was to examine the effects of chestbands on both global and local thoracic response. A total of twenty-two frontal impacts were imposed on two post-mortem human surrogates, using a 23 kg pneumatic impactor. Impacts were at speeds of 0.8 m/s, 1.0 m/s, 1.5 m/s, and 2.0 m/s, and there were either 0, 1, or 2 chestbands on the subject. The baseline configuration of 0.8 m/s with zero chestbands was tested initially, then was repeated intermittently throughout testing. For each impact speed, the difference between response with and without chestbands was calculated. Results showed average changes of +0.79 mm in chest deflection, -0.42 N/mm in thoracic stiffness, and -96 µS in rib strain when chestbands were used, none of which were statistically significant (t-test, p=0.35 p=0.42 and p=0.42, respectively). The results provide support for the commonly employed assumption that chestbands do not alter the response of the thorax in frontal impact.

Introduction

Fatal and injurious automotive collisions occur at a rate of 1.7 million per year in the United States, and accounted for nearly 33,000 deaths in 2014 (NHTSA 2016).
Among such collisions, frontal crashes are the most prevalent, accounting for over 50% (NHTSA 2016). Brumbelow and Zuby (2009) reported that chest injuries are the most common injuries observed among those seriously injured in frontal crashes of vehicles with good safety ratings. During crashes, chest deflection produces rib fractures in vehicle occupants, thus chest deflection can be used to predict thoracic injury (Kroell 1974, Kroell 1986, Rouhana 2003, Cavanaugh 2015).

Several different values for chest compression ([deflection/chest depth] x 100%) injury threshold in frontal and side impacts have been reported, including 30% (Tarriere 1979, Pintar 1997), 34% (Kroell 1974), 35% (half-chest compression) (Stalnaker 1979), 37% (Kuppa 2003), and 38% (Viano 1989). In a series of studies, Kemper et al. (2011, 2016) used strain gages to identify fracture timing, and found that fractures had occurred at chest compressions as low as 16%, 12%, and even 6%. The current injury assessment reference value (IARV) in use for chest deflection in the Hybrid III 50th percentile male anthropomorphic test device (ATD) is 63 mm, or 29% compression (Eppinger 1999). Because of the utility of chest deflection data, it is desirable in automotive testing to obtain such data in order to predict injuries and evaluate vehicle safety. Chest deflection is typically acquired through chestband instrumentation (Cesari 1994, Pintar 1997, Crandall 2006, Rhule 2011, Shaw 2014).

A chestband, also called an External Peripheral Instrument for Deformation Measurement (EPIDM), is a strip of steel with a series of strain gages attached to it, all encased in polyurethane (Eppinger 1989). The gage readings provide a measure of the curvature of the chestband at each gage location. Chestbands are commonly used in
biomechanics as an instrument to measure the contour of the thorax throughout impact, from which chest deflection may be calculated (Cesari 1994, Pintar 1997, Crandall 2006, Shaw 2014).

Several studies have validated the accuracy of chestband contours reconstructed from strain gage measurements (Eppinger 1989, Cesari 1994, Pintar 1996, Bass 2000). Taking validation a step further, measurement errors were specifically examined and quantified in the study by Bass (2000). Although it has been verified that the measurements are accurate, there has not yet been a study which has examined whether, and to what extent, the use of chestbands may alter the actual response of the thorax to impact. Should such effects exist, the validity and value of the collected data could be compromised. Thus, there exists a concern that by wrapping a chestband, or especially multiple chestbands, around the thorax of a post-mortem human surrogate (PMHS), the thorax characteristics and impact response may be altered. Of particular concern are the effects on small, frail subjects, as their low mass and low bone strength could amplify potential chestband effects. The purpose of the present work is to determine the effects of chestbands on both the global and local responses of the human thorax to frontal impact.

Materials and Methods

Chestband effects on global thoracic response were investigated through a series of 22 low-energy, non-injurious, frontal ram impacts to two PMHS. The number of chestbands present on the subject was varied throughout testing in order to provide a comparison of response with and without chestbands. Speed was also varied in order to have multiple points for comparison. Chest deflection and thoracic stiffness were used to
represent the global thoracic response, while rib strain was used to characterize the local response.

Subject Selection

Two PMHS were used in the study, the first being a small, frail (osteopenic) female, and the second being a mid-size male. The small female was selected in order to evaluate chestband effects under conditions in which such effects should be most pronounced. The mid-size male was selected to represent the size of subjects most commonly used historically in biomechanics studies (Hu 2012). The small female, subject 1, was 83 years old, 162 cm in height and 59 kg in mass. Areal bone mineral density (aBMD) was obtained using dual-energy x-ray absorptiometry and the dual femoral neck T-score was calculated as -1.6, which indicates osteopenia (Kanis 1994). The male, subject 2, was 64 years old, 178 cm tall, with a mass of 79 kg and a lumbar spine aBMD T-score of -0.6.

After the BMD was checked, each of the two subjects had a pre-testing CT scan performed to screen for pre-existing injuries and thoracic abnormalities. Each subject’s anthropometry measurements were collected prior to instrumentation, and are presented in Table 1. Additionally, the breasts were removed from the female in order to eliminate their influence on thoracic response and chestband effects.
<table>
<thead>
<tr>
<th>Characteristic</th>
<th>PMHS 1</th>
<th>PMHS 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex</td>
<td>F</td>
<td>M</td>
</tr>
<tr>
<td>Age</td>
<td>83</td>
<td>64</td>
</tr>
<tr>
<td>aBMD T-score</td>
<td>-1.6</td>
<td>-0.6</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>59</td>
<td>79</td>
</tr>
<tr>
<td>Stature (cm)</td>
<td>162</td>
<td>178</td>
</tr>
<tr>
<td>Chest Breadth at Axilla (cm)</td>
<td>29.5</td>
<td>30.5</td>
</tr>
<tr>
<td>Chest Breadth at Xiphoid Process (cm)</td>
<td>28.5</td>
<td>32.5</td>
</tr>
<tr>
<td>Chest Circumference at Axilla (cm)</td>
<td>92</td>
<td>101.5</td>
</tr>
<tr>
<td>Chest Circumference at Xiphoid Process (cm)</td>
<td>86</td>
<td>100</td>
</tr>
<tr>
<td>Chest Depth at Axilla (cm)</td>
<td>16</td>
<td>21.5</td>
</tr>
<tr>
<td>Chest Depth at Xiphoid Process (cm)</td>
<td>17</td>
<td>24.9</td>
</tr>
<tr>
<td>Seated Height (cm)</td>
<td>79</td>
<td>84</td>
</tr>
</tbody>
</table>

Table 1. Subject information

**Test Setup**

Frontal impacts were conducted on each PMHS using a 23 kg pneumatic impactor, with a flat plate impactor surface (6”H x 12”W) centered at mid-sternum (Figure 1). The PMHS was seated against a 90°, flat back fixture, thus impeding spinal motion. The rigid-back setup enabled the ram displacement, from initial contact to peak displacement, to be used as a measure of chest deflection. The PMHS was supported, and the seated posture maintained by use of a head harness which was placed on a linear track, allowing for anterior-posterior motion of the head during impact. The PMHS’ arms
and forearms were flexed 90°, which prevented impactor interaction without raising the thoracic region.

Figure 1. Test setup including a 23 kg impactor ram, 90° back fixture, and PMHS with arms and forearms flexed at 90° (left). Position of the 2 chestbands on the PMHS (right).

Instrumentation

The instrumentation used was nearly identical for both subjects, the only difference being that subject 2 had additional strain gages on the ribs. For both subjects, two chestbands were wrapped around the PMHS’ thorax; the superior chestband at the level of the axilla (40 gage, Humanetics Innovative Solutions, Plymouth MI) and the inferior chestband at the level of the xiphoid process (59 gage, Humanetics Innovative Solutions, Plymouth MI). A 6 degree of freedom motion block containing 3 accelerometers and 3 angular rate sensors (6DX Pro Sensor, Model 2000g 18K deg/sec, DTS, Seal Beach CA) was placed on the 4th thoracic vertebra (T4) to verify there was no spinal motion, and to provide a correction in the event of spinal motion occurrence. Strain gages (Model CEA-13-062UW-350/P2, Micro Measurements, Wendell NC) were placed
anterolaterally (approximately 60% of the curve length, the costotransverse junction [CTJ] being 0% and the costocondral junction [CCJ] being 100%) on ribs 3-8 bilaterally, in order to identify fracture timing. In the case of subject 2, up to three strain gages were placed on each rib 2-8. Ribs 3-8 had gages placed at 30% and 60% of the curve length. At the 90% (of curve length) location, gages were placed on ribs 2-7 in order to be centered under the chestbands. Instrumentation placement on the thorax is shown in Figure 2.

Figure 2: Instrumentation placed on each PMHS thorax prior to impact testing

The test setup used a linear potentiometer (Model CLWG-600-MC4, Celesco, Chatsworth CA) on the impactor, which served as the consistent measure of chest deflection throughout testing. Other instrumentation included an accelerometer (Model 7264C-2K, Endevco, Irvine CA) on the impactor to acquire impact velocity, as well as a load cell (Model 2944JFL, Humanetics Innovative Solutions, Plymouth MI) between the ram shaft and the impactor face.
**Test Matrix**

The combined set of 22 impacts included variations both in the impact speed and the number of chestbands used. A baseline case was defined as 0.8 m/s impact velocity with 0 chestbands present. The baseline scenario was tested first, repeated twice to check repeatability, then also repeated intermittently during the testing process. Deviations from the baseline scenario were systematically applied, including adjustments to impact velocity and to the number of chestbands. Impact velocities were approximately 0.8 m/s, 1.0 m/s, 1.5 m/s, and 2.0 m/s. The number of chestbands was 0, 1, or 2. The general approach with each subject was to begin with a low-energy impact, and gradually increase the impact energy until damage to any of the ribs occurred. Once rib damage was observed, testing was ended because the system being tested (the thorax) had changed. The order in which the impacts were conducted is portrayed in Figure 3.

![Figure 3: Flow of testing for the two test subjects. Each box represents an impact. Each * indicates a baseline impact within the test flow to verify that the system had not changed.](image-url)
Data Collection and Analysis

All data were collected using a SlicePro data acquisition system (DTS, Seal Beach CA) at a sampling rate of 20,000 Hz. Time zero in each test was defined as the time of initial contact between the impactor face and the thorax, and was determined electronically by using conductive tape on the contacting surfaces. All data were filtered during post-processing in Matlab using a two-direction (phaseless), second order Butterworth filter with a cutoff frequency of 300 Hz, which is comparable to the SAE Channel Frequency Class (CFC) 180 (SAE J211, 2007). Although chestbands were placed on the subject, chest deflection data was obtained from the ram displacement – not from the chestbands. This provided a consistent measure for deflection for both impacts with and without any chestbands. Normalized chest deflection and thoracic stiffness were examined as the basis for evaluating the effects on global response, while rib strains were used to evaluate effects on localized loading. The overall structure of the data collection and analysis process is shown in Figure 4. The analytical methods for the impact velocity, deflection, and stiffness are explained in greater detail in the following subsections.
Multiple redundant sensors were used to calculate impact velocity. The filtered ram acceleration (from accelerometer) was integrated to get the ram velocity. Additionally, the filtered ram position (from potentiometer) was differentiated to get the velocity. The differentiated ram position was selected as the best method for calculating velocity because of vibrational noise experienced by the accelerometer. Impact velocities for each test are included in the supplemental material.

**Chest Deflection**

The values for absolute chest deflection (c) were obtained for each test as the ram displacement after initial contact. In order to remove variation in actual impact velocity ($v_a$) as a potential factor for variation in peak chest deflection, the deflections were
normalized (d) about the target impact velocity (\(v_t\)), as shown in Equation 1. Target velocities, actual velocities, and peak absolute deflections are included in the supplemental material.

\[
d = c \frac{v_t}{v_a}
\]

Equation (1)

With the normalized chest deflections calculated, deflection differences were then calculated as the basis for comparing the deflection for each number of chestbands used. Uncertainty was then calculated for individual deflections and extended to deflection differences. The individual uncertainty was calculated as the 3-degree-of-freedom 95% confidence interval, which was 3.2 times the standard deviation of the first 4 baseline impacts. The uncertainty in each chest deflection difference was calculated as the root sum of squares of two impacts, each impact having an uncertainty equal to the individual deflection uncertainty (Moffat 1982).

In order to determine whether observed differences were significant, a paired two-tailed t-test with six degrees of freedom was conducted on the combined set of eight deflection differences. The null hypothesis of the test was that there is no difference between response with and without chestbands (\(d_1 \text{ or } d_2 - d_0 = 0\)). The alternative hypothesis was that there is a difference between response with and without chestbands (\(d_1 \text{ or } d_2 - d_0 \neq 0\)). A pooled standard deviation was used for the test, which was calculated as the average standard deviation from the two subjects because an equal number of data points were used from each subject to calculate the individual standard deviations.
Thoracic Stiffness

The A/P force from the load cell was inertially compensated to account for the mass of the impactor plate, thus representing the complete force exerted on the thorax. The compensated force (F) was then used to produce force-deflection curves as well as to calculate the thoracic stiffness. Stiffness (k) was calculated for the linear spring model containing equal potential energy (PE) as the thorax at peak deflection (c) (Equation 2). Stiffness values are included in the supplemental material.

\[ k = \frac{2PE}{c^2}, \text{where } PE = \int_{0}^{\text{Peak Deflection}} F \cdot dc \]  
Equation (2)

The methods for calculating stiffness differences, stiffness difference uncertainty, and for testing the significance of stiffness differences were identical to the methods evaluating the differences in the chest deflection.

Rib Strain

Analysis of rib strain sought to determine whether chestbands concentrate the input load, thus altering the observed rib strain in the contacted ribs. Thus, analyses were focused specifically on those ribs which were in direct contact with a chestband (ribs 3-4 and ribs 6-7). As with chest deflection, rib strain was first normalized by impact velocity in order to directly compare impacts. Changes in peak strain were then calculated for bilateral ribs 3-4 with the first chestband added to the system (s_{1}-s_{0}). Similarly, changes in peak strain were calculated for ribs 6-7 when adding the second chestband after the first was already in place (s_{2}-s_{1}).
The uncertainty for each strain difference was calculated for each rib by the same methodology as was used in the uncertainty of deflection differences. Three two-tailed t-tests were conducted to evaluate significance: 1) the dataset of ribs 3-4, 2) the dataset of ribs 6-7, and 3) the combined dataset of ribs 3-4 and 6-7. In each instance, a pooled standard deviation was calculated as the average standard deviation for each rib within the dataset. The three t-tests had 15, 15, and 30 degrees of freedom, respectively.

Results

The results presented here provide the injuries observed in the two PMHS tests, then focus on the key data and the output from the analyses. Raw data for the key variables are contained in Appendix A.

Injuries

Rib fractures were identified during testing by polarity changes in the strain gage output during loading (Troseille 2008, Kemper 2011). For subject 1, fractures occurred in the 3rd and 4th right ribs during the 17th impact, which was the second impact to occur at the 2.0 m/s impact velocity (see Figure 5). One chestband, at the level of the axilla, was present on the subject during the injurious impact. Both fractures were transverse and were located slightly posterior of the strain gages, but still anterior of lateral (approximately 60% of rib curve length). Subject 2 had one fracture occur on the right 8th rib during the 7th impact, which was the first impact to occur at 1.5 m/s. The fracture was located at 95% of the rib curve length (anterior, near the CCJ), and both chestbands were in use when the injury occurred.
Figure 5: Fractures in right ribs 3 and 4 from subject 1 and right rib 8 fracture from subject 2 (left). Each fracture is shown across the top, and each associated strain gage plot is shown across the bottom (right).

Chest Deflection

As the analysis in the study is focused on changes in deflection resulting from chestband use, the differences in peak deflection are of greater consequence than the actual deflection values themselves. An example of the normalized deflection plots, from which the key data were extracted, is shown in Figure 6.

Figure 6. Chest deflection plots for impacts conducted on PMHS 1 at impact speeds of 0.8 m/s (left) and 1.5 m/s (right)
Peak deflection values were identified for each impact, and are presented in Figure 7. Actual deflection values for the various impacts are included in Appendix A, Table 9. Deflection differences were calculated from these peak values, as shown in the figure.

Figure 7. Peak normalized deflection values for impacts on PMHS 1 at 0.8 m/s (top left), on PMHS 1 at 1.0 m/s (top right), on PMHS 2 at 1.0 m/s (bottom left), and PMHS 1 at 1.5 m/s (bottom right). Values shown for the baseline cases are the average of the first four baseline impacts. The color of each difference bracket corresponds to the color of the bar in Figure 8.

In order to visualize any effect of chestbands on chest deflection, differences in normalized deflection based on the number of chestbands are shown in Figure 8. Because the figure is showing differences in deflection, a value of zero indicates that the deflection did not change when the number of chestbands changed (i.e. chestbands had no effect). Looking at the individual impact comparisons, a difference of 0 is contained...
within the 95% confidence interval for the deflection difference in every case except for one. Viewing the combined set of 8 deflection differences which compare impacts with at least one chestband to impacts without chestbands, the differences in deflection appear to vary about zero, having a 0.79 mm average increase with chestband use. Using the same combined set of differences, a two-sided t-test identifying the significance of the change in chest deflection from using chestbands produced a p-value of 0.35. When comparing impacts with one chestband versus two chestbands, differences in chest deflection were even smaller, showing an average 0.26 mm decrease in deflection for adding the second chestband.

Figure 8: Effects of chestbands on thoracic deflection. Peak normalized deflection for impacts on PMHS 1 at 0.8 m/s (left). Differences between peak deflections for impacts at the same speed, comparing 0 chestbands with 1 chestband (d₁-d₀), 0 chestbands with 2 chestbands (d₂-d₀), and 1 chestband with 2 chestbands (d₂-d₁) (right). Error bars indicate the 95% confidence interval.
Thoracic Stiffness

Force and deflection were used to calculate the thoracic stiffness. Example Force-Deflection plots are shown in Figure 9.

![Force-deflection plots for impacts conducted on PMHS 1 at impact speeds of 0.8 m/s (left) and 1.5 m/s (right)](image)

Figure 9. Force-deflection plots for impacts conducted on PMHS 1 at impact speeds of 0.8 m/s (left) and 1.5 m/s (right)

Results for thoracic stiffness appeared much the same as results for chest deflection, and stiffness values for the various impacts are shown in Figure 11. Actual stiffness values for all impacts are included in Appendix A, Table 9.
Figure 10. Thoracic stiffness values for impacts on PMHS 1 at 0.8 m/s (top left), on PMHS 1 at 1.0 m/s (top right), on PMHS 2 at 1.0 m/s (bottom left), and PMHS 1 at 1.5 m/s (bottom right). Values shown for the baseline cases are the average of the first four baseline impacts. The color of each difference bracket corresponds to the color of the bar in Figure 11.

Calculated stiffness differences for comparison are shown in Figure 11. Every individual impact comparison has a 95% confidence interval which crosses the line for zero difference. The combined set of differences comparing impacts with at least one chestband versus impacts without chestbands showed a 0.42 N/mm decrease in stiffness with chestband use. The associated two-sided t-test for statistical significance yielded a p-value of 0.42.
Figure 11: Effects of chestbands on thoracic stiffness. Stiffness values for impacts on PMHS 1 at 0.8 m/s (left). Differences between thoracic stiffness for impacts at the same speed, comparing 0 chestbands with 1 chestband ($k_1-k_0$), 0 chestbands with 2 chestbands ($k_2-k_0$), and 1 chestband with 2 chestbands ($k_2-k_1$) (right). Error bars indicate the 95% confidence interval.

Rib Strain

Peak strain values for impacts on the right third rib are shown on the left in Figure 12 as an example of the strain values from which differences were calculated. Peak strain values for all ribs in all impacts are reported in Appendix A, Table 10. Average differences in peak strain for each rib level contacted by a chestband are shown on the right in Figure 12. Rib levels 3-4 were in contact with the superior chestband and the rib levels 6-7 were in contact with the inferior chestband. Average changes in rib strain were 42 $\mu$S and 235 $\mu$S, from use of the superior chestband and the inferior chestband, respectively. T-tests were conducted to evaluate whether the observed strain differences were significant. The statistical test was performed on both datasets individually as well as for the combined dataset in the figure. None of the t-tests produced statistically
significant p-values: rib levels 3-4 had a p-value of 0.7, rib levels 6-7 had a p-value of 0.09, and the combined set of levels had a p-value of 0.42.

Figure 12: Peak strain values in the right 3rd rib during impacts with zero chestbands and one chestband (left). Average change in peak strain for ribs in contact with a chestband (right). Ribs level 3-4 are shown on the left, comparing impacts with one chestband vs. zero chestbands. Ribs level 6-7 are shown on the right, comparing impacts with two chestbands vs. one chestband. Error bars represent a 95% confidence interval for the average strain difference.

Discussion

The present study was reliant upon data from repeated impacts to the same thorax, and the test setup was designed to maximize the number of impacts which could be conducted without thoracic damage. Previous studies have used a linear impactor to interact with the thorax, and have commonly used a 23 kg impactor with a 6” circular impactor face (Kroell 1974, Kent 2003b, Trosseille 2008). The current study applied the same impactor mass, but used a larger rectangular impact face in order to minimize the chance of fracture due to edge effects. Additionally, the testing began at the lowest
impact velocity which could be repeatedly produced by the impactor, and was gradually increased.

Global thoracic response was characterized in the present study by the chest deflection and the thoracic stiffness. It was observed in tests with chestbands that discrepancies between chestband-based deflection measurements and impactor displacement-based deflection measurements were within 2 mm. In order to maintain consistency across all tests in the analysis, including impacts without chestbands, the impactor displacement-based measure was used for all tests. Looking at chest deflections for individual impact comparisons on the right in Figure 8, the 95% confidence interval crosses over zero in every case except one. This indicates that the observed differences in chest deflection could simply be due to random variation – human thoracic response being not perfectly repeatable - rather than to the use of chestbands. Furthermore, when the deflection data were combined and tested for statistical significance, it was found that the data was far from significant with a p-value of 0.35 for a mean deflection difference of less than 1 mm from chestband use.

Calculated stiffness values in the present work were observed to increase as impact velocity was increased. Impacts at 1.5 m/s showed stiffness values very comparable to the hub loading case in Kent et al. (2003a). Stiffness differences from chestband use were even smaller than differences in chest deflection, relative to their individual variability (Figure 11). The 95% confidence intervals for the observed differences in deflection included zero in every case, again suggesting that random variation may be the cause of the observed stiffness differences. The attribution of

33
observed differences to random variation was supported by the statistical treatment of the
dataset, having a p-value of 0.42. Both aspects of global response failed to show any
effect from the use of chestbands.

Local response was evaluated based on the strain observed in the individual ribs. As observed in on the right Figure 12, the average difference in strain for each rib level from chestband contact was much smaller than the variability in strain from test-to-test. Viewing the observed differences statistically, changes in rib strain from chestband use were not significant, whether looking at the first chestband, the second chestband, or both. As with global response, the local response also failed to show any effect from chestband use and interaction with the ribs.

Prior to the advent of the chestband, chest deflection was observed through various methods including video capture of surface targets and transthoracic rods (Kroell 1974, Patrick 1967). Concerns about accuracy in these methods, and particularly about the transthoracic rod’s effects on thoracic response and injuries, motivated the development of the chestband (Eppinger 1989). The chestband improved upon available techniques through an ability to observe complete chest contours rather than just point comparisons, and did not have to disturb the thoracic cavity.

Previous use of the thoracic rod inherently assumed it did not affect thoracic response, an assumption which was recognizably false. Subsequently, the use of chestbands has also relied upon an inherent assumption that they do not alter thoracic response (Cesari 1994, Pintar 1997, Crandall 2006, Shaw 2014). The results of the present work provide evidence to support the assumption of negligible effects on the
thoracic response, both at the global and local response levels. Consequentially, chestbands may be used with some confidence that the thoracic system under study has not been significantly changed by the instrumentation.

*Limitations*

While the present work provides evidence to support the assumption of negligible thoracic effects from chestbands, there are also important limitations to consider in the application of the results. First, the sample size of two PMHS makes it impossible to provide definitive conclusions. Additionally, the need to avoid fracture for the repeated loading necessitated low-energy impacts and thus did not replicate impacts of the same energy typically utilized in vehicle occupant crash studies. It was expected, though, that any observed chestband effects should be most greatly manifested in low-energy impacts and should become more negligible as the impact energy increases. Thus, effects should be negligible at higher energy impacts because the effects appear to be negligible at lower energy impacts. Another limitation in the application of this study is that it specifically examined frontal impact, assuming that the results will be similar for oblique and lateral impacts. Finally, while the results failed to show a significant effect in thoracic response as a result of chestband use, the statistical methods employed do not necessarily indicate the chestbands have no effect on response. The data serves as evidence to support the common assumption of negligible chestband effects, but does not constitute conclusive proof.
Acknowledgements

The author acknowledges the support of Autoliv in sponsoring the research activities. Funding for the student was provided by the National Science Foundation’s Graduate Research Fellowship Program, NSF grant no. DGE-1343012. The views stated herein are those of the author, and not of the funding entities. Finally, we are greatly indebted to the donors and families for their gift to further scientific inquiry.
Chapter 3: Strain-Deflection (S-D) Relationship in the Human Thorax for Fixed-back Frontal Impacts

Abstract

The purpose of this study was to explore the relationship between rib strain and chest deflection during thoracic impact. A series of 20 frontal impacts were conducted on five post-mortem human surrogates (PMHS), using a pneumatic linear impactor with each subject seated against a rigid back fixture. Chest deflection was measured as the impactor displacement after initial contact with the subject, and cutaneous rib strain was measured laterally on ribs 3-8. Strain vs. deflection (or S-D) curves are presented and described. Descriptive models were fit to the set of S-D curves for each rib level, and it was found that a two-part piecewise linear model was the best fit. Response corridors were created to capture inter-subject variation in the response trajectory. It is intended that the data presented may be applied to finite element human body models to help bridge the gap between a general thoracic response (chest deflection) for which injury criteria have been derived, and the local strain response of the individual ribs from which finite element models predict injury.
Introduction

Motor vehicles are an important mode of transportation in the US, there being 6 registered vehicles for every 7 people living in the US (NHTSA 2016). Several other countries also show high per-capita vehicle ownership rates (Millard-Ball et al. 2011). With passenger vehicle travel being such an integral part of life in many countries, vehicle occupant protection is of great interest. Multiple countries have observed particular risk of thoracic injury to motor vehicle occupants, making the thorax of great interest in occupant protection (Brumbelow and Zuby 2009, Japan NPA 2012).

Historically, vehicle safety has been assessed through component impact testing and full vehicle crash testing, and these modalities remain as the gold standard for safety evaluations (GPO 2006, NHTSA 2007). Such testing, however, is quite expensive, both in time and financial resources. Consequently, there is much interest in utilizing finite element models to simulate crashes and predict injuries throughout the vehicle design process. Much work in recent decades has been focused on developing and improving finite element human body models (HBMs) for application in automotive crash simulations (Robin 2001, Yang et al. 2006, Gayzik et al. 2011). A great hurdle, though, for HBM use is the need for model validation (Poulard et al. 2015).

Validation comes from testing of post-mortem human surrogates (PMHS), and comparing the HBM simulation results to the PMHS response and injuries (Li et al. 2010, Vavalle et al. 2013, Poulard et al. 2015). In the thoracic region, further complexity is added to model validation by the mode of injury prediction as HBMs predict specific rib injuries when simulated strain values cross a particular threshold from a material model.
(Kemper et al. 2005, Kemper et al. 2007, Guleyupoglu et al. 2017). Human thoracic injury criteria, however, use variables which describe general thoracic response, such as chest deflection and spinal acceleration, to predict an AIS injury level for the overall outcome (Kroell et al. 1971, Viano et al. 1989, Eppinger et al. 1999, Kuppa et al. 2003, Yoganandan et al. 2007). Thus, there exists a gap in injury prediction methodology between PMHS testing and HBM simulations.

Some work has already been done toward bridging the data gap between PMHSs and HBMs. Charpail et al. (2005) developed a testing methodology to compare rib deflection and strain through a direct bending test. Additional studies at The Ohio State University (Agnew et al. 2015, Schafman et al. 2016) then used the same testing methodology, but contributed a much larger data set. While these studies provided some relationship between rib deflection and strain, the relationship between chest deflection and rib deflection was not considered. Troseille et al. (2008) contributed valuable data relating rib strain to injuries in full-body PMHS tests. However, chest deflection was not included in the study. Despite the previous PMHS work done, the relationship between chest deflection and rib strain remains unknown. The purpose of the present work is to examine this strain-deflection (S-D) relationship in PMHS for frontal impact.

Materials and Methods

In order to initially examine the strain-deflection relationship, a series of twenty frontal impacts were conducted on five PMHS. Subjects were exposed to blunt trauma from a pneumatic impactor while seated with the spine fixed against a rigid seat back.
Deflection and strain were both measured during the event. Further details are provided in the following sections.

Subject Selection

A total of five subjects were used in this study, one female and four male. The average age of the subjects was 67 years old and ranged from 55-83 years old. Prior to selection, the aerial bone mineral density (aBMD) of each subject was measured using dual-energy x-ray absorptiometry and a CT scan was performed to check for pre-existing injuries. A variety of bone mineral densities were represented in this study, the T-scores ranging from +1.6 to -1.6 with an average T-score of 0.2. Prior to testing, the breasts of the female PMHS were removed in order to eliminate their influence, and associated variability, on thoracic response. Anthropometry measurements were taken for each subject before testing, and are presented in Table 2.
Table 2. Subject Information

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>PMHS 1</th>
<th>PMHS 2</th>
<th>PMHS 3</th>
<th>PMHS 4</th>
<th>PMHS 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex</td>
<td>F</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>Age</td>
<td>83</td>
<td>64</td>
<td>73</td>
<td>62</td>
<td>55</td>
</tr>
<tr>
<td>aBMD T-score</td>
<td>-1.6</td>
<td>-0.6</td>
<td>0.4</td>
<td>1.6</td>
<td>1.1</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>59</td>
<td>79</td>
<td>62</td>
<td>84</td>
<td>75</td>
</tr>
<tr>
<td>Stature (cm)</td>
<td>162</td>
<td>178</td>
<td>170</td>
<td>173</td>
<td>183</td>
</tr>
<tr>
<td>Chest Breadth at Axilla (cm)</td>
<td>29.5</td>
<td>30.5</td>
<td>32</td>
<td>33</td>
<td>30</td>
</tr>
<tr>
<td>Chest Breadth at Xiphoid Process (cm)</td>
<td>28.5</td>
<td>32.5</td>
<td>33.5</td>
<td>34</td>
<td>32.5</td>
</tr>
<tr>
<td>Chest Circumference at Axilla (cm)</td>
<td>92</td>
<td>101.5</td>
<td>90.5</td>
<td>106.5</td>
<td>94</td>
</tr>
<tr>
<td>Chest Circumference at Xiphoid Process (cm)</td>
<td>86</td>
<td>100</td>
<td>89.5</td>
<td>110</td>
<td>95</td>
</tr>
<tr>
<td>Chest Depth at Axilla (cm)</td>
<td>16</td>
<td>21.5</td>
<td>19.5</td>
<td>20.5</td>
<td>22.5</td>
</tr>
<tr>
<td>Chest Depth at Xiphoid Process (cm)</td>
<td>17</td>
<td>24.9</td>
<td>20</td>
<td>27.5</td>
<td>22.5</td>
</tr>
<tr>
<td>Seated Height (cm)</td>
<td>79</td>
<td>84</td>
<td>89.5</td>
<td>92</td>
<td>93</td>
</tr>
</tbody>
</table>

Test Setup

The general test setup for all subjects utilized the same strategy as was described in the chestband effects study comprising chapter 2 of this dissertation. For convenience, the setup description is repeated here. A 23 kg pneumatic linear impactor with a 6”x12” flat plate impactor face impacted each subject at mid-sternum. Each subject was seated upright against a 90°, flat back fixture which prevented spinal motion during the impact. The fixed-spine setup allowed chest deflection to be measured as the ram displacement after initial contact. A head harness attached to a linear track was used to support the
head and maintain seated posture during testing. The PMHS’ arms and forearms were flexed 90°, which prevented impactor interaction without raising the thoracic region.

A small adjustment was made to the test setup after the first two subjects had been tested. For the first two subjects, the impactor was permitted to move freely through its free-flight stroke, transferring all of the kinetic energy into the subject’s thorax. For the subsequent three subjects, stoppers were placed to limit the ram stroke, thus limiting thoracic deflection (Figure 13).

Figure 13: Test setup including a 23 kg impactor ram, 90° back fixture, and PMHS with arms and forearms flexed at 90° (left). The test setup with added ram stoppers (right). The red box identifies the stoppers.

Instrumentation

The test setup used a linear potentiometer (Model CLWG-600-MC4, Celesco, Chatsworth CA) on the impactor to measure the chest deflection. A load cell (Model 2944JFL, Humanetics Innovative Solutions, Plymouth MI) was placed on the impactor to collect impact force, which is used in the discussion section of this paper. Each PMHS
had a 6 degree of freedom motion block containing 3 accelerometers and 3 angular rate sensors (6DX Pro Sensor, Model 2000g 18K deg/sec, DTS, Seal Beach CA) placed on the 4th thoracic vertebra (T4) to verify there was no spinal motion, and to provide a correction in the event of spinal motion occurrence. Strain gages (Model CEA-13-062UW-350/P2, Micro Measurements, Wendell NC) were placed anterolaterally (approximately 60% of the curve length, the costotransverse junction [CTJ] being 0% and the costocondral junction [CCJ] being 100%) on ribs 3-8 bilaterally. Single strain gages were used, and were oriented along the long axis of the bone. Instrumentation placement on the thorax is shown in Figure 14.

Figure 14: Instrumentation placed on each PMHS thorax prior to impact testing

Test matrix

Testing for each subject began with a low impact velocity and gradually increased speed for subsequent impacts, shown in Figure 15. Impact speeds were 0.8 m/s, 1.0 m/s, 1.5 m/s, 2.0 m/s, 2.5 m/s, and 3.0 m/s. For PMHS 1, a lowest impact speed of 0.8 m/s was
tested three times before increasing the speed. Then, after each instance of increasing the impact speed, the baseline case was repeated. This was continued until significant thoracic damage was observed on the impact at 2 m/s, at which point testing was concluded. PMHS 2 was subjected to the same trend of impacts, except that 1 m/s was used as the lowest speed. Data collection with PMHS 2 was discontinued when significant thoracic damage was encountered during the 2.5 m/s impact. PMHS 3, 4, and 5 were subjected to deflection-limited impacts in order to be tested at higher impact speeds. Two impacts were conducted on each subject, first at 2.0 m/s and then at 3.0 m/s.

Data Collection and Analysis

The data were collected using a SlicePro data acquisition system (DTS, Seal Beach CA) at a sampling rate of 20,000 Hz. Time zero was defined in each test as the time of initial contact between the impactor face and the impacted thorax, and was
determined electronically through conductive tape across the contacting surfaces. All data
were filtered during post-processing in Matlab using a two-direction (phaseless), second
order Butterworth filter with a cutoff frequency of 300 Hz, which is comparable to the
SAE Channel Frequency Class (CFC) 180 (SAE J211, 2007). Absolute chest deflection
was determined as the distance traveled by the impactor after initial contact, then was
divided by the chest depth at the level of the xiphoid process and multiplied by 100 to
arrive at percent deflection.

As the purpose of this study was to examine how rib strain (S) varied as a
function of chest deflection (D), the analysis was focused on studying this relationship.
First, plots were generated portraying strain vs. deflection. Additionally, five models
were fit to the data, including linear, exponential, and power models.

*Model 1: Basic linear model to peak (BL model)*

The first model used was the most simple and straightforward, being a linear
model for the peak deflection. This model is referred to as the BL model in the results.

\[
S = aD \quad \text{where} \quad a = \frac{S(D_{\text{max}})}{D_{\text{max}}} \quad \text{Equation (1)}
\]

*Model 2: Piecewise linear model for direct loading (PL model)*

The second model used was a piecewise linear model, fit to the direct loading
portion of the response curve. This model was selected because some of the subjects’ ribs
exhibited an initial toe region of deflection without much strain followed by a nearly
linear loading region. Thus, the piecewise linear model could capture both regions. In
order to solve for the model parameters, the first step was to identify the region of direct loading, which was selected as the deflection from 5% to peak deflection. The exact length of the toe region varied for each subject and each impact, so the 5% deflection value was selected because it eliminated much or all of the toe region from consideration and provided consistency in the methodology. A linear model was then fit to the region of direct loading using the linear least squares method (Equation 2).

\[ S = aD + b \quad \text{for} \quad 5\% < D \leq D_{max} \quad \text{Equation (2)} \]

The model parameters coming from Equation 2 were then applied to the final piecewise model (Equation 3). The piecewise model includes an initial toe region where strain is zero, followed by a linearly increasing positive strain.

\[ S = \begin{cases} 0 & \text{if } aD + b \leq 0 \\ aD + b & \text{if } aD + b > 0 \end{cases} \quad \text{Equation (3)} \]

**Model 3: Exponential model for direct loading (E1 model)**

An exponential model was next applied to the dataset (Equation 4). In addition to the exponential term, the model included a difference term to make the model indicate zero strain when deflection is zero. In order to provide a direct comparison with the piecewise linear model, the exponential model was fit to the same direct loading region as the piecewise model was fit to. The model parameters were solved for using the Matlab function ‘fit’.
Model 4: Exponential model for all thoracic loading (E2 model)

Because the S-D begins shallow then demonstrates an increasing slope, an exponential model could be fit to the response throughout all of the thoracic loading, not just the direct rib loading. The fourth model is thus also an exponential model, but applied to the entire range of thoracic loading (Equation 5). Again, the model includes a difference term to provide zero strain at zero deflection and the model parameters were calculated using the Matlab function ‘fit’.

\[ S = ae^{bD} - a \quad \text{fit to} \quad 0 < D \leq D_{max} \quad \text{Equation (5)} \]

Model 5: Power model for all thoracic loading (Po model)

The final model used was a power model, applied to the entire range of thoracic loading (Equation 6). Again, the model parameters were calculated using the Matlab function ‘fit’. This model allows for curvature as the exponential model does, but without the same strong upturn.

\[ S = aD^b \quad \text{fit to} \quad 0 < D \leq D_{max} \quad \text{Equation (6)} \]
Response Corridors

Response corridors were obtained for the S-D response of each rib level as the average strain at a given deflection +/- 1 standard deviation of strain values (Kent 2003b). This was accomplished by first dividing the deflection range of 0-35% deflection into increments, or bins, of 0.2% deflection. Then all measured strain values occurring within the deflection bin were identified, and the corresponding average and standard deviation were calculated. Finally, the response corridors were plotted as the mean strain at each deflection value +/- 1 standard deviation from the mean.

Results

The results presented here show the relationship between lateral rib strain and chest deflection. It is first shown and described visually. This is followed by a quantitative description through the fitting of mathematical models to the data. Finally, the variation in the S-D relationship is portrayed through response corridors.

S-D Curve Shape

An example of some S-D curves is shown in Figure 16, with rib strain plotted as a function of chest deflection. The curves in Figure 16 show an initial toe region where the chest is deflecting but little strain is being observed. A sharp turn is then observed and strain increases almost linearly through peak deflection, after which the strain smoothly returns to where it began. The strain response as a function of deflection also appears to be consistent among impacts, even when impacts are conducted at different velocities.
Figure 16: Representative S-D curves from the L3 rib on PMHS 1. S-D curve for 1m/s and 1.5m/s impact speeds (left) and for all impacts on PMHS 1 (right).

Although the response appears consistent within the subject, more variation is observed between subjects (Figure 17). Not all subjects exhibit the nearly linear relationship between strain and deflection during rib loading which was observed for the L3 rib on PMHS 1. The same rib on PMHS 2 shows a similar toe region but then a more nonlinear rib loading phase.

Figure 17: Variation in S-D curve shape. Complete S-D curves from L3 for PMHS 1 and PMHS 2 (left). S-D curves for L3 during thoracic loading only, for PMHS 1 and PMHS 2 (right).
Although there is inter-subject variation, there is also consistency which will be helpful in the development and application of human body models. Figure 18 shows two different sets of loading-phase S-D curves: each rib level of PMHS 1 for all impacts (left), and the right 4th rib during all impacts for all subjects in this study (right). The plot of PMHS 1 shows consistency across impacts for each rib level, but variation among the rib levels. Trends were similar for the other subjects. The plot of the right 4th rib shows greater consistency in the response across subjects for a given rib than was observed across ribs within the subject. This consistency in response is encouraging for use in models.

Figure 18: S-D curves for PMHS 1 during thoracic loading for all impacts on all rib levels (left). S-D curves for R4 during thoracic loading for all impacts on all subjects (right).
Response Characterization

In order for the S-D relationship to be applied to HBMs, the relationship must be characterized for comparison. This was accomplished here through 1) fitting standard models to the response curves and 2) producing response corridors.

Model Fits

As described previously, the various models were fit to either the full region of thoracic loading or the region from 5% deflection to peak, removing the toe region from consideration. These regions are shown in Figure 19.

![Figure 19](image)

Figure 19: Complete S-D curve (left). S-D curve for thoracic loading only (center). S-D curve for 5% deflection to peak deflection during loading (right).

Various standard models, including linear, exponential, and power models, were fit to the S-D response as described in the methods. Examples of the models for the individual ribs are plotted in Figure 20 along with the PMHS response. The ribs represented in Figure 20 are the same two ribs represented in Figure 17 earlier, the left third rib on PMHS 1 and PMHS 2.
In working toward HBM application, a practical approach would be to have a target model for each rib level, representing a typical response for those ribs across subjects. Thus the models were fit to the combined set of responses for each rib level. Figure 21 shows the S-D responses for ribs level 3 and 5, along with their best-fit models. The basic linear model could not be applied to the combined dataset as it is calculated from only a single point for an individual response curve.
The values for each of the model parameters accompanied by the $r^2$ value for the model are presented in Table 3. The 95% confidence intervals for the model parameters are included in Appendix B. The piecewise linear and power models had nearly identical values for $r^2$ at every rib level considered in this study, and they were consistently higher than the $r^2$ values for the exponential models.

<table>
<thead>
<tr>
<th>Rib Level</th>
<th>PL: $S=aD+b$</th>
<th>E1: $S=a\times\exp(bD)-a$</th>
<th>E2: $S=a\times\exp(bD)-a$</th>
<th>Po: $S=a\times(D^b)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>a 87 b -127</td>
<td>$r^2$ 0.70</td>
<td>$a$ 11000 $b$ 0.007 $r^2$ 0.68</td>
<td>$a$ 8400 $b$ 0.007 $r^2$ 0.68</td>
</tr>
<tr>
<td>4</td>
<td>a 154 b -165</td>
<td>$r^2$ 0.61</td>
<td>$a$ 98000 $b$ 0.001 $r^2$ 0.56</td>
<td>$a$ 37000 $b$ 0.003 $r^2$ 0.55</td>
</tr>
<tr>
<td>5</td>
<td>a 249 b -815</td>
<td>$r^2$ 0.69</td>
<td>$a$ 2500 $b$ 0.053 $r^2$ 0.64</td>
<td>$a$ 1900 $b$ 0.062 $r^2$ 0.65</td>
</tr>
<tr>
<td>6</td>
<td>a 156 b 121</td>
<td>$r^2$ 0.42</td>
<td>$a$ 130000 $b$ 0.001 $r^2$ 0.28</td>
<td>$a$ 190000 $b$ 0.001 $r^2$ 0.37</td>
</tr>
<tr>
<td>7</td>
<td>a 111 b -285</td>
<td>$r^2$ 0.32</td>
<td>$a$ 93000 $b$ 0.001 $r^2$ 0.24</td>
<td>$a$ 1400 $b$ 0.36 $r^2$ 0.22</td>
</tr>
<tr>
<td>8</td>
<td>a 120 b -837</td>
<td>$r^2$ 0.33</td>
<td>$a$ 280 $b$ 0.099 $r^2$ 0.31</td>
<td>$a$ 220 $b$ 0.11 $r^2$ 0.31</td>
</tr>
</tbody>
</table>

Table 3. Parameter values for models fit to the S-D response, by rib level. Shaded boxes indicate that they are the highest $r^2$ value for that rib level.

Response Corridors

Presented in Figures 22-Figure 27 are the calculated S-D response corridors for each rib level 3-8. The corridors shown are the mean strain at a given deflection value +/- 1 standard deviation (Kent et al. 2006). In each figure, the PMHS S-D response curves for a particular rib level are shown on the left, the associated response corridor is shown in the center, and the combination is shown on the right. As the response corridors are only extending 1 standard deviation from the mean response value.
at a given deflection, only about two-thirds of the data are expected to fall within the corridor.

Figure 22: PMHS S-D curves for 3rd level ribs (left). S-D response corridor for 3rd level ribs (center). PMHS S-D curves and response corridor for 3rd level ribs (right).

Figure 23: PMHS S-D curves for 4th level ribs (left). S-D response corridor for 4th level ribs (center). PMHS S-D curves and response corridor for 4th level ribs (right).

Figure 24: PMHS S-D curves for 5th level ribs (left). S-D response corridor for 5th level ribs (center). PMHS S-D curves and response corridor for 5th level ribs (right).
Figure 25: PMHS S-D curves for 6th level ribs (left). S-D response corridor for 6th level ribs (center). PMHS S-D curves and response corridor for 6th level ribs (right).

Figure 26: PMHS S-D curves for 7th level ribs (left). S-D response corridor for 7th level ribs (center). PMHS S-D curves and response corridor for 7th level ribs (right).

Figure 27: PMHS S-D curves for 8th level ribs (left). S-D response corridor for 8th level ribs (center). PMHS S-D curves and response corridor for 8th level ribs (right).
Discussion

S-D Curve Shape

The strain-deflection curve portrays how strain increases in a particular rib as the chest deflection increases. In particular, the curves presented in this study describe the strain on the lateral cutaneous aspect of the rib while the chest is deflected. It begins with zero strain at zero deflection, then tensile strain increases as deflection increases.

The general shape of the S-D response curves from the five subjects in this study indicated a 4-part loading phase. The first part is a toe region, where soft tissue is compressing without actually deflecting the ribs and inducing bending strain. The second part is initial loading as the ribs are being deflected. The curve then levels off to a shallower slope, and then increases the slope into a final ascent (Figure 28 left).

The general S-D shape description has qualitative similarities with the description of force-deflection curves, as Kroell et al. (1974) discussed a “plateau force level” and shows an increase in force often occurring soon before reaching peak deflection. The general S-D shape may be subcategorized into a case in which the leveling off never occurs, resulting in only a 2-part loading, which was exhibited in PMHSs 1, 3, and 4 of this study (Figure 28 right).

Consideration of the unloading segment of the curve also provides some hysteresis information. PMHS 1, with the almost linear loading, shows almost no hysteresis (Figure 28 right). PMHS 2, having the nonlinear loading, also exhibited hysteresis (Figure 28 left). Unloading was not considered for the other three subjects due to the confounding role of the ram stoppers interacting with the impactor.
In discussing the shape of the S-D curve, it is noteworthy that the cutaneous aspect of the rib commonly goes into compression in the toe region before moving into tension, as is seen in Figure 16. This is likely attributable to the combination of the loading condition and the placement location of the strain gages. As is shown in Figure 29, the two input forces (the impactor anteriorly and the back fixture posteriorly) act to compress the thorax, and thus a compressive strain should be observed laterally. Then as bending is produced, the cutaneous aspect of the rib moves into tension.

Figure 29: Free-body diagram of the external forces acting on the thorax and how those forces affect the lateral aspect of the rib.
Comparison to Existing Data

Although no previous study could be found which presents or discusses the S-D curve and relationship, Charpail et al. (2005), Li et al. (2010) and Kemper et al. (2011) were a few previous studies which had reported both strain and deflection data. Charpail et al. (2005) conducted isolated rib bending tests and reported peak deflection values for all tested ribs, but only included peak strain values for the 5th level ribs. Li et al. (2010) did similar isolated bending tests on three ribs but only their L4 rib coincided with the ribs in this study. Finally, Kemper et al. (2011) conducted frontal belt loading on 2 PMHS and reported both peak strain and deflection at fracture. The data from the 4th and 5th level ribs from Kemper et al. (2011) were combined with the results from this study for comparison (Figure 30).

In Figure 30, the circles represent each strain-deflection data point obtained from the previous studies, and the dashed/dotted lines leading to the circles represent the assumed linear loading path. Since the data from this study displayed a toe region where the chest was being deflected but the rib was not, the deflections presented in the isolated rib studies (Charpail et al. 2005, Li et al. 2010) were shifted by the 5% deflection value approximating the toe region. Since Kemper et al. (2011) reported the thoracic deflection, the values from that study were directly used for comparison here and it was merely assumed that the strain remained near zero for the first 5% of the reported deflections.
Figure 30: Comparison of data from previous studies to data from this study for 4th level ribs (left) and 5th level ribs (right).

Overall, the data from the previous studies show nice agreement with the data obtained in this study. For each of the 4th and 5th level rib S-D plots there is one comparative data point which lies outside of the main group of data points in this study. However, that is not too alarming as the data from this study also contains a few data points lying apart from the rest of the group. Consistency is particularly observed in the fact that both the Li et al. (2010) data and Charpail et al. (2005) data each have one point which is nearly collinear with data from Kemper et al. (2011), and that in each case those points lie approximately in the center of the main grouping of data from this study.

Response Characterization

The contribution this study makes toward HBM development is to provide direct experimental data, applicable descriptive models, and corridors of the strain response in ribs as a function of chest deflection. The descriptive models were selected as a first step because they are simple models, not because they necessarily represent any known physical relationship between strain and deflection. The S-D plots from some subjects
exhibited a very linear relationship while others showed some amount of curvature. Despite the curvature in some of the data, the piecewise linear model still had the highest $r^2$ value in nearly every case, though the power model was in a close second place. The results from this study may be used by researchers who are seeking to validate rib fracture prediction in HBMIs, such as was done by Poulard et al. (2015) and Guleyupoglu et al. (2017).

Strain as a Function of Deflection

A particularly valuable observation from this study is that it seems apparent that the strain may vary directly as a function of chest deflection. This is why it was sufficient to create response corridors as the mean strain +/- one standard deviation at a given deflection. Some previous studies, in creating force-deflection (F-D) response corridors have used more elaborate methods. Bolte et al. (2003) constructed a response corridor which was +/- one standard deviation in force and also +/- one standard deviation in deflection. Shaw et al. (2006) constructed corridors which utilized an ellipse method, including the variance in both the force and deflection. In both instances, it was indicated that it is necessary to include the variation in both directions because they are both variables. Otherwise stated, the F-D curve is a comparison of $F(t)$ vs. $D(t)$. However, it appeared in this study that the strain varies as a function of deflection, $S(D)$, as is shown in Figure 31.

While the shape of the F-D curve is consistent across different impact velocities, the force trajectory is scaled by the impact velocity and thus the F-D relationship is different for each impact speed. The S-D curves exhibit an important difference from the
F-D curves: the S-D plot trajectory remains consistent across various impact speeds, it simply extends further along that path as higher impact speeds produce higher deflections. This observation will be useful in HBM validation for injury prediction because it provides a direct relationship between existing deflection-based injury criteria and strain-based injury prediction in HBMs. However, as the response corridors included multiple impact speeds, HBMs at this point can only identify an appropriate direction of the S-D trajectory but cannot yet identify how far along that path their response should extend for a particular impact speed. Additionally, as there is subject-to-subject variation in the S-D relationship, it will be most particularly useful in cases of a specific PMHS being modeled to replicate an experimental dataset. Three of the five PMHS were impacted until fractures occurred, and half of the fractures were located approximately 1-2 cm from the strain gage. Thus, in the case of PMHS 1 the data not only conveys the relationship between chest deflection and the lateral strain, but also shows the strain values near the fracture site.

Figure 31: Comparison of F-D curves (left) and S-D curves (right) for three impacts on PMHS 1.
Limitations

The data collected in this study were all from frontal impacts using a linear pneumatic impactor in a restrained-back system. While the data showed a consistent relationship between strain and deflection, even among different impact speeds, the same may not be true for free-back, airbag, or seatbelt loading conditions. Furthermore, the strain gages were located on the lateral aspect of the rib for this study, so the relationships observed here only apply to said aspect. Further testing considering other regions of the rib, such as the anterior or posterior portions, would be of value in characterizing the relationship between chest deflection and strain throughout the entire rib. Finally, only 5 PMHS were used in this study, and the majority of the test data came from only 2 PMHS. With additional testing, the dataset can be expanded and the strength of the results will likely be increased. Nonetheless, the results of this study provide an initial idea of the relationship between lateral rib strain and chest deflection.

Future Work

There are several ways in which this work can be built upon and expanded. First, only basic, generic models were applied to the S-D curves. The next step in the model description is to derive the theoretical, subject-specific S-D relationship from solid mechanics and add that model to the set. Another future step is in the response corridors. The corridors presented here were constructed using available data containing different impact speeds, which is not ideal. As the dataset is expanded, corridors should be constructed for individual impact speeds.
Acknowledgements

The author acknowledges the help of Michelle Murach for collecting and analyzing some of the data contained within this study. The author also acknowledges the support of Autoliv in sponsoring the research activities. Funding for the student was provided by the National Science Foundation’s Graduate Research Fellowship Program, NSF grant no. DGE-1343012. The views stated herein are those of the author, and not of the funding entities. Further, we are greatly indebted to the donors and families for their generous gift to further scientific inquiry.
Chapter 4: Thoracic Response of Small, Osteopenic, Elderly Females in Side Impact Vehicular Crashes

Abstract

Thoracic injury criteria have been previously developed to predict thoracic injury for vehicle occupants as a function of biomechanical response. Historically, biomechanical testing of post-mortem human surrogates (PMHS) for injury criteria development has primarily been focused on mid-sized males. Response targets and injury criteria for other demographics, including small females, have been determined by scaling values from mid-sized males. The objective of this study was to provide response and injury data from small, elderly females which can contribute to future injury criteria development based on representative data. Two PMHS were subjected to a side-impact loading condition which replicates a near-side, MDB-to-vehicle impact for the driver. This was accomplished using the Advanced Side Impact System, or ASIS, on a HYGE sled. The sled acceleration matched the acceleration profile of an impacted vehicle, while the four pneumatic cylinders of the ASIS produced realistic door intrusion. Subjects were targeted to be elderly females age 60+, approximately 5th percentile in height and weight, with osteopenic bone mineral density. Each subject was placed in a mass-production driver seat equipped with a side airbag, and was restrained with a 3-point belt.
Instrumentation on the test structure included accelerometers on the sled and ASIS intrusion cylinders along with four seatbelt load cells. Instrumentation on each PMHS included strain gages on ribs 3-10 bilaterally. Two chestbands were used to measure chest deflection, one at the level of the axilla and one at the level of the xiphoid process. Additionally, 6DXPro motion blocks were placed on T1, T4, T12, and S1 vertebrae, as well as on the manubrium and left ilium. Finally, a 6aω tetrahedron was placed on the head. A full anatomical dissection was performed subsequent to each impact and AIS injury codes were assigned to the observed injuries. Fracture timings were identified using the strain gage readings. Observed injuries were primarily rib fractures, located near the two ends of the ribs. Both subjects experienced AIS = 3 injury severities, but their response values were in the AIS<3 prediction range from previous studies, thus demonstrating the need for data representing vulnerable populations.

Introduction

Approximately 6 million motor vehicle crashes occur each year in the United States, and 28% of these result in injuries or fatalities (NHTSA 2016). Among these fatal and injurious crashes, 55% are frontal crashes, 18% are side crashes, and 27% are in other modalities. Consequently, frontal collisions have been the focus of much research and developmental advancement over the past half century (Kent et al. 2005a, Poulard et al. 2013). However, among all fatal and injurious crashes in the US, the side impact crashes have the highest fatality rate, nearly 11 fatalities per 1000 collisions compared to 8 fatalities per 1000 collisions for frontal (NHTSA 2016).
Growing interest in protecting vehicle occupants involved in side impact has led to advancements such as the side airbag and inflatable curtain, as well as improved structural design of the vehicle. Refinement is still needed however, to maximize protection provided to the vehicle occupants (Yoganandan et al. 2007). Side impact sled testing has been conducted on PMHS in several studies in the past (Melvin 1976, Cavanaugh et al. 1990, Pintar et al. 1997, Kuppa et al. 2003, Yoganandan et al. 2012a). However, previous work has been focused on the mid-sized male.

Demographics in the US are changing as the elderly segment of the population grows (He et al. 2016). With an increasing number of elderly occupants in vehicles on the road, the National Highway Traffic Safety Administration (NHTSA) has shown interest in protecting this vulnerable segment of the population (NHTSA 2013). Furthermore, Hill et al. (2006) found that older females have the greatest risk for severe injury in frontal, side, and rear collisions when compared to other demographic groups. The need to design for vulnerable occupants has a tremendous impact on the design of safety systems because these occupants are more fragile than healthy young and middle-aged adults. As such, it is important for PMHS data to be collected for vulnerable populations, and not just the mid-sized male.

Some previous work has been done to study the response of small elderly females. The majority of the reported data has been for frontal impact (Crandall et al. 1998, Kent et al. 2003a, Kent et al. 2003b, Shaw et al. 2017). Some work has also considered side impact, but still has not yet led to injury criteria derived strictly from small female data (Yoganandan et al. 2005, Baudrit et al. 2014). The purpose of this study is to present
response and injury data for small, fragile females in side impact. The intent is that these results might be combined with future impact tests to establish injury criteria for small females which are derived directly from small female PMHS responses.

Materials and Methods

Epidemiology Study

Although some previous studies, such as by Hill and Boyle (2006), have shown certain demographic groups to be at particular risk for injury in automotive crashes, an epidemiology study was undertaken in the Injury Biomechanics Research Center to identify the segment of the population at greatest risk for severe injury in side impact. The epidemiology work was conducted by Ramachandra et al. (2017), and the results are shown here with permission (Figure 32). The epidemiology study utilized data from the NASS/CDS database, years 2000-2011. Inclusion criteria were for vehicle model years 2000 or newer, near-side impact, and driver or right front passenger.

![Figure 32. Risk of AIS 3+ injury to vehicle occupants engaged in near-side impact, grouped by male (left) and female (right) from Ramachandra et al. (2017)](image)
Three key observations came from the epidemiology study, which are apparent in Figure 32. First, risk for serious injury increases for elderly occupants. Second, elderly females are at higher risk for serious injury than elderly males. Third, the thorax is the body region most likely to sustain the serious injuries. Because of these observations, the side impact study presented here is focused on studying thoracic response and injuries in elderly females.

**Subject Selection**

Subjects were selected for inclusion in the study which were female, age 60+, approximately 5th percentile height and weight, and who were osteopenic (Kanis et al. 1994). The sex and age criteria were selected to correspond with the results of the epidemiology study. The size criteria were selected to correspond with the SID-IIs anthropomorphic test device (ATD), and were given a range of 136-166 cm height and 42-56 kg weight. Because the study is targeting a very vulnerable population group, the osteopenic range for bone mineral density (BMD) was selected, which is a T-score between -1 and -2.5 (Kanis et al. 1994).

Each subject was tested for bloodborne pathogens prior to selection. Subsequently the areal BMD was obtained using dual-energy x-ray absorptiometry and the T-score for the lumbar spine was evaluated to determine eligibility. A CT scan was performed to screen for pre-existing injuries, and additional CT scans were performed after subject instrumentation and after impact. The breasts were removed during subject preparation in order to eliminate their influence on thoracic response. Anthropometry measurements
were taken prior to instrumenting the subject, and the anthropometry data is contained in Table 4.

Two PMHS were tested in the study, both representing the two extrema of the selection ranges. The first was 61 years old, 166 cm in height, 56 kg in weight, and had a T-score of -2.0. The second subject was much smaller, being 83 years old, 155 cm in height, 44 kg in weight, with a T-score of -1.6.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>PMHS 1</th>
<th>PMHS 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex</td>
<td>F</td>
<td>F</td>
</tr>
<tr>
<td>Age</td>
<td>61</td>
<td>83</td>
</tr>
<tr>
<td>aBMD T-score</td>
<td>-2.0</td>
<td>-1.6</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>56</td>
<td>44</td>
</tr>
<tr>
<td>Stature (cm)</td>
<td>166</td>
<td>155</td>
</tr>
<tr>
<td>Chest Breadth at Axilla (cm)</td>
<td>29</td>
<td>23.5</td>
</tr>
<tr>
<td>Chest Breadth at Xiphoid Process (cm)</td>
<td>25.5</td>
<td>23.5</td>
</tr>
<tr>
<td>Chest Circumference at Axilla (cm)</td>
<td>78.5</td>
<td>79</td>
</tr>
<tr>
<td>Chest Circumference at Xiphoid Process (cm)</td>
<td>72.5</td>
<td>78</td>
</tr>
<tr>
<td>Chest Depth at Axilla (cm)</td>
<td>12</td>
<td>17</td>
</tr>
<tr>
<td>Chest Depth at Xiphoid Process (cm)</td>
<td>15</td>
<td>19</td>
</tr>
<tr>
<td>Seated Height (cm)</td>
<td>81</td>
<td>71</td>
</tr>
</tbody>
</table>

Table 4. Subject information

*Test Setup*

The general test setup simulated an MDB to vehicle side impact collision with a delta V of 50 kmph. The 50 kmph value was selected by the study’s industry sponsor.
through modeling, as an impact velocity targeted to produce AIS=3 injuries. In a near-side collision, the occupant is affected by both the motion of the impacted vehicle as well as by a door intrusion. In this study, the motion of the impacted vehicle was replicated in a HYGE sled at Transportation Research Center Inc. The door intrusion was produced by the Advanced Side Impact System, or ASIS (DSD, Linz, Austria), which was placed on the HYGE sled (see Figure 33). The ASIS had four pneumatic rams, each being independently actuated and controlled. Each cylinder occupied one quadrant of the intruding door, and the cylinder moved its quadrant in accordance with the door motion from a full vehicle test.

![HYGE sled track and ASIS](image)

Figure 33. HYGE sled track which simulated the motion of the impacted vehicle (left), and ASIS which produced a door intrusion (right)

On the ASIS platform, each subject was seated on a standard production seat, equipped with a side airbag. The airbag was extended out from the seat and left with a single fold in the lower half of the bag. Each subject was restrained using a 3-point belt with a pretensioner. The ASIS cylinders were fitted with a standard door liner. No inflatable curtain was used, so a foam block was placed above the door to produce similar
head kinematics. This was deemed acceptable because the focus of the study is thoracic response and injury. In order to have each subject in a realistic driving posture, the head and arms were suspended from overhead rods and the suspension tape was partially cut just prior to the test (see Figure 34).

![Figure 34. Pre-test positioning of the occupant](image)

_**Instrumentation**_

**Test Structure**

The test structure had instrumentation on the sled, the ASIS, the seatbelt, and the airbag. The sled buck was instrumented with 2 accelerometers, redundant in the Y direction. The ASIS had 6 accelerometers, each also in the Y direction. Of the ASIS accelerometers, one was placed on each intrusion cylinder (4 total), and 2 were on the ASIS frame which were redundant with the sled accelerometers. The 3-point restraint
was instrumented with 4 load cells to measure seatbelt tension. The 4 load cells were placed: 1) between the D-ring and retractor, 2) between the D-ring and occupant shoulder, 3) on the shoulder belt segment at the buckle, and 4) on the lap belt segment between occupant hip and the belt anchor point. The side airbag was instrumented with 2 pressure transducers, one at an upper forward location and one at a lower rear location. A table summarizing the instrumentation on the test structure is contained in Appendix C.

Subject Instrumentation

Each subject was instrumented with a combination of strain gages, 6DX Pro motion blocks, chestbands, and a 6αω tetrahedron. The instrumentation setup was nearly identical for the two subjects, but the arrangement of strain gages was adjusted for the second subject as detailed below. An overview of the subject instrumentation is shown in Figure 35.
The strain gages (Model CEA-13-062UW-350/P2, Micro Measurements, Wendell NC) were located on the lateral aspect of the left clavicle, the sternum, the lateral aspect of ribs 4-10, and the posterior aspect of ribs 5-9 on the first subject. The second subject had strain gages on the lateral aspect of the left clavicle, the sternum, the anterior aspect of ribs 2-10 on the left and 3-10 on the right, and the posterior aspect of ribs 5-10 on the left and 5-8 on the right. Tables showing the strain gage locations are contained in Appendix C. The strain gages were secured to these boney sites using quick drying contact cement and sealed by acrylic (Figure 36). These gages were used to look at strain in the bone at the instrumented sites and to determine the time of failure if the instrumented bones fractured during the event. The instrumented sites were sutured closed before the impact event.
Both subjects were also instrumented with 6DX Pro motion blocks (2000g 18K deg/sec, DTS, Seal Beach CA) on the manubrium, T1 vertebra, T4 vertebra, T12 vertebra, sacrum, and pelvis, Figure 4. A flat mount was used to attach the manubrium block, while a u-shaped mount was attached to the vertebrae. These motion blocks contain 3 accelerometers and 3 angular rate sensors that are used to define the motion of the instrumented bone (Figure 37). All of the six motion blocks were placed on the subject in the same orientation when possible. A table containing details regarding the orientation for each block is contained in Appendix C.
Based on the study presented in chapter 2 of this dissertation, it was decided that chestbands could be used in this study without fear of altering thoracic response. In order to capture chest deflection during the event, 2 chestbands (Humanetics Innovative Solutions, Plymouth MI) were used, one at the level of the axilla and one at the level of the xiphoid process (Figure 35). One chestband had 40 channels on it and the other chestband had 59 channels. For the first subject, the 40 channel chestband was placed at the axilla and the 59 channel chestband was placed at the level of the xiphoid process. The locations for each chestband were switched for the second subject. Each chestband was wrapped around the subject thorax at 10 lbs. of tension and then secured in place. The readings from each channel were then used to digitally reconstruct the chestband contour throughout the event (Figure 38). Chest deflection was calculated from the reconstruction as the change in distance between the two lateral-most points along the chestband.
As the primary focus of the test was to examine thoracic response, most of the subject instrumentation was located on the thorax. However, in order to track head kinematics, a $6\alpha\omega$ tetrahedron was placed on the head (Figure 39). The tetrahedron had 3 faces, each face containing 2 accelerometers (2K, Endevco, Irvine CA) and 1 angular rate sensor (18K deg/sec, DTS, Seal Beach CA). A summary of the instrumentation used on each subject is contained in Appendix C.
Figure 39. 6aω tetrahedron, placed on the occupant head

**Vicon Motion Capture**

In addition to the instrumentation directly placed on the structure and the subject, a Vicon motion capture system was employed. A total of 54 retroreflective markers were placed on the subject and on the test structure to capture point trajectories and segment kinematics. A summary of the marker locations is presented in Table 1 and a detailed list is contained in Appendix C.

<table>
<thead>
<tr>
<th>Location</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASIS frame</td>
<td>10</td>
</tr>
<tr>
<td>Door panel</td>
<td>5</td>
</tr>
<tr>
<td>Seat</td>
<td>5</td>
</tr>
<tr>
<td>Seatbelt</td>
<td>6</td>
</tr>
<tr>
<td>Head</td>
<td>6</td>
</tr>
<tr>
<td>Thorax</td>
<td>4</td>
</tr>
<tr>
<td>Upper limbs</td>
<td>8</td>
</tr>
<tr>
<td>Lower limbs</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 5. Summary of Vicon marker locations
Data Collection and Analysis

All data were collected using a combination of the SlicePro data acquisition system (DTS, Seal Beach CA) belonging to OSU and a KT system belonging to TRC. Both systems collected data at a sampling rate of 20,000 Hz. Time zero was defined in both tests as the time at which the trigger signal actuated the system. All data were filtered during post-processing in Matlab in accordance with SAE J211 guidelines for each channel type using a second order two-directional (phaseless) Butterworth filter. The strain data were numerically differentiated to get strain rate on the ribs. Accelerations from the 6DX Pros were numerically integrated to get velocity and displacement. Resultant accelerations were also calculated for each 6DX Pro as the root sum of squares of all 3 directional accelerations. Chestband processing was completed using CrashStar 2.7 software, which is run in Matlab. Chest deflection was calculated from the chestband data as the change in distance between the two lateral-most gages.

Three high speed cameras were used in both tests, capturing at 1,000 frames per second. The first camera was a frontal view mounted onto the ASIS platform at the height of the umbilicus. The second camera is an offboard frontal view of the event, showing both the occupant kinematics and the motion of the sled. The third view was a view looking down on the subject from overhead. The second test had a fourth camera set up in an offboard oblique view (Figure 40).
Figure 40. The four high speed camera views employed in this study: frontal onboard (top left), frontal offboard (top right), overhead (bottom left), and oblique offboard (bottom right)

Results

Test Input

The test setup and input pulses were designed to replicate an MDB to vehicle side impact with a delta V of 50 kmph. There was some variation in how the equipment performed in the two tests, resulting in some variation to the input case, shown in Figure 41. In the second test, the sled actuated 10 ms later into the sequence than it did on the first test. However, the ASIS was able to compensate for this and maintained a nearly
identical intrusion velocity relative to the occupant for the first 16 ms and also achieved
the same peak value for occupant-relative intrusion velocity. Consequently, input from
the door, as observed by the occupant, was close to the same for both tests.

![Sled Velocity](image1)

![Occupant-Relative Intrusion Velocity](image2)

Figure 41. Velocity of the sled for test 1 and test 2 (left) and relative intrusion velocity of
the door with respect to the occupant (right)

There was an observed difference in airbag pressure at the lower port between the
two tests, shown in Figure 42. The pressure deep inside the bag (not near the vents) had
both a faster rise and a higher peak in the second test than in the first test. Additional
plots and further details comparing the two tests are contained in Appendix C.
Injuries

Injuries consisted primarily of rib fractures, but also included a clavicle fracture, fibula fracture, and a spleen laceration. For the damaged bones which were instrumented with strain gages, fracture timings were identified as a sudden, sharp change in strain (Troseille et al. 2008, Kemper et al. 2011, Kemper et al. 2016). Two examples are shown in Figure 43. Plots of strain and strain rate for all gages are contained in Appendix C.
Figure 43. Strain measured during test 2 on the left 7th rib (left) and the left 3rd rib (right). Fracture timing was identified from these as the sudden, sharp change in strain.

Table 6 contains a list of all documented injuries which were attributable to the impact and their time of occurrence within the event, if known. Subject 2 had many more injuries than did subject 1. Interestingly, though, the overall severity according to the AIS coding was the same for both tests at AIS=3. Pictures of the injuries are included in Appendix C. There were a few additional injuries observed, but which were deemed to be not attributable to the impact. These injuries on test 1 were fractures to the left radius and left ulna, attributed to a screw placed in the radius, and a sternum fracture where there was a pre-existing defect. For test 2, the coccyx was fractured.
Table 6. Documented injuries in the two side impact tests

**Test 1 Injuries**

<table>
<thead>
<tr>
<th>Part</th>
<th>Description</th>
<th>Time</th>
<th>Part</th>
<th>Description</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rib L2</td>
<td>Fracture, anterior</td>
<td>N/A</td>
<td>Rib L6</td>
<td>Fracture, anterior</td>
<td>39 ms</td>
</tr>
<tr>
<td>Rib L3</td>
<td>Fracture, anterior</td>
<td>N/A</td>
<td>Rib R4</td>
<td>Fracture, anterior</td>
<td>47 ms</td>
</tr>
<tr>
<td>Rib L4</td>
<td>Fracture, anterior</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Test 2 Injuries**

<table>
<thead>
<tr>
<th>Part</th>
<th>Description</th>
<th>Time</th>
<th>Part</th>
<th>Description</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spleen</td>
<td>Laceration, inferior</td>
<td>N/A</td>
<td>Rib L6</td>
<td>Fracture, posterior</td>
<td>29 ms</td>
</tr>
<tr>
<td>L. Fibula</td>
<td>Fracture, proximal</td>
<td>~35 ms</td>
<td>Rib L7</td>
<td>Fracture, anterior</td>
<td>19 ms</td>
</tr>
<tr>
<td>L. Clavicle</td>
<td>Fracture, distal</td>
<td>20 ms</td>
<td>Rib L7</td>
<td>Fracture, posterior</td>
<td>29 ms</td>
</tr>
<tr>
<td>Rib L3</td>
<td>Fracture, anterior</td>
<td>26 ms</td>
<td>Rib L8</td>
<td>Fracture, posterior</td>
<td>29 ms</td>
</tr>
<tr>
<td>Rib L3</td>
<td>Fracture, anterior</td>
<td>N/A</td>
<td>Rib R3</td>
<td>Fracture, anterior</td>
<td>26 ms</td>
</tr>
<tr>
<td>Rib L4</td>
<td>Fracture, anterior</td>
<td>27 ms</td>
<td>Rib R4</td>
<td>Fracture, anterior</td>
<td>31 ms</td>
</tr>
<tr>
<td>Rib L4</td>
<td>Fracture, posterior</td>
<td>N/A</td>
<td>Rib R5</td>
<td>Fracture, anterior</td>
<td>38 ms</td>
</tr>
<tr>
<td>Rib L5</td>
<td>Fracture, anterior</td>
<td>21 ms</td>
<td>Rib R6</td>
<td>Fracture, anterior</td>
<td>39 ms</td>
</tr>
<tr>
<td>Rib L5</td>
<td>Fracture, posterior</td>
<td>29 ms</td>
<td>Rib R7</td>
<td>Fracture, anterior</td>
<td>N/A</td>
</tr>
<tr>
<td>Rib L6</td>
<td>Fracture, anterior</td>
<td>20 ms</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Occupant Acceleration*

Peak lateral acceleration (to the occupant right) and resultant acceleration values for each of the two tests are presented in Table 7. The general trend observed in the peak acceleration values along the spine is that lateral acceleration is highest in the superior spine and is lower in the inferior spine. The resultant acceleration values, in nearly every case, are only slightly higher than the lateral acceleration, indicating that nearly all of the acceleration is in the lateral direction. The exception is the manubrium acceleration in test 2, which had a resultant acceleration 45% higher than the lateral acceleration.
Peak Accelerations (m/s²)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Test 1 Lateral</th>
<th>Test 1 Resultant</th>
<th>Test 2 Lateral</th>
<th>Test 2 Resultant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manubrium</td>
<td>386</td>
<td>399</td>
<td>697</td>
<td>1,012</td>
</tr>
<tr>
<td>T1</td>
<td>450</td>
<td>463</td>
<td>531</td>
<td>543</td>
</tr>
<tr>
<td>T4</td>
<td>376</td>
<td>378</td>
<td>533</td>
<td>537</td>
</tr>
<tr>
<td>T12</td>
<td>342</td>
<td>368</td>
<td>564</td>
<td>634</td>
</tr>
<tr>
<td>Sacrum</td>
<td>267</td>
<td>278</td>
<td>263</td>
<td>272</td>
</tr>
<tr>
<td>Pelvis</td>
<td>306</td>
<td>307</td>
<td>247</td>
<td>260</td>
</tr>
</tbody>
</table>

Table 7. Table of maximum acceleration values

In order to visualize the motion happening in the upper thorax, the lateral and A/P accelerations as a function of time are shown for both the manubrium and the T4 vertebra in each of the tests in Figure 44. Similar general trends and shapes are observed in the accelerations between the two tests, though there are also some large differences in magnitude, especially in the A/P direction. This shows why the resultant acceleration was higher for the manubrium in test 2.
Figure 44. Acceleration vs. time during impact for the manubrium and T4 vertebra in the lateral direction (top) and A/P direction (bottom) in test 1 (left) and test 2 (right)

**Chest Deflection**

Chest deflection was calculated as the change in distance between the two lateral-most points on the chestband from the pre-impact contour. Deflection values for each chestband were then divided by the initial chest breadth at that location to obtain percent deflection, shown in Figure 45. Having noted the high manubrium A/P accelerations shown earlier in Figure 44, the motion was further analyzed for the first 25 ms of the event by integrating the manubrium and T4 accelerations twice to get displacements. The difference between the manubrium and T4 A/P displacements was then taken and divided by the initial axillary chest depth to arrive at an approximate percent deflection. These
approximate A/P deflection values are shown in Figure 45 along with the lateral deflections.

Figure 45. Percent lateral chest deflection for the axillary and xiphoid level chestbands on both tests, accompanied by approximate A/P deflection from the manubrium to the T4 vertebra

Seatbelt Force

Load cells on the seatbelt recorded tension in the belt. The peak values read by each of the four load cells are contained in Table 8 and plots of the seatbelt load cell force versus time are contained in Appendix C. Similar peak magnitudes are observed for both tests at the retractor, shoulder, and buckle locations, while the anchor location saw forces approximately 5 times the magnitude observed in the first test.
<table>
<thead>
<tr>
<th>Location</th>
<th>Test 1 Peak (N)</th>
<th>Test 2 Peak (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retractor</td>
<td>1812</td>
<td>2090</td>
</tr>
<tr>
<td>Shoulder</td>
<td>945</td>
<td>796</td>
</tr>
<tr>
<td>Buckle</td>
<td>1157</td>
<td>945</td>
</tr>
<tr>
<td>Anchor</td>
<td>265</td>
<td>1189</td>
</tr>
</tbody>
</table>

Table 8. Seatbelt tension values from both tests

Discussion

Previous side impact sled tests have been designed to produce a particular impact velocity to the occupant such as 6.7, 9, and 12 m/s, which correspond to 25, 33, and 43 kmph (Melvin et al. 1976, Cavanaugh et al. 1993, Pintar et al. 1997, Kuppa et al. 2003, Yoganandan et al. 2005, Yoganandan et al. 2012b). No indication, however, was given to what vehicle crash speed might correspond to the selected occupant impact speeds. This study, however, took the approach of simulating a particular vehicle crash scenario rather than controlling for specific impact velocity on the occupant. The selected crash scenario was an MDB to vehicle impact in the same configuration as used in the NCAP, with a delta V of 50 kmph. The delta V of 50 kmph was selected, rather than the standard NCAP speed of 63 kmph, from computational simulations which indicated 50 kmph as the optimal speed for observing AIS = 3 injuries. In examining the occupant-relative intrusion velocities in Figure 11, it is observed that the relative intrusion speed was 5 m/s at the time the airbag became engaged with the occupant, rose to a peak intrusion rate of 12 m/s during airbag ride-down, and was 2 m/s at the time the thorax engaged the door directly.
The injuries observed in this study were mostly rib fractures. The most common location for the rib fractures was near the sternal end of the rib, and the second most common location was near the vertebral end of the rib. Melvin et al. (1976) reported specific injuries which illustrated the same fracture pattern as this study.

The mechanism and timing of injuries were quite different between the two tests. Timing of fractures from Table 6 were used to determine the loading conditions in the response data and the high speed video. PMHS 1 had two rib fractures for which timing could be determined, and the earlier fracture occurred at 39 ms into the event, corresponding to peak lateral chest deflection (Figure 45). The timing also corresponded to interactions between the occupant and the door after the airbag had deflated. For PMHS 2, the first three rib fractures occurred at 19, 20, and 21 ms into the event, corresponding to the peak airbag pressure (Figure 42) and the peak A/P chest deflection being produced by the seatbelt pretensioner (Figure 45). The timing of these fractures also corresponded to interactions between the occupant and the airbag.

Peak chest deflection values in this study were in the range of 12-20% of chest breadth. While the timing of the first identifiable rib fracture in test one corresponded to peak lateral deflection, the second test was much different, with the first three rib fractures occurring at less than 5% deflection. Kuppa et al. (2003) reported injury outcome vs. chest deflection, and both tests in this study had deflections which fall in their AIS<3 prediction range. Yoganandan et al. (2005) reported chest deflection time-histories for small females in multiple impact conditions, and the padded wall condition most closely matched the conditions of this study. The chest deflection time-histories of
the current study each had a similar shape and peak value as was reported by Yoganandan *et al.* (2005), but the deflections in this study had a shallower rise up to the peak with the peak occurring 5 ms later into the impact. This indicates that the airbag is a softer cushion than the foam which was used in previous work.

Pintar *et al.* (1997) reported peak lateral acceleration of the T12 vertebra, which was also measured in this study. The peak lateral accelerations of the thorax from tests in this study (Table 3) were most similar to the peak accelerations of the 24 km/h and 32 km/h impacts on the padded wall conducted by Pintar *et al.* (1997). Additionally, Kuppa *et al.* (2003) reported AIS injury level vs. resultant upper spine acceleration. The resultant peak acceleration values for T1 in the two impacts from this study correspond to AIS<3 and AIS3+ in Kuppa *et al.* (2003). For both chest deflection and spine acceleration, the subjects in this study experienced more severe injuries at lower response values when compared to the subjects examined by Kuppa *et al.* (2003). This once again highlights the need for data representing vulnerable populations. Yoganandan *et al.* (2005) reported upper spine, lower spine, and sacrum acceleration time-histories, and just like chest deflection, the time-histories in this study had similar shape and peak values but a longer time to peak.

A noticeable inconsistency between tests in this study was the response of the manubrium (Table 3). While all of the peak lateral acceleration values except the pelvis were higher in test 2 than in test 1, the difference was much greater in the manubrium than in the other locations. Furthermore, the manubrium had significant non-lateral contributions to acceleration in test 2, observed in the higher resultant value. Figure 44
shows that in test 1, the motion of the manubrium was very similar to the motion of the T4 vertebra. However, in test 2 it is observed that the manubrium has a quicker and more extreme response than T4 in both the lateral and A/P directions. These observations seem to indicate that the thorax of subject 1 moved somewhat as a rigid structure while the thorax of subject 2 was more deformable.

Acknowledgements

The author also acknowledges the support of Autoliv in sponsoring a portion of the research activities. Funding for the student was provided by the National Science Foundation’s Graduate Research Fellowship Program, NSF grant no. DGE-1343012. The views stated herein are those of the author, and not of the funding entities. Finally, we are greatly indebted to the donors and families for their generous gift to further scientific inquiry.
Chapter 5: Summary and Conclusions

The work presented in this dissertation evaluated the response of the human thorax to traumatic impact events. Three studies were discussed, each applying some variation to the impact conditions and the analysis conducted. The first study examined thoracic instrumentation, to assess the legitimacy of data obtained through use of chestbands. The second study introduced and discussed a novel analysis method in which strain is viewed as a function of chest deflection, their relationship having particular relevance in the development and validation of finite element human body models. The final study presented response and injury data for small, fragile, elderly females who are involved in side impact motor vehicle crashes.

Study 1: Chestband Effects

The purpose of the chestband effects study was to determine whether chestbands alter the response of the thorax to impact. As chestbands are commonly used to measure the chest contour throughout the impact event and calculate chest deflection, it is important to know whether the instrument is affecting the system under observation.

In order to assess chestband effects, a series of twenty-two impacts were conducted on two post-mortem human surrogates (PMHS). For each impact, the subject was fitted with either 0, 1, or 2 chestbands and all other test factors were held constant.
This was done at multiple impact speeds to provide multiple points for assessment. Comparisons were then made among impacts conducted at the same speed on the same subject to determine chestband effects on thoracic response. ‘Response’ was divided into two parts for this study, 1) global response describing the response of the thorax as a whole, and 2) local response describing the response of the individual components within the thorax. Global response was defined as chest deflection and thoracic stiffness, and local response was defined as individual rib strain.

Results of the study showed no significant differences in global or local response when chestbands were used. Consequently, it was concluded that chestbands may be used without the fear of them compromising the data by altering the thoracic response.

Study 2: The Strain-Deflection (S-D) Relationship in the Thorax

The purpose of this study was to explore the relationship between lateral rib strain and chest deflection during frontal impacts. The S-D relationship is useful in understanding the relationship between global thoracic response and the specific injuries which occur as the chest is deflected. This understanding has particular implication in bridging the gap between previously established injury criteria and the specific response and injury predictions of finite element human body models.

Impact testing was conducted to examine the S-D relationship. A series of 20 impacts were completed on five PMHS, and chest deflection and lateral rib strain data were collected. The testing configuration included frontal impacts from a 23 kg pneumatic linear impactor with the subject seated against a rigid back fixture. Impacts
were conducted at speeds ranging from 0.8 m/s up to 3.0 m/s. Deflection was limited for three of the subjects in order to allow for the higher impact speeds.

Plots were generated portraying chest deflection on the independent axis and rib strain on the dependent axis. The plots showed several consistencies in the S-D relationship. First, there is an initial toe region in which soft tissue is being compressed but the ribs are not being loaded. The toe region generally constitutes chest deflection up to about 5%. Second, there is next a loading region, which may have a plateau in it for some subjects. The S-D responses were grouped by rib level and five mathematical models were fit to each set of curves. A two-part piecewise linear model, consisting of a strain of zero for a toe region and a linear model for the rib loading region, was found to most accurately represent the relationship between strain and deflection. Response corridors were generated to represent the range of variation in the curve trajectory for each rib level. Finally, it was observed that the trajectory of the S-D curve for a given rib typically remains consistent across impacts, even when those impacts are conducted at different impact velocities within the same loading configuration.

Study 3: Side Impact Response of Small Females

The purpose of this study was to report the thoracic response and injuries of two small female PMHS subjected to a side impact. It is intended that this data may contribute to future development of response corridors and a thoracic injury criterion for small, fragile, elderly females, the products being derived from actual small female data rather than by scaling data from mid-sized males.
The test setup utilized the Advanced Side Impact System (ASIS) on a HYGE sled. The sled produced an underbody motion replicating the motion of the impacted vehicle and the ASIS produced a door intrusion. Subjects were placed on a mass-production driver seat equipped with a side airbag, and restrained with a standard 3-point belt with pretensioner. A mass-production door panel was attached to the intrusion cylinders of the ASIS in order to provide a realistic door interaction for the occupant. Foam was placed where the head normally interacts with the inflatable curtain. The acceleration profiles of the sled and ASIS cylinders were designed to simulate a Side-NCAP configuration, MDB-to-vehicle impact, with a delta V of 50 kmph. During the event, data was collected from chestbands, strain gages, 6DXPro motion blocks, and a 6aω tetrahedron on the subject, as well as from accelerometers, airbag pressure transducers, and seatbelt load cells on the test setup.

Injuries observed were primarily rib fractures, along with a fractured clavicle, fibula, and a spleen laceration. Rib fractures typically occurred first near the sternal end of the ribs on the struck side, followed by fractures near the sternal end on the non-struck side and fractures near the vertebral end on the struck side. PMHS 1 experienced 5 rib fractures, all located near the sternal end of the ribs. PMHS 2 experienced 16 rib fractures, including 4 flail ribs. PMHS 2 also had the non-rib injuries. Despite the differences in injuries, both subjects had MAIS=3 injury severity. The assumed time for which AIS=3 injury severity was reached in test 1 corresponded to peak lateral chest deflection and interaction with the door, while timing of AIS=3 in test 2 corresponded to peak A/P chest deflection, peak airbag pressure, and interaction with the airbag.
Peak lateral chest deflection values ranged from 12-20% and peak lateral spinal acceleration values ranged from 250-600 m/s². It was noted that while most of the lateral acceleration values along the spine and manubrium were similar between tests 1 and 2, the manubrium behavior was quite different. Higher peak accelerations in the A/P direction on test 2 as the pretensioner retracted the belt produced approximately 10% A/P chest deflection.
References


### Appendix A: Supplement to Chapter 2

#### Data Tables

<table>
<thead>
<tr>
<th>Subject #</th>
<th>Impact #</th>
<th># Chestbands</th>
<th>Target Velocity (m/s)</th>
<th>Actual Velocity (m/s)</th>
<th>Peak Absolute Deflection (mm)</th>
<th>Peak Normalized Deflection (mm)</th>
<th>Stiffness (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0.8</td>
<td>0.85</td>
<td>33.51</td>
<td>31.73</td>
<td>10.89</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0.8</td>
<td>0.79</td>
<td>30.41</td>
<td>30.91</td>
<td>12.03</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0.8</td>
<td>0.78</td>
<td>30.36</td>
<td>31.27</td>
<td>11.68</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>1.0</td>
<td>0.92</td>
<td>33.48</td>
<td>36.50</td>
<td>13.27</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0.8</td>
<td>0.83</td>
<td>31.98</td>
<td>30.64</td>
<td>12.13</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>1.5</td>
<td>1.54</td>
<td>46.49</td>
<td>45.30</td>
<td>20.06</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0.8</td>
<td>0.79</td>
<td>30.91</td>
<td>31.21</td>
<td>11.28</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>0.8</td>
<td>0.83</td>
<td>34.43</td>
<td>33.01</td>
<td>10.10</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>1.0</td>
<td>0.98</td>
<td>37.23</td>
<td>38.07</td>
<td>12.94</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>1.5</td>
<td>1.49</td>
<td>46.69</td>
<td>46.88</td>
<td>18.49</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>0.8</td>
<td>0.91</td>
<td>35.28</td>
<td>31.13</td>
<td>12.23</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>2</td>
<td>0.8</td>
<td>0.68</td>
<td>28.57</td>
<td>33.86</td>
<td>10.82</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>2</td>
<td>1.0</td>
<td>0.93</td>
<td>35.30</td>
<td>37.78</td>
<td>13.22</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>2</td>
<td>1.5</td>
<td>1.53</td>
<td>47.79</td>
<td>46.86</td>
<td>19.14</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>2</td>
<td>2.0</td>
<td>2.02</td>
<td>55.47</td>
<td>55.03</td>
<td>24.02</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>0</td>
<td>0.8</td>
<td>0.84</td>
<td>34.11</td>
<td>32.64</td>
<td>10.91</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subject #</th>
<th>Impact #</th>
<th># Chestbands</th>
<th>Target Velocity (m/s)</th>
<th>Actual Velocity (m/s)</th>
<th>Peak Absolute Deflection (mm)</th>
<th>Peak Normalized Deflection (mm)</th>
<th>Stiffness (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1.0</td>
<td>0.96</td>
<td>40.75</td>
<td>42.48</td>
<td>7.09</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>1.0</td>
<td>1.01</td>
<td>43.33</td>
<td>42.95</td>
<td>7.06</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>1.0</td>
<td>1.11</td>
<td>47.23</td>
<td>42.37</td>
<td>7.51</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1.0</td>
<td>1.18</td>
<td>49.07</td>
<td>41.49</td>
<td>8.10</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>1.0</td>
<td>1.16</td>
<td>46.70</td>
<td>40.14</td>
<td>8.09</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>1.0</td>
<td>1.14</td>
<td>47.78</td>
<td>41.92</td>
<td>7.43</td>
<td></td>
</tr>
</tbody>
</table>

Table 9. Global response summary
<table>
<thead>
<tr>
<th>2</th>
<th>1</th>
<th>Subject #</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0</td>
<td>Impact #</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td># Chestbands</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>Target Velocity (m/s)</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>Actual Velocity (m/s)</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>R3 Peak Strain (uS)</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>R4 Peak Strain (uS)</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>R5 Peak Strain (uS)</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>R6 Peak Strain (uS)</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>R7 Peak Strain (uS)</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>R8 Peak Strain (uS)</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>L3 Peak Strain (uS)</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>L4 Peak Strain (uS)</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>L5 Peak Strain (uS)</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>L6 Peak Strain (uS)</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>L7 Peak Strain (uS)</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>L8 Peak Strain (uS)</td>
</tr>
</tbody>
</table>

Table 10. Local response summary
Selected Matlab Codes for Data Processing and Plotting

**Arranging the data**

After importing the data, I arrange it and assign variable names to the channels. This is code from processing the data of PMHS 2.

```matlab
%% Arrage the data into usable variables
%Identify the SlicePro variable names in order
varNames=char('LT','RamPot','RamAcc','R290','R390','R490','R590','R690','R790','R360','R460','R560','R660','R760','L290','L390','L490','L590','L690','L790','L360','L460','L560','L660','L760','L330','L430','L530','L630','L730','L830','LCF1','LCF2','LCF3','LCM1','LCM2','LCM3','DXA1','DXA2','DXA3','DXR1','DXR2','DXR3');

nV=51; %number of data variables
nI=46; %number of impacts

%Create variable names for raw, filtered, and corrected data
addRaw=repmat(char('Raw'),nV,1);
addF=repmat(char('F'),nV,1);
addC=repmat(char('C'),nV,1);

varNamesRaw=strcat(varNames,addRaw);
varNamesF=strcat(varNames,addF);
varNamesC=strcat(varNames,addC);
```

**Data Processing**

This code processed the data from PMHS 2.

```matlab
%% Define basic processing variables

% Variable locations within varNames (51 variables)
LCVars=40:45;
RamVars=[2,3,40,41,42,43,44,45]; %Pot, Accel, Load Cell
SGVars=4:39;
DXVars=46:51;
SubjVars=horzcat(SGVars,DXVars); %Strain Gages, 6DX
NotSGVars=horzcat(1,RamVars,DXVars); %Everything but the SGs
```
% Impact types (columns within the variable)
Baselines=[1,2,3,6,10,14,16,18,20,22,24,26,28,30,32,34,37,39,42,44,46];
FirstTen=1:10;
First18=1:18;
Mid18=15:32;
Last18=29:46;
AllImps=1:46;
All110=[1,2,3,4,5,6,10,14,16,18,20,22,24,26,28,30,32,34,37,39,42,44,46];
All115=[7,8,9];
All120=[11,12,13];
All125=[15,17,19];
All130=[21,23,25];
All135=[27,29,31];
All140=[33,35,36];
All145=[38,40,41];
All150=[43,45];
typeNames=char('All110','All115','All120','All125','All130','All135',
'All140','...','All145','All150','Baselines','FirstTen','First18','Mid18','Last18',
'AllImps');
nVt=size(typeNames,1);
speedNames=char('All110','All115','All120','All125',
'All130','All135','All140','All145','All150');
Vs=size(speedNames,1);
addN=char('N');
for i=SGVars
  SGNormVars(i,:)=strcat(varNames(i,:),addN);
end
%nSG=size(SGNormVars,1);

% Impacts in which thoracic changes are observed
% Change times R2-R8,L2-L8
ThoraxChanges=char('[47]', '[19]', '[11]', '[9,11,36]', '[8,9,38]',
', ...', '[11,12,13,15,38,45]', '[7,21]', '[47]', '[17]', '[13,15]',
', ...', '[8,9]', '[13,15]', '[15]', '[47]');
ThoraxChanges=char('[0]', '[0]', '[0]',
', ...', '[47,48]', '[19,48]', '[11,48]', '[9,36,48]', '[8,9,38,48]', '[15,38,48]',
', ...', '[19,48]', '[11,48]', '[9,36,48]', '[8,9,38,48]', '[15,38,48]', '[7,21,48]',
', ...', '[19,48]', '[11,48]', '[9,36,48]', '[8,9,38,48]', '[15,38,48]', '[7,21,48]',
', ...', '[47,48]', '[17,48]', '[13,15,48]', '[8,9,48]', '[13,15,48]', '[15,48]'
', ...', '[17,48]', '[13,15,48]', '[8,9,48]', '[13,15,48]', '[15,48]', '[47,48]'
', ...'}
%Ranges within varNames which group strain gages by location
range30=[16:21,34:39];
range60=[10:15,28:33];
range90=[4:9,22:27];

% Points of significance within each impact (row within the variable)
Init=1:200;
PreAct=16002;
% Act=
PreImp=19875:19975;
Imp=20002;
InitV=1:20;
% Act=
PreImpV=975:999;
ImpV=1001;

dt=1/20000;
dtV=1/1000;
ChestDepth=250; %mm
% Filter the data

% Set up the second-order butterworth filters for cutoff frequencies of 300 Hz
[bf,af]=butter(2,0.03);
[bfV,afV]=butter(2,0.6);

% Filter the SlicePro data
for i=1:nV
    for j=1:nI
        eval(strcat(varNamesF(i,:),',(:,j)=filtfilt(bf,af,',',varNamesRaw(i,:,')(:,j)));
    end
end

% Filter the Vicon data
for i=1:3
    for j=1:10
        eval(strcat(varNamesVF(i,:),',(:,j)=filtfilt(bfV,afV,',',varNamesVRaw(i,:,')(:,j)));
    end
end
%% Correct any bias and polarity issues
% Unbias all data
for i=1:nV
    for j=1:nI
        eval(strcat(varNamesC(i,:),'(:,j)=',varNamesF(i,:),'(:,j)-mean(','varNamesF(i,:),'(Init,j));'))
    end
end
for i=1:nVV
    for j=1:nIV
        eval(strcat(varNamesVC(i,:),'(:,j)=',varNamesVF(i,:),'(:,j)-mean(','varNamesVF(i,:),'(InitV,j));'))
    end
end

% Correct polarities
RamPotC=-RamPotC;
RamAccC=-RamAccC*9.81;  %Convert acceleration to m/s^2
LCF3C=-LCF3C;
for i=4:39
    eval(strcat(varNamesC(i,:),'=-',varNamesC(i,:),';'))
end

%% Copy the filtered, corrected data into the variables without suffixes
for i=1:nV
    eval(strcat(varNames(i,:),'=',varNamesC(i,:),';'))
end
for i=1:nVV
    eval(strcat(varNamesV(i,:),'=',varNamesVC(i,:),';'))
end

%% To conserve memory, clear unnecessary variables
% All filtered and corrected data variables
for i=1:nV
    eval(char(strcat('clear ',{ ' '},varNamesC(i,:))));
eval(char(strcat('clear ',{ ' '},varNamesF(i,:))));
end
for i=1:nVV
    eval(char(strcat('clear ',{ ' '},varNamesVC(i,:))));
eval(char(strcat('clear ',{ ' '},varNamesVF(i,:))));
end
% Also clear the raw variables for all but the strain gages
for i=NotSGVars
    eval(char(strcat('clear ',{ ' '},varNamesRaw(i,:))));
end
for i=1:nVV
    eval(char(strcat('clear ',{ ' '},varNamesVRaw(i,:))));
end
% Temporary variables
clear addC; clear addCV; clear addF; clear addFV; clearaddin;
clear addRaw;
clear addRawV; clear sTemp; clear tempData; clear tempFile; clear tempName;
clear tempRange; clear vT; clear vTV; clear zero10row;

%% Calculate chest deflection and peak deflection
% Use Vicon displacement data for impacts 1-7
for i=0:3250
    ChestDef(i*20+2,1:7)=RamDV(i+2,1:7)-RamDV(ImpV+1,1:7);
end
ChestDef(1,1:7)=ChestDef(2,1:7);
for i=0:3249
    k=i*20+2;
    l=1;
    for j=k+1:k+19
        ChestDef(j,1:7)=((ChestDef(k+20,1:7)-ChestDef(k,1:7))*(l/20))+ChestDef(k,1:7);
        l=l+1;
    end
end
% Use Ram Pot data for impacts 8-46
for i=8:nI
    ChestDef(:,i)=RamPot(:,i)-RamPot(Imp,i);
end
% Identify the deflection peaks
for i=1:nI
    ChestDefPeaks(i)=max(ChestDef(:,i));
end

%% Calculate Ram Velocity
% Differentiate the ram displacement to get ram velocity
RamVel=diff(ChestDef/1000)/dt;
for j=1:nI
    RamVel(:,j)=filtfilt(bf,af,RamVel(:,j));
end
% Identify impact velocity
ImpVel=RamVel(Imp,:);
for i=1:nVs
    eval(strcat('temp=',speedNames(i,:),',');)
    ImpVelAve(i)=mean(ImpVel(temp));
    clear temp
end
% Calculate impact velocity by integrating accelerometer data
ImpVelA=trapz(timeSP(PreAct:Imp),RamAcc(PreAct:Imp,:));

%% Normalize the chest deflection and strains
for i=1:nVs
eval(strcat('temp=',speedNames(i,:),'\';'))
for j=temp
    ChestDefN(:,j)=ChestDef(:,j)*ImpVelAve(i)/ImpVel(j);
end

[ChestDefNPeaks(j), ChestDefNPeakTimes(j)]=max(ChestDefN(:,j));
for k=SGVars
eval(strcat(SGNormVars(k,:),'(:,j)='\',varNames(k,:),'(:,j)*ImpVelAve(i)/ImpVel(j);'))
end
end
clear temp
end

%% Inertially compensate the load cell
% LCF3 is the measurement of interest in the load cell (impactor force)
mass=1.86; %kg
LCF3=LCF3-(RamAcc*mass);

%% Calculate Chest Stiffness via stored energy
for i=AllImps
    PE(i)=trapz(ChestDef(:,i),LCF3(:,i));
    K_energy(i)=2*PE(i)/(ChestDefPeaks(i)^2);
end

%% Identify peak strains for each gage (rows) for each impact (columns)
for i=SGVars
    for j=AllImps
        eval(strcat('strainPeaks(i,j)=max(abs(','\',varNames(i,:),')(:,j)));'))
        eval(strcat('strainPeaksN(i,j)=max(abs(','\',SGNormVars(i,:),')(:,j))';))
    end
end
strainPeaks(strainPeaks>15000)=-1000;
strainPeaksN(strainPeaksN>15000)=-1000;

%% Find the range of peak strain within the baseline impacts for each rib
j=1;
for i=range60
    temp=strainPeaksN(i,[1,2,3]); % baseline impacts to be considered
    strainRangeBaselines(j,1)=max(temp); %maximum
    strainRangeBaselines(j,2)=min(temp); %minimum
j=j+1;
end
clear temp
strainRangeBaselines(:,3)=strainRangeBaselines(:,1)-strainRangeBaselines(:,2); % range value
strainRangeBaselines(:,4)=(strainRangeBaselines(:,3)./strainRangeBaselines(:,1))*100; % range of variation as a percent of the maximum value
strainRangeBaselinesAvg=mean(strainRangeBaselines(1:11,4));

%% Find differences in resting strain pre/post impact for each rib in each impact
for i=SGVars
    eval(strcat('temp=',varNames(i,:),','));)
    sizetemp=size(temp,1);
    for j=1:17
        strainDiffs(i,j)=mean(temp(sizetemp-100:sizetemp,j))-mean(temp(1:100,j));
    end
    strainDiffs(abs(strainDiffs)>5000)=0;
    clear temp
    clear sizetemp
end
strainDiffs([1,2,3,33],:)=NaN;
for j=[4,5,7,8],40,41
    strainDiffs([16,17,28],j)=NaN;
end
%% Calculate the S-D slope as S/D
Aext=0:0.2:55;Aext=Aext';Aext=[Aext,ones(size(Aext))];
for i=AllImps
    temp=find(ChestDefN(:,i)>ChestDefNPeaks(i)*0.7);
    %temp=find(R460N(:,i)>strainPeaksN(11,i)*0.5);
    %SDstart(i)=Imp;
    SDstart(i)=temp(1);
    SDlength(i)=size(temp,1);
    SDend(i)=SDstart(i)+SDlength(i);
    fitLength=max(ChestDefNPeakTimes)+10000;
    A(:,1)=ChestDefN(temp,i)*100/ChestDepth;
    A=[A,ones(size(A))];
    for k=SGVars
        %eval(strcat('B=',varNames(k,:),',N(SDstart(i):SDend(i),i);'))
        eval(strcat('B=',varNames(k,:),',N(temp,i);'))
        B(B<0) = 0; %Comment out for linear fit; include for exponential fit
        B=log(B);
        %Comment out for linear fit; include for exponential fit
        X=A\B;
        kSDfit_slope(k,i)=X(1);
kSDfit_int(k,i)=X(2);
eval(strcat(varNames(k,:),'Nfit(:,i)=zeros(fitLength,1);'))

%eval(strcat(varNames(k,:),'Nfit(SDstart(i):SDend(i),i)=exp(A*X);')) %Use =A*X for linear; use =exp(A*X) for exponential
    eval(strcat(varNames(k,:),'Nfit(temp,i)=exp(A*X);')) %Use =A*X for linear; use =exp(A*X) for exponential
    eval(strcat(varNames(k,:),'NfitExt(:,i)=exp(Aext*X);'))
%Use =A*X for linear; use =exp(A*X) for exponential

clear B;clear X;
end

clear A; clear temp;
end

%% Plotting preparations
%Define colors
C1=[0 0 1];
c2=[1 0 0];
c3=[0.2 0.7 0.2];
c4=[0 0 0];
c5=[0 0.7 0.7];
c6=[0.7 0.7 0.2];
c7=[0.5 0.3 0.1];
c8=[0.3 0.6 0.1];
c9=[0.9 0.9 0];
c10=[0.1 0.4 0.7];
c11=[0.5 0.5 0.5];
c12=[0.7 0.3 0.3];
c13=[0 0.7 0.3];
c14=[0.4 0.4 0.7];
c15=[0.7 0.5 0.3];
c16=[0.9 0.1 0.5];
c17=[0.1 0.8 0.5];
c18=[0.6 0.8 0.1];
colors18=[c1;c2;c3;c4;c5;c6;c7;c8;c9;c10;c11;c12;c13;c14;c15;c16;
c17;c18];
%Font sizes
fs1=13;
fs2=11;
fs3=15;

% Create character arrays of impact types for legends
addChar=repmat(char('Char'),nVt,1);
typeNamesChar=strcat(typeNames,addChar);
%BaselinesChar=repmat(char('00'),20,1);
for i=1:nVt
eval(strcat('temp=',typeNames(i,:),',');')
end
for j=1:size(temp,2)
 eval(strcat(typeNamesChar(i,:),'
(j,:)=sprintf(''%02i'' ,temp(j));'
))
end
clear temp
end

OutRight='''Location'',''eastoutside''';

**Plotting**

This code comes from PMHS 1. I changed my approach to coding the analyses and plotting after test 1, so a stylistic change will be observed between this code and the analysis code shown above (which came from PMHS 2). However, the code here is what produced some of the plots in Chapter 2.

%% Create plots of normalized chest deflection (with T4 correction) from ram pot

figure
for i=1:18
 plot(time,ChestDefPot_normC(:,i),'Color',colors18(i,:), 'LineWidth',2);
 hold on
 end
 legend('Test 1','Test 2','Test 3','Test 4','Test 5','Test 6','Test 7','Test 8','Test 9',...
 'Test 10','Test 11','Test 12','Test 13','Test 14','Test 15','Test 16','Test 17','Test 18','location','northeast')
title('Normalized Chest Deflection (Ram Pot) vs. Time','fontsize',fs1)
ylabel('Deflection (mm)','fontsize',fs1)
xlabel('Time (s)','fontsize',fs1)
ylim([0,60])
xlim([-0.05,0.3])

figure
subplot(2,2,1)
 plot(time(contS:contE),ChestDefPot_normC(contS:contE,1), 'Color',colors18(6,:), 'LineWidth',2);hold on
 plot(time(contS:contE),ChestDefPot_normC(contS:contE,2), 'Color',colors18(6,:), 'LineWidth',2);hold on
plot(time(contS:contE),ChestDefPot_normC(contS:contE,3), 'Color', colors18(6,:), 'LineWidth', 2); hold on
plot(time(contS:contE),ChestDefPot_normC(contS:contE,5), 'Color', colors18(6,:), 'LineWidth', 2); hold on
plot(time(contS:contE),ChestDefPot_normC(contS:contE,7), 'Color', colors18(6,:), 'LineWidth', 2); hold on
plot(time(contS:contE),ChestDefPot_normC(contS:contE,8), 'Color', colors18(5,:), 'LineWidth', 2); hold on
plot(time(contS:contE),ChestDefPot_normC(contS:contE,11), 'Color', colors18(6,:), 'LineWidth', 2); hold on
plot(time(contS:contE),ChestDefPot_normC(contS:contE,12), 'Color', colors18(4,:), 'LineWidth', 2); hold on
plot(time(contS:contE),ChestDefPot_normC(contS:contE,13), 'Color', colors18(4,:), 'LineWidth', 2); hold on
plot(time(contS:contE),ChestDefPot_normC(contS:contE,14), 'Color', colors18(4,:), 'LineWidth', 2); hold on
plot(time(contS:contE),ChestDefPot_normC(contS:contE,16), 'Color', colors18(6,:), 'LineWidth', 2); hold on
plot(time(contS:contE),ChestDefPot_normC(contS:contE,18), 'Color', colors18(6,:), 'LineWidth', 2); hold on

title('0.8 m/s', 'FontSize', fs3)
%title('Normalized Chest Deflection (Ram Pot) vs. Time for 0.8m/s', 'FontSize', fs1)
ylabel('Deflection (mm)', 'FontSize', fs1)
xlabel('Time (s)', 'FontSize', fs1)
ylim([0,60])
xlim([0,0.25])

subplot(2,2,2)
plot(time(contS:contE),ChestDefPot_normC(contS:contE,4), 'Color', colors18(6,:), 'LineWidth', 2); hold on
plot(time(contS:contE),ChestDefPot_normC(contS:contE,9), 'Color', colors18(5,:), 'LineWidth', 2); hold on
plot(time(contS:contE),ChestDefPot_normC(contS:contE,10), 'Color', colors18(5,:), 'LineWidth', 2); hold on
plot(time(contS:contE),ChestDefPot_normC(contS:contE,11), 'Color', colors18(6,:), 'LineWidth', 2); hold on
plot(time(contS:contE),ChestDefPot_normC(contS:contE,12), 'Color', colors18(4,:), 'LineWidth', 2); hold on
plot(time(contS:contE),ChestDefPot_normC(contS:contE,13), 'Color', colors18(4,:), 'LineWidth', 2); hold on
%legend('0 Chestbands','1 Chestband','2 Chestbands','location','northwest')

%title('1 m/s', 'FontSize', fs3)
%title('Normalized Chest Deflection (Ram Pot) vs. Time for 1m/s', 'FontSize', fs1)
ylabel('Deflection (mm)', 'FontSize', fs1)
xlabel('Time (s)', 'FontSize', fs1)
ylim([0,60])
xlim([0,0.25])

subplot(2,2,3)
plot(time(contS:contE),ChestDefPot_normC(contS:contE,6), 'Color', colors18(6,:), 'LineWidth', 2); hold on
plot(time(contS:contE),ChestDefPot_normC(contS:contE,10), 'Color', colors18(5,:), 'LineWidth', 2); hold on
plot(time(contS:contE),ChestDefPot_normC(contS:contE,11), 'Color', colors18(5,:), 'LineWidth', 2); hold on
plot(time(contS:contE),ChestDefPot_normC(contS:contE,12), 'Color', colors18(4,:), 'LineWidth', 2); hold on
plot(time(contS:contE),ChestDefPot_normC(contS:contE,13), 'Color', colors18(4,:), 'LineWidth', 2); hold on
%title('1.5 m/s', 'FontSize', fs3)
%title('Normalized Chest Deflection (Ram Pot) vs. Time for 1.5m/s', 'FontSize', fs1)
ylabel('Deflection (mm)', 'fontsize', fs1)
xlabel('Time (s)', 'fontsize', fs1)
ylim([0,60])
xlim([0,0.25])
subplot(2,2,4)
plot(time(contS:contE), ChestDefPot_normC(contS:contE,15), 'Color', colors18(4,:), 'LineWidth', 2); hold on
plot(time(contS:contE), ChestDefPot_normC(contS:contE,17), 'Color', colors18(5,:), 'LineWidth', 2); hold on
title('2 m/s', 'fontsize', fs3)
%title('Normalized Chest Deflection (Ram Pot) vs. Time for
2m/s', 'fontsize', fs1)
ylabel('Deflection (mm)', 'fontsize', fs1)
xlabel('Time (s)', 'fontsize', fs1)
ylim([0,60])
xlim([0,0.25])
figure
subplot(2,2,1)
plot(time(contS:contE), ChestDefPot_normC(contS:contE,1), 'Color', colors18(1,:), 'LineWidth', 2); hold on
plot(time(contS:contE), ChestDefPot_normC(contS:contE,2), 'Color', colors18(2,:), 'LineWidth', 2); hold on
plot(time(contS:contE), ChestDefPot_normC(contS:contE,3), 'Color', colors18(3,:), 'LineWidth', 2); hold on
plot(time(contS:contE), ChestDefPot_normC(contS:contE,5), 'Color', colors18(5,:), 'LineWidth', 2); hold on
plot(time(contS:contE), ChestDefPot_normC(contS:contE,7), 'Color', colors18(7,:), 'LineWidth', 2); hold on
plot(time(contS:contE), ChestDefPot_normC(contS:contE,8), 'Color', colors18(8,:), 'LineWidth', 2); hold on
plot(time(contS:contE), ChestDefPot_normC(contS:contE,11), 'Color', colors18(11,:), 'LineWidth', 2); hold on
plot(time(contS:contE), ChestDefPot_normC(contS:contE,12), 'Color', colors18(12,:), 'LineWidth', 2); hold on
plot(time(contS:contE), ChestDefPot_normC(contS:contE,16), 'Color', colors18(16,:), 'LineWidth', 2); hold on
plot(time(contS:contE), ChestDefPot_normC(contS:contE,18), 'Color', colors18(18,:), 'LineWidth', 2); hold on
title('Normalized Chest Deflection (Ram Pot) vs. Time for
0.8m/s', 'fontsize', fs1)
legend('Test 1','Test 2','Test 3','Test 5','Test 7','Test 8','Test 11','Test 12','Test 16','Test 18', 'location', 'northwest')
ylabel('Deflection (mm)', 'fontsize', fs1)
xlabel('Time (s)', 'fontsize', fs1)
ylim([0,60])
xlim([-0.05,0.3])
subplot(2,2,2)
plot(time(contS:contE), ChestDefPot_normC(contS:contE,4), 'Color', colors18(4,:), 'LineWidth', 2); hold on
plot(time(contS:contE), ChestDefPot_normC(contS:contE,9), 'Color', colors18(9,:), 'LineWidth', 2); hold on
plot(time(contS:contE), ChestDefPot_normC(contS:contE,13), 'Color', colors18(13,:), 'LineWidth', 2); hold on
legend('Test 4', 'Test 9', 'Test 13', 'location', 'northwest')
title('Normalized Chest Deflection (Ram Pot) vs. Time for 1m/s', 'fontsize', fs1)
ylabel('Deflection (mm)', 'fontsize', fs1)
xlabel('Time (s)', 'fontsize', fs1)
ylim([0,60])
xlim([-0.05,0.3])
subplot(2,2,3)
plot(time(contS:contE), ChestDefPot_normC(contS:contE,6), 'Color', colors18(6,:), 'LineWidth', 2); hold on
plot(time(contS:contE), ChestDefPot_normC(contS:contE,10), 'Color', colors18(10,:), 'LineWidth', 2); hold on
plot(time(contS:contE), ChestDefPot_normC(contS:contE,14), 'Color', colors18(14,:), 'LineWidth', 2); hold on
legend('Test 6', 'Test 10', 'Test 14', 'location', 'northwest')
title('Normalized Chest Deflection (Ram Pot) vs. Time for 1.5m/s', 'fontsize', fs1)
ylabel('Deflection (mm)', 'fontsize', fs1)
xlabel('Time (s)', 'fontsize', fs1)
ylim([0,60])
xlim([-0.05,0.3])
subplot(2,2,4)
plot(time(contS:contE), ChestDefPot_normC(contS:contE,15), 'Color', colors18(15,:), 'LineWidth', 2); hold on
plot(time(contS:contE), ChestDefPot_normC(contS:contE,17), 'Color', colors18(17,:), 'LineWidth', 2); hold on
legend('Test 15', 'Test 17', 'location', 'northwest')
title('Normalized Chest Deflection (Ram Pot) vs. Time for 2m/s', 'fontsize', fs1)
ylabel('Deflection (mm)', 'fontsize', fs1)
xlabel('Time (s)', 'fontsize', fs1)
ylim([0,60])
xlim([-0.05,0.3])

%% Plot force deflection
figure
for i=1:18
    plot(ChestDef_potC(:,i),-Fz_comp(:,i), 'Color', colors18(i,:), 'LineWidth', 2);
    hold on
end
legend('Test 1', 'Test 2', 'Test 3', 'Test 4', 'Test 5', 'Test 6', 'Test 7', 'Test 8', 'Test 9',...
'Test 10', 'Test 11', 'Test 12', 'Test 13', 'Test 14', 'Test 15', 'Test 16', 'Test 17', 'Test 18', 'location', 'northeast')
title('Force vs. Chest Deflection (Ram Pot)', 'fontsize', fsl)
ylabel('Force (N)', 'fontsize', fsl)
xlabel('Deflection (mm)', 'fontsize', fsl)
ylim([0,1200])
xlim([0,80])

figure
subplot(2,2,1)
plot(ChestDef_potC(contS:contE,1),-Fz_comp(contS:contE,1),
    'Color', colors18(6,:), 'LineWidth', 2);hold on
plot(ChestDef_potC(contS:contE,2),-Fz_comp(contS:contE,2),
    'Color', colors18(6,:), 'LineWidth', 2);hold on
plot(ChestDef_potC(contS:contE,3),-Fz_comp(contS:contE,3),
    'Color', colors18(6,:), 'LineWidth', 2);hold on
plot(ChestDef_potC(contS:contE,5),-Fz_comp(contS:contE,5),
    'Color', colors18(6,:), 'LineWidth', 2);hold on
plot(ChestDef_potC(contS:contE,7),-Fz_comp(contS:contE,7),
    'Color', colors18(6,:), 'LineWidth', 2);hold on
plot(ChestDef_potC(contS:contE,8),-Fz_comp(contS:contE,8),
    'Color', colors18(6,:), 'LineWidth', 2);hold on
plot(ChestDef_potC(contS:contE,11),-Fz_comp(contS:contE,11),
    'Color', colors18(6,:), 'LineWidth', 2);hold on
plot(ChestDef_potC(contS:contE,12),-Fz_comp(contS:contE,12),
    'Color', colors18(6,:), 'LineWidth', 2);hold on
plot(ChestDef_potC(contS:contE,16),-Fz_comp(contS:contE,16),
    'Color', colors18(6,:), 'LineWidth', 2);hold on
plot(ChestDef_potC(contS:contE,18),-Fz_comp(contS:contE,18),
    'Color', colors18(6,:), 'LineWidth', 2);hold on

%title('Force vs. Chest Deflection (Ram Pot) for 0.8 m/s', 'fontsize', fsl)
ylabel('Force (N)', 'fontsize', fsl)
xlabel('Deflection (mm)', 'fontsize', fsl)
ylim([0,1200])
xlim([0,80])
subplot(2,2,2)
plot(ChestDef_potC(contS:contE,4),-
Fz_comp(contS:contE,4), 'Color', colors18(6,:), 'LineWidth', 2); hold on
plot(ChestDef_potC(contS:contE,9),-
Fz_comp(contS:contE,9), 'Color', colors18(5,:), 'LineWidth', 2); hold on
plot(ChestDef_potC(contS:contE,13),-
Fz_comp(contS:contE,13), 'Color', colors18(4,:), 'LineWidth', 2); hold on
%legend('0 Chestbands','1 Chestband','2 Chestbands','location','northwest')
title('1 m/s', 'fontsize', fs3)
%title('Force vs. Chest Deflection (Ram Pot) for 1m/s', 'fontsize', fs1)
ylabel('Force (N)', 'fontsize', fs1)
xlabel('Deflection (mm)', 'fontsize', fs1)
ylim([0,1200])
xlim([0,60])
subplot(2,2,3)
plot(ChestDef_potC(contS:contE,6),-
Fz_comp(contS:contE,6), 'Color', colors18(6,:), 'LineWidth', 2); hold on
plot(ChestDef_potC(contS:contE,10),-
Fz_comp(contS:contE,10), 'Color', colors18(5,:), 'LineWidth', 2); hold on
plot(ChestDef_potC(contS:contE,14),-
Fz_comp(contS:contE,14), 'Color', colors18(4,:), 'LineWidth', 2); hold on
%title('1.5 m/s', 'fontsize', fs3)
%title('Force vs. Chest Deflection (Ram Pot) for 1.5m/s', 'fontsize', fs1)
ylabel('Force (N)', 'fontsize', fs1)
xlabel('Deflection (mm)', 'fontsize', fs1)
ylim([0,1200])
xlim([0,60])
subplot(2,2,4)
plot(ChestDef_potC(contS:contE,15),-
Fz_comp(contS:contE,15), 'Color', colors18(4,:), 'LineWidth', 2); hold on
plot(ChestDef_potC(contS:contE,17),-
Fz_comp(contS:contE,17), 'Color', colors18(5,:), 'LineWidth', 2); hold on
%title('2 m/s', 'fontsize', fs3)
%title('Force vs. Chest Deflection (Ram Pot) for 2m/s', 'fontsize', fs1)
ylabel('Force (N)', 'fontsize', fs1)
xlabel('Deflection (mm)', 'fontsize', fs1)
ylim([0,1200])
xlim([0,60])
figure
subplot(2,2,1)
plot(ChestDef_potC(contS:contE,1),-Fz_comp(contS:contE,1),'
Color',colors18(1,:),'
LineWidth',2);hold on
plot(ChestDef_potC(contS:contE,2),-Fz_comp(contS:contE,2),'
Color',colors18(2,:),'
LineWidth',2);hold on
plot(ChestDef_potC(contS:contE,3),-Fz_comp(contS:contE,3),'
Color',colors18(3,:),'
LineWidth',2);hold on
plot(ChestDef_potC(contS:contE,5),-Fz_comp(contS:contE,5),'
Color',colors18(5,:),'
LineWidth',2);hold on
plot(ChestDef_potC(contS:contE,7),-Fz_comp(contS:contE,7),'
Color',colors18(7,:),'
LineWidth',2);hold on
plot(ChestDef_potC(contS:contE,8),-Fz_comp(contS:contE,8),'
Color',colors18(8,:),'
LineWidth',2);hold on
plot(ChestDef_potC(contS:contE,11),-Fz_comp(contS:contE,11),'
Color',colors18(11,:),'
LineWidth',2);hold on
plot(ChestDef_potC(contS:contE,12),-Fz_comp(contS:contE,12),'
Color',colors18(12,:),'
LineWidth',2);hold on
plot(ChestDef_potC(contS:contE,16),-Fz_comp(contS:contE,16),'
Color',colors18(16,:),'
LineWidth',2);hold on
plot(ChestDef_potC(contS:contE,18),-Fz_comp(contS:contE,18),'
Color',colors18(18,:),'
LineWidth',2);hold on
legend('Test 1','Test 2','Test 3','Test 5','Test 7','Test 8','Test 11','Test 12','Test 16','Test 18','location','northwest')
title('Force vs. Chest Deflection (Ram Pot) for 0.8m/s',
'fontsize',fs1)
ylabel('Force (N)',
'fontsize',fs1)
xlabel('Deflection (mm)',
'fontsize',fs1)
ylim([0,1200])
xlim([0,70])
subplot(2,2,2)
plot(ChestDef_potC(contS:contE,4),-Fz_comp(contS:contE,4),'
Color',colors18(4,:),'
LineWidth',2);hold on
plot(ChestDef_potC(contS:contE,9),-Fz_comp(contS:contE,9),'
Color',colors18(9,:),'
LineWidth',2);hold on
plot(ChestDef_potC(contS:contE,13),-
Fz_comp(contS:contE,13),'Color',colors18(13,:), 'LineWidth',2);hold on
legend('Test 4', 'Test 9', 'Test 13', 'location', 'northwest')
title('Force vs. Chest Deflection (Ram Pot) for
1m/s', 'fontsize', fs1)
ylabel('Force (N)', 'fontsize', fs1)
xlabel('Deflection (mm)', 'fontsize', fs1)
ylim([0,1200])
xlim([0,70])
subplot(2,2,3)
plot(ChestDef_potC(contS:contE,6),-
Fz_comp(contS:contE,6), 'Color', colors18(6,:), 'LineWidth',2);hold on
plot(ChestDef_potC(contS:contE,10),-
Fz_comp(contS:contE,10), 'Color', colors18(10,:), 'LineWidth',2);hold on
plot(ChestDef_potC(contS:contE,14),-
Fz_comp(contS:contE,14), 'Color', colors18(14,:), 'LineWidth',2);hold on
legend('Test 6', 'Test 10', 'Test 14', 'location', 'northwest')
title('Force vs. Chest Deflection (Ram Pot) for
1.5m/s', 'fontsize', fs1)
ylabel('Force (N)', 'fontsize', fs1)
xlabel('Deflection (mm)', 'fontsize', fs1)
ylim([0,1200])
xlim([0,70])
subplot(2,2,4)
plot(ChestDef_potC(contS:contE,15),-
Fz_comp(contS:contE,15), 'Color', colors18(15,:), 'LineWidth',2);hold on
plot(ChestDef_potC(contS:contE,17),-
Fz_comp(contS:contE,17), 'Color', colors18(17,:), 'LineWidth',2);hold on
legend('Test 15', 'Test 17', 'location', 'northwest')
title('Force vs. Chest Deflection (Ram Pot) for
2m/s', 'fontsize', fs1)
ylabel('Force (N)', 'fontsize', fs1)
xlabel('Deflection (mm)', 'fontsize', fs1)
ylim([0,1200])
xlim([0,70])
Appendix B: Supplement to Chapter 3

Model Fits

Model Parameter Tables

The parameters of best fit for each of the models applied to the S-D curves were presented in Table 3 within Chapter 3. In solving for the best-fit values, the Matlab function ‘fit’ produced not only the best-fit values, but also identified a 95% confidence interval for each. This section contains a table for each model (Table 11-Table 14), presenting the best-fit parameter values along with their 95% confidence intervals. In each table, ‘a-‘ indicates the lower bound on ‘a’ and ‘a+‘ indicates the upper bound on ‘a’. The same is the case for ‘b’.

<table>
<thead>
<tr>
<th>Level</th>
<th>a</th>
<th>a-</th>
<th>a+</th>
<th>b</th>
<th>b-</th>
<th>b+</th>
<th>r2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 3</td>
<td>86.75</td>
<td>86.01</td>
<td>87.49</td>
<td>-126.8</td>
<td>-138.9</td>
<td>-114.7</td>
<td>0.70</td>
</tr>
<tr>
<td>Level 4</td>
<td>154.2</td>
<td>152.5</td>
<td>155.9</td>
<td>-164.8</td>
<td>-192</td>
<td>-137.6</td>
<td>0.61</td>
</tr>
<tr>
<td>Level 5</td>
<td>248.5</td>
<td>245.8</td>
<td>251.2</td>
<td>-815</td>
<td>-852.9</td>
<td>-777</td>
<td>0.69</td>
</tr>
<tr>
<td>Level 6</td>
<td>156</td>
<td>153.1</td>
<td>158.9</td>
<td>121.1</td>
<td>76.98</td>
<td>165.3</td>
<td>0.42</td>
</tr>
<tr>
<td>Level 7</td>
<td>110.9</td>
<td>108.9</td>
<td>112.9</td>
<td>-285.2</td>
<td>-318.4</td>
<td>-252</td>
<td>0.32</td>
</tr>
<tr>
<td>Level 8</td>
<td>119.5</td>
<td>117</td>
<td>121.9</td>
<td>-837.4</td>
<td>-872.9</td>
<td>-801.9</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Table 11. Parameter values for the piecewise linear model (PL) by rib level
Model 3 E1: \( S = (a \exp(bD)) - a \)

<table>
<thead>
<tr>
<th>Level</th>
<th>( a )</th>
<th>( a^- )</th>
<th>( a^+ )</th>
<th>( b )</th>
<th>( b^- )</th>
<th>( b^+ )</th>
<th>( r^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 3</td>
<td>11000</td>
<td>8800</td>
<td>12000</td>
<td>0.0066</td>
<td>0.0055</td>
<td>0.0078</td>
<td>0.68</td>
</tr>
<tr>
<td>Level 4</td>
<td>98000</td>
<td>6200</td>
<td>190000</td>
<td>0.0012</td>
<td>0.0001</td>
<td>0.0024</td>
<td>0.56</td>
</tr>
<tr>
<td>Level 5</td>
<td>2500</td>
<td>2400</td>
<td>2600</td>
<td>0.0534</td>
<td>0.0518</td>
<td>0.0552</td>
<td>0.64</td>
</tr>
<tr>
<td>Level 6</td>
<td>130000</td>
<td>-480000</td>
<td>738800</td>
<td>0.0008</td>
<td>-0.0032</td>
<td>0.0049</td>
<td>0.28</td>
</tr>
<tr>
<td>Level 7</td>
<td>93000</td>
<td>-720000</td>
<td>910000</td>
<td>0.0007</td>
<td>-0.0058</td>
<td>0.0073</td>
<td>0.24</td>
</tr>
<tr>
<td>Level 8</td>
<td>280</td>
<td>256</td>
<td>297</td>
<td>0.0987</td>
<td>0.0954</td>
<td>0.102</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Table 12. Parameter values for the exponential model for rib loading only (E1) by rib level

Model 4 E2: \( S = (a \exp(bD)) - a \)

<table>
<thead>
<tr>
<th>Level</th>
<th>( a )</th>
<th>( a^- )</th>
<th>( a^+ )</th>
<th>( b )</th>
<th>( b^- )</th>
<th>( b^+ )</th>
<th>( r^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 3</td>
<td>8400</td>
<td>6800</td>
<td>9900</td>
<td>0.008</td>
<td>0.007</td>
<td>0.01</td>
<td>0.69</td>
</tr>
<tr>
<td>Level 4</td>
<td>29000</td>
<td>16000</td>
<td>42000</td>
<td>0.004</td>
<td>0.002</td>
<td>0.006</td>
<td>0.57</td>
</tr>
<tr>
<td>Level 5</td>
<td>1930</td>
<td>1870</td>
<td>2000</td>
<td>0.062</td>
<td>0.061</td>
<td>0.063</td>
<td>0.65</td>
</tr>
<tr>
<td>Level 6</td>
<td>190000</td>
<td>--</td>
<td>--</td>
<td>0.001</td>
<td>--</td>
<td>--</td>
<td>0.38</td>
</tr>
<tr>
<td>Level 7</td>
<td>1190</td>
<td>1140</td>
<td>1250</td>
<td>0.038</td>
<td>0.037</td>
<td>0.039</td>
<td>0.22</td>
</tr>
<tr>
<td>Level 8</td>
<td>221</td>
<td>213</td>
<td>229</td>
<td>0.108</td>
<td>0.106</td>
<td>0.109</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Table 13. Parameter values for the exponential model for all thoracic loading (E2) by rib level

Model 5 Po: \( S = a \cdot (D^b) \)

<table>
<thead>
<tr>
<th>Level</th>
<th>( a )</th>
<th>( a^- )</th>
<th>( a^+ )</th>
<th>( b )</th>
<th>( b^- )</th>
<th>( b^+ )</th>
<th>( r^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 3</td>
<td>63</td>
<td>62</td>
<td>65</td>
<td>1.08</td>
<td>1.07</td>
<td>1.09</td>
<td>0.69</td>
</tr>
<tr>
<td>Level 4</td>
<td>123</td>
<td>119</td>
<td>127</td>
<td>1.05</td>
<td>1.04</td>
<td>1.07</td>
<td>0.60</td>
</tr>
<tr>
<td>Level 5</td>
<td>69</td>
<td>66</td>
<td>72</td>
<td>1.37</td>
<td>1.36</td>
<td>1.39</td>
<td>0.68</td>
</tr>
<tr>
<td>Level 6</td>
<td>189</td>
<td>181</td>
<td>198</td>
<td>0.95</td>
<td>0.93</td>
<td>0.96</td>
<td>0.43</td>
</tr>
<tr>
<td>Level 7</td>
<td>70</td>
<td>65</td>
<td>74</td>
<td>1.10</td>
<td>1.08</td>
<td>1.12</td>
<td>0.31</td>
</tr>
<tr>
<td>Level 8</td>
<td>3.8</td>
<td>3.3</td>
<td>4.3</td>
<td>2.01</td>
<td>1.96</td>
<td>2.06</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Table 14. Parameter values for the power model (Po) by rib level
Plots

In chapter 3, Figure 21 presents example plots of the four models fit to the data for rib levels 3 and 5. Only the two plots were presented there in order to provide a visual idea of quality of fit, but to not be cumbersome to the reader. For completeness, the plots for all six rib levels (3-8) are presented here in Figure 46.
Figure 46. S-D curves from rib levels 3-8 for all impacts on all PMHS, plotted by rib level, and shown with four models fit to the data.
Selected Matlab Codes for Data Processing

% SubjVars=char('CB1','CB2','TH');
ImpVars=char('Imp1','Imp2','Imp3','Imp4','Imp5','Imp6','Imp7');
DataVars=char('Time','Deflection','R3','R4','R5','R6','R7','R8',...
   'L3','L4','L5','L6','L7','L8');
SGVars=char('R3','R4','R5','R6','R7','R8',...
   'L3','L4','L5','L6','L7','L8');

nSV=3;
SVs=1:3;
nIV=[7,7,6];
nDV=14;
nSG=12;
SGs=3:14;
Time=1;
Def=2;
R3=3;
R4=4;
R5=5;
R6=6;
R7=7;
R8=8;
L3=9;
L4=10;
L5=11;
L6=12;
L7=13;
L8=14;
Right=3:8;
Left=9:14;
Level3=[3,9];
Level4=[4,10];
Level5=[5,11];
Level6=[6,12];
Level7=[7,13];
Level8=[8,14];
dt=1/20000;

% Bad gages are CB2Imp4-7R6, CB2Imp1-7L8, THImp1-2R3, THImp1-2L3
% Damaged ribs are CB2Imp6-7R4, CB2Imp4-7R5, CB2Imp4-7R8,
% CB2Imp7L4,
% CB2Imp4-7L5, CB2Imp7L6, THImp3-4R6, THImp4L5
GageCheck=ones(3,7,14);
for j=1:7
    GageCheck(2,j,L8)=0;
end
GageCheck(2,4:7,R6)=0;
for j=1:2
    GageCheck(3,j,R3)=0;
    GageCheck(3,j,L3)=0;
end
GageCheck(3,7,:)=0;
for j=6:7
    GageCheck(2,j,R4)=0;
end
for j=4:7
    GageCheck(2,j,R5)=0;
    GageCheck(2,j,R8)=0;
    GageCheck(2,j,L5)=0;
end
GageCheck(2,7,L4)=0;
GageCheck(2,7,L6)=0;
GageCheck(3,3:4,R6)=0;
GageCheck(3,4,L5)=0;

% Strain and deflection values from Li et al 2010 for comparison
% - R2 L4
% L10
LiStrain=[0.65 0.65 0.3]*(10^6)/100; % the 2nd rib is either 0.3 or 0.65, the 10th rib is either 0.3 or 1.6
LiDef=[18.9*100/107.1 41*100/149.9 61*100/171.5];

% Strain and deflection values from Charpail 2005 L5 rib
CharpStrain=[0.89 0.83 1.15 0.51]*(10^6)/100;
CharpDef=[19.4 25.1 16.6 16.9];

% Strain and deflection values from Kemper 2011; use rib levels 4 and 5
KempStrain4=[10800;4300;6500;9200];
KempStrain5=[3600;5500];
KempDef4=[31.6;22.2;24.9;15.8];
KempDef5=[22.6;23.5];

% Identify peak deflection values and timing of them
for i=SVs
    for j=1:nIV(i)
        eval(strcat('temp=',SubjVars(i,:),ImpVars(j,:),':',num2str(Def),','))
        [DefPeak(i,j),DefPeakTime(i,j)]=max(temp);
        templ=find(temp>5);
        Reach5Time(i,j)=templ(1);
        clear temp
    end
%% Calculate mean strain values for each rib level for use in r-squared later

for m=3:8
    counter=0;
    meanTotal=0;
    for i=SVs
        for j=1:nIV(i)
            eval(strcat('Ribs=Level',num2str(m),';'))
            for k=Ribs
                if GageCheck(i,j,k)==1
                    eval(strcat('StrainTemp=',SubjVars(i,:),ImpVars(j,:),(1:DefPeakTime(i,j),k);'))
                    meanTotal=meanTotal+sum(StrainTemp);
                    counter=counter+size(StrainTemp,1);
                    clear StrainTemp
                end
            end
        end
    end
    eval(strcat('MeanStrainLevel',num2str(m),'=meanTotal/counter;'))
end
clear counter meanTotal

%% Calculate SD fits for individual impacts, Fit 1 as PeakStrain/PeakDef % model: Y=Ax+B, B=0
for i=SVs
    for j=1:nIV(i)
        for k=SGs
            eval(strcat('StrainTemp=',SubjVars(i,:),ImpVars(j,:),(DefPeakTime(i,j),k);'))
            eval(strcat(SubjVars(i,:),'Fit1A(j,k)=StrainTemp/DefPeak(i,j);'))
            eval(strcat(SubjVars(i,:),'Fit1B(j,k)=0;'))
        end
    end
end

%% Calculate SD fits for individual impacts, Fit 2 as piecewise linear % model: Y=Ax+B for Ax+B>0, Y=0 for Ax+B<0, from 5%Def to peak
for i=SVs
    for j=1:nIV(i)
eval(strcat('DefTemp(:,1)=',SubjVars(i,:),ImpVars(j,:),'(Reach5Time(i,j):DefPeakTime(i,j),Def);'))
    XTemp=[DefTemp,ones(size(DefTemp))];
    for k=SGs
        eval(strcat('StrainTemp=',SubjVars(i,:),ImpVars(j,:),'(Reach5Time(i,j):DefPeakTime(i,j)-1,Def);'))
    end
end
end
end

%% Calculate SD fits for individual impacts, Fit 3 as exponential corresponding to Fit 2
% model: Y=Aexp(Bx), from 5% Def to peak
for i=SVs
    for j=1:nIV(i)
        eval(strcat('DefTemp(:,1)=',SubjVars(i,:),ImpVars(j,:),'(Reach5Time(i,j):DefPeakTime(i,j)-1,Def);'))
        for k=SGs
            eval(strcat('StrainTemp=',SubjVars(i,:),ImpVars(j,:),'(Reach5Time(i,j):DefPeakTime(i,j)-1,k);'))
            % eval(strcat(SubjVars(i,:),ImpVars(j,:),DataVars(k,:),'Fit3=coeffvalues(fit(DefTemp,StrainTemp,''exp1''));'))
            % eval(strcat(SubjVars(i,:),'Fit3A(j,k)=',SubjVars(i,:),ImpVars(j,:),DataVars(k,:),'Fit3(1);'))
            % eval(strcat(SubjVars(i,:),'Fit3B(j,k)=',SubjVars(i,:),ImpVars(j,:),DataVars(k,:),'Fit3(2);'))
            % ATemp=coeffvalues(fit(DefTemp,StrainTemp,'exp1'));
            % eval(strcat(SubjVars(i,:),'Fit3A(j,k)=ATemp(1);'))
            % eval(strcat(SubjVars(i,:),'Fit3B(j,k)=ATemp(2);'))
            ATemp=coeffvalues(fit(DefTemp,StrainTemp,'exp1'));
            eval(strcat(SubjVars(i,:),'Fit3A(j,k)=ATemp(1);'))
            eval(strcat(SubjVars(i,:),'Fit3B(j,k)=ATemp(2);'))
        end
    end
end
%% Calculate SD fits for individual impacts, Fit 4 as exponential for all loading
% model: Y=Aexp(Bx), from 0 to peak def
for i=SVs
  for j=1:nIV(i)
    eval(strcat('DefTemp(:,1)=' ,SubjVars(i,:),ImpVars(j,:),'(2:DefPeakTime(i,j)-1,Def);'))
    for k=SGs
      eval(strcat('StrainTemp=' ,SubjVars(i,:),ImpVars(j,:),DataVars(k,:),'Fit4=coeffvalues(fit(DefTemp,StrainTemp,''exp1''));'))
      eval(strcat(SubjVars(i,:),'Fit4A(j,k)=',SubjVars(i,:),ImpVars(j,:),DataVars(k,:),'Fit4(1);'))
      eval(strcat(SubjVars(i,:),'Fit4B(j,k)=',SubjVars(i,:),ImpVars(j,:),DataVars(k,:),'Fit4(2);'))
      ATemp=coeffvalues(fit(DefTemp,StrainTemp,'exp1'));
      eval(strcat(SubjVars(i,:),'Fit4A(j,k)=ATemp(1);'))
      eval(strcat(SubjVars(i,:),'Fit4B(j,k)=ATemp(2);'))
    end
  end
end

%% Calculate SD fits for individual impacts, Fit 5 as power for all loading
% model: Y=A*x^B, from 0 to peak def
%CB1Imp3(1,2)=0.00001;
for i=SVs
  for j=1:nIV(i)
    eval(strcat('DefTemp(:,1)=' ,SubjVars(i,:),ImpVars(j,:),'(2:DefPeakTime(i,j)-1,Def);'))
      for k=SGs
eval(strcat('StrainTemp=',SubjVars(i,:),ImpVars(j,:),'(2:DefPeakTime(i,j)-1,k);'))

 eval(strcat(SubjVars(i,:),ImpVars(j,:),DataVars(k,:),'Fit5=coeffvalues(fit(DefTemp,StrainTemp,'power1');'))) 
 eval(strcat(SubjVars(i,:),'Fit5A(j,k)=',SubjVars(i,:),ImpVars(j,:),DataVars(k,:),'Fit5(1);')) 
 eval(strcat(SubjVars(i,:),'Fit5B(j,k)=',SubjVars(i,:),ImpVars(j,:),DataVars(k,:),'Fit5(2);')) 

 ATemp=coeffvalues(fit(DefTemp,StrainTemp,'power1')); 
 eval(strcat(SubjVars(i,:),'Fit5A(j,k)=ATemp(1);')) 
 eval(strcat(SubjVars(i,:),'Fit5B(j,k)=ATemp(2);'))
 clear StrainTemp 
 clear DefTemp XTemp 
 end 
 end 
 clear 
 end 

definition text

%% Calculate SD fits for each level, Fit 2 as piecewise linear
% model: Y=Ax+B for Ax+B>0, Y=0 for Ax+B<0, from 5%Def to peak

clear Deflections Strains 
for m=3:8 
for i=SVs 
 for j=1:nIV(i) 

eval(strcat('DefTemp(:,1)=',SubjVars(i,:),ImpVars(j,:),(Reach5Time(i,j):DefPeakTime(i,j),Def);')) 
 XTemp=[DefTemp,ones(size(DefTemp))]; 
 eval(strcat('Ribs=Level',num2str(m),';')) 
 for k=Ribs 

 if GageCheck(i,j,k)==1

eval(strcat('StrainTemp=',SubjVars(i,:),ImpVars(j,:),(Reach5Time(i,j):DefPeakTime(i,j),k);')) 
 if exist('Deflections')==0 
 Deflections=XTemp; 
 Deflections1=DefTemp; 
 Strains=StrainTemp; 
 else 
 Deflections=[Deflections;XTemp]; 
 Deflections1=[Deflections1;DefTemp]; 
 Strains=[Strains;StrainTemp]; 
 end 
 clear StrainTemp 
 end 
 end
end

clear DefTemp XTemp Ribs
end

end

% eval(strcat('Level',num2str(m),'Fit2=Deflections\Strains;'))
 eval(strcat('LevelsEach38Fit2(:,',num2str(m),')=Deflections\Strains;'))
%[fit1,gof1]=fit(Deflections1,Strains,'poly1')
clear Deflections Strains
end
% LevelsEach38Fit2(:,3)=Level3Fit2;
% for m=4:8
% eval(strcat('LevelsEach38Fit2=[LevelsEach38Fit2
Level',num2str(m),')=Level2Fit2;'))
% end

%% Calculate SD fits for each level, Fit 3 as exponential
% corresponding to Fit 2
% model: Y=Aexp(Bx) , from 5%Def to peak

clear Deflections Strains
for m=3:8
    for i=SVs
        for j=1:nIV(i)
            eval(strcat('DefTemp(:,1)=',SubjVars(i,:),ImpVars(j,:),(Reach5Time(i,j):DefPeakTime(i,j),Def);'))
            eval(strcat('Ribs=Level',num2str(m),';'))
            for k=Ribs
                if GageCheck(i,j,k)==1
                    eval(strcat('StrainTemp=',SubjVars(i,:),ImpVars(j,:),(Reach5Time(i,j):DefPeakTime(i,j),k);'))
                    if exist('Deflections')==0
                        Deflections=DefTemp;
                        Strains=StrainTemp;
                    else
                        Deflections=[Deflections;DefTemp];
                        Strains=[Strains;StrainTemp];
                    end
                    clear StrainTemp
                end
            end
        end
    end
end

eval(strcat('Deflections',num2str(m),')=Deflections;'))
eval(strcat('Strains',num2str(m),')=Strains;'))
% Strains(Strains<1)=1;
% eval(strcat('Level',num2str(m),'Fit3=coeffvalues(fit(Deflections,
Strains,''exp1''));'))
 eval(strcat('LevelsEach38Fit3(:,',num2str(m),')=coeffvalues(fit(D
eflections,Strains,''exp1''));')) %,''Robust'',''LAR''
%[fit1,gof1]=fit(Deflections,Strains,'exp1')
%size(Deflections)
clear Deflections Strains
end
% LevelsEach38Fit3(:,3)=Level3Fit3;
% for m=4:8
%     eval(strcat('LevelsEach38Fit3=[LevelsEach38Fit3
Level',num2str(m),'Fit3;']);)
% end

%% Calculate SD fits for each level, Fit 4 as exponential for all
loading
% model: Y=Aexp(Bx) , from 0 to peak def

clear Deflections Strains
for m=3:8
  for i=SVs
    for j=1:nIV(i)
      eval(strcat('DefTemp(:,1)='
SubjVars(i,:),ImpVars(j,:),(2:DefPeakTime(i,j)-1,Def);'))
      eval(strcat('Ribs=Level',num2str(m),';'))
      for k=Ribs
        if GageCheck(i,j,k)==1
          eval(strcat('StrainTemp='
SubjVars(i,:),ImpVars(j,:),(2:DefPeakTime(i,j)-1,k);'))
          if exist('Deflections')==0
            Deflections=DefTemp;
            Strains=StrainTemp;
          else
            Deflections=[Deflections;DefTemp];
            Strains=[Strains;StrainTemp];
          end
          clear StrainTemp
        end
      end
    end
  end
end
clear DefTemp Ribs
end

val(strcat('Deflections',num2str(m),'=Deflections;'))
eval(strcat('Strains',num2str(m),'=Strains;'))
%Strains(Strains<1)=1;
eval(strcat('Level',num2str(m),'Fit4=coeffvalues(fit(Deflections, Strains,''exp1''));'))
eval(strcat('LevelsEach38Fit4(:,',num2str(m),')=coeffvalues(fit(Deflections, Strains,''exp1''));'))
%[fit1,gof1]=fit(Deflections,Strains,'exp1')
%size(Deflections)
clear Deflections Strains
eval(strcat('Level',num2str(m),')=Level3Fit4;'))
end

eval(strcat('Level',num2str(m),'Fit5=coeffvalues(fit(Deflections, Strains,'''power1''));'))
eval(strcat('LevelsEach38Fit5(:,',num2str(m),')=coeffvalues(fit(Deflections,Strains,''power1''));'))
%[fit1,gof1]=fit(Deflections,Strains,'power1')
%size(Deflections)
clear Deflections Strains
del
for m=4:8
eval(strcat('LevelsEach38Fit5=[LevelsEach38Fit5
Level',num2str(m),']'))
end
%% Calculate r-squared of fits for each level
for p=2:5 %Fit number
for m=3:8 %Rib level
SSE=0;
SST=0;
for i=SVs %Subject
for j=1:nIV(i) %Impact
    eval(strcat('DefTemp(:,1)='
    SubjVars(i,:),ImpVars(j,:),'
    '1:DefPeakTime(i,j),Def);'))
    eval(strcat('Ribs=Level','
    num2str(m),';'))
    for k=Ribs %Rib (or strain gage)
        if GageCheck(i,j,k)==1
            eval(strcat('StrainTemp='
            SubjVars(i,:),ImpVars(j,:),'
            1:DefPeakTime(i,j),k);'))
            if p==2
                FitTemp(:,1)=(LevelsEach38Fit2(1,m)*DefTemp)+LevelsEach38Fit2(2,m);
                FitTemp(FitTemp<0)=0;
                elseif p==3
                    FitTemp(:,1)=LevelsEach38Fit3(1,m)*exp(DefTemp*LevelsEach38Fit3(2,
                    m));
                    elseif p==4
                        FitTemp(:,1)=LevelsEach38Fit4(1,m)*exp(DefTemp*LevelsEach38Fit4(2,
                        m));
                        elseif p==5
                            FitTemp(:,1)=LevelsEach38Fit5(1,m)*(DefTemp.^LevelsEach38Fit5(2,
                            m));
                                end
                                FitDifs=StrainTemp-FitTemp;
eval(strcat('MeanDifs=StrainTemp-
        MeanStrainLevel',num2str(m),';'))
SSE = SSE + (FitDifs'*FitDifs);
SST = SST + (MeanDifs'*MeanDifs);
clear StrainTemp FitTemp FitDifs MeanDifs
end
end
clear DefTemp Ribs
end
eval(strcat('rSqLevel',num2str(m),'Fit',num2str(p),')=1-(SSE/SST);'))
rSqLevels38Fits(p,m) = 1-(SSE/SST);
end
end
clear SSE SST
\% Calculate response corridors for each level

clear Strains
\% CorLen=max(max(DefPeakTime));
  DefCor=0:0.2:35; DefCor=DefCor';
  CorLen=size(DefCor,1);
  Corridors=zeros(CorLen,20);
  Corridors(:,Def)=DefCor;
for m=3:8
  for n=2:CorLen
    for i=SVs
      for j=1:nIV(i)
        eval(strcat('temp=',SubjVars(i,:),ImpVars(j,:),');'))
        % Find the points on this impact for which the deflection is within % our deflection bin of the corridor
        if temp(DefPeakTime(i,j),Def)>DefCor(n-1) % make sure the deflection for this impact enters into our range
          temp1=find(temp(1:DefPeakTime(i,j),Def)>DefCor(n-1));
          Sstart=temp1(1);
        if temp(DefPeakTime(i,j),Def)>DefCor(n) % pick either the top end of our deflection bin or the peak deflection as our end point
          temp2=find(temp(1:DefPeakTime(i,j),Def)>DefCor(n));
          Send=temp2(1);
        else
          Send=DefPeakTime(i,j);
        end % end picking the end point
clear templ1 templ2
eval(strcat('Ribs=Level',num2str(m),')'))
  for k=Ribs % which rib is being read from
    if GageCheck(i,j,k)==1 % make sure the gage is good before using it
      StrainTemp(:,1)=temp(Sstart:Send,k);
if exist('Strains')==0
    Strains=StrainTemp;
else
    Strains=[Strains;StrainTemp];
end %end the strains if
clear StrainTemp
end % end the gage check if
end %end the rib for
end %end the if check for deflection entering into our bin
clear Ribs temp Sstart Send
end %end the impact
end %end the subject

if exist('Strains')==1
Corridors(n,m)=mean(Strains);
if size(Strains,1)>2
    Corridors(n,m+6)=Corridors(n,m)+std(Strains);
    Corridors(n,m+12)=Corridors(n,m)-std(Strains);
else
    Corridors(n,m+6)=Corridors(n,m);
    Corridors(n,m+12)=Corridors(n,m);
end %end the if where corridors are calculated
clear Strains
end %end the if checking that Strains exists
end %end this data point
temp=find(Corridors(:,Def)>15);
temp1=find(Corridors(temp(1):CorLen,m)<0.1);
CorridorEnd(m)=temp1(1)+temp(1)-2;
clear temp temp1
end %end the rib level

%% Data for plotting
DefFits=0:0.2:35;
DefFits=DefFits';

%Individualized data
for i=SVs
    S1=SubjVars(i,,:);
    for j=1:nIV(i)
        CurrentImp=strcat(S1,ImpVars(j,:));
        %eval(strcat(CurrentImp,'Fit1(:,Def)=DefFits;'))
        for k=SGs
            for m=1:size(DefFits,1)
                eval(strcat(CurrentImp,'Fit1(m,k)=(',S1,'Fit1A(j,k)*DefFits(m))+','
                           ,S1,'Fit1B(j,k);'))
            end
        end
    end
end
eval(strcat(CurrentImp,'Fit2(m,k)=(',S1,'Fit2A(j,k)*DefFits(m))+' ,S1,'Fit2B(j,k);'))

eval(strcat(CurrentImp,'Fit3(m,k)=',S1,'Fit3A(j,k)*exp(DefFits(m) *',S1,'Fit3B(j,k));'))

eval(strcat(CurrentImp,'Fit4(m,k)=',S1,'Fit4A(j,k)*exp(DefFits(m) *',S1,'Fit4B(j,k));'))

eval(strcat(CurrentImp,'Fit5(m,k)=',S1,'Fit5A(j,k)*(DefFits(m)^', S1,'Fit5B(j,k));'))
    end
    end
    eval(strcat(CurrentImp,'Fit2(',CurrentImp,'Fit2<0)=0;'))
    clear CurrentImp
end

clear S1

%Data grouped in levels
for m=3:8
    for j=1:size(DefFits,1)
        LevelsEach38Fit2Y(j,m)=(LevelsEach38Fit2(1,m)*DefFits(j))+Levels Each38Fit2(2,m);
        LevelsEach38Fit3Y(j,m)=LevelsEach38Fit3(1,m)*exp(DefFits(j)*Levels Each38Fit3(2,m));
        LevelsEach38Fit4Y(j,m)=LevelsEach38Fit4(1,m)*exp(DefFits(j)*Levels Each38Fit4(2,m));
        LevelsEach38Fit5Y(j,m)=LevelsEach38Fit5(1,m)*(DefFits(j)^LevelsEach38Fit5(2,m));
    end
end
LevelsEach38Fit2Y(LevelsEach38Fit2Y<0)=0;

%% Plotting preparations
%Define colors
  c1=[0 0 1];
  c2=[1 0 0];
  c3=[0.2 0.7 0.2];
  c4=[0 0 0];
  c5=[0 0.7 0.7];
  c6=[0.7 0.7 0.2];
c7=[0.5 0.3 0.1];
c8=[0.3 0.6 0.1];
c9=[0.9 0.9 0];
c10=[0.1 0.4 0.7];
c11=[0.5 0.5 0.5];
c12=[0.7 0.3 0.3];
c13=[0 0.7 0.3];
c14=[0.4 0.4 0.7];
c15=[0.7 0.5 0.3];
c16=[0.9 0.1 0.5];
c17=[0.1 0.8 0.5];
c18=[0.6 0.8 0.1];
colors18=[c1;c2;c3;c4;c5;c6;c7;c8;c9;c10;c11;c12;c13;c14;c15;c16;
c17;c18];

%Font sizes
fs1=13;
fs2=11;
fs3=15;

Plotting

%% Plot all gages strain-time on 1 plot with a plot for each impact
range=SGs;
for i=SVs
  for j=1:nIV(i)
    figure
    eval(strcat('temp=',SubjVars(i,:),ImpVars(j,:),'';'))
    for k=range
      if GageCheck(i,j,k)==1
        plot(temp(:,1),temp(:,k),'Color',colors18(k-2,:), 'LineWidth',2); hold on
      end
    end
    title(strcat('Strain:',SubjVars(i,:),ImpVars(j,:)))
    legend(SGVars,'location','eastoutside')
    %xlim([-0.05,TimeOfInterestEnd])
    %ylim([-6000,6000])
    xlabel('Time (s)')
    ylabel('Strain (uS)')
    clear temp
  end
end
%% Plot SD for each level, colored by CB1 CB2 TH
for m=3:8
    eval(strcat('range=Level',num2str(m),';'))
    figure
    for i=SVs
        for j=1:nIV(i)
            eval(strcat('temp=',SubjVars(i,:),ImpVars(j,:),';'))
            for k=range
                if GageCheck(i,j,k)==1
                    plot(temp(:,2),temp(:,k),'
Color',colors18(i,:),'
LineWidth',2);
                    hold on
                end
            end
            clear temp
        end
    end
    title(strcat('Level ',num2str(m),' Ribs'))
    xlim([0,35])
    %ylim([-6000,6000])
    xlabel('Deflection (%)')
    ylabel('Strain (uS)')
    clear range
end

%% Plot SD for each level, colored by PMHS#
for m=3:8
    eval(strcat('range=Level',num2str(m),';'))
    q=3; r=0;
    figure
    hold on
    for i=SVs
        for j=1:nIV(i)
            eval(strcat('temp=',SubjVars(i,:),ImpVars(j,:),';'))
            for k=range
                if GageCheck(i,j,k)==1
                    if i==3
                        plot(temp(:,2),temp(:,k),'
Color',colors18(q,:),'
LineWidth',2);
                        hold on %use for full curves
                    else
                        %plot(temp(1:DefPeakTime(i,j),2),temp(1:DefPeakTime(i,j),k),'
Color',colors18(q,:),'
LineWidth',2); hold on %use for loading only
                    end
                end
            end
        end
    end
    plot(temp(:,2),temp(:,k),'
Color',colors18(q,:),'
LineWidth',2);
    hold on %use for full curves
end

%plot(temp(1:DefPeakTime(i,j),2),temp(1:DefPeakTime(i,j),k),'
Color',colors18(q,:),'
LineWidth',2); hold on %use for loading only
else
end

%plot(temp(:,2),temp(:,k),'
Color',colors18(i,:),'
LineWidth',2);
hold on %use for full curves
plot(temp(1:DefPeakTime(i,j),2),temp(1:DefPeakTime(i,j),k), 'Color', colors18(i,:), 'LineWidth', 2); hold on %use for loading only
    end
end
if i==3
    if r==0
        r=1;
    else
        q=q+1;
        r=0;
    end
end
clear temp
end
title(strcat('Level ',num2str(m),' Ribs'))
title(strcat('R ',num2str(m),' Rib'))
xlim([0,25])
ylim([-1000,8500])
xlabel('Deflection (%)')
ylabel('Strain (uS)')
clear range q
end

%% Plot SD and fits for each level, colored by fit
for m=[3,5] 3:8
    eval(strcat('range=Level',num2str(m),';'))
    figure
    for i=SVs
        for j=1:nIV(i)
            eval(strcat('temp=',SubjVars(i,:),ImpVars(j,:),';'))
            for k=range
                if GageCheck(i,j,k)==1
                    %plot(temp(:,2),temp(:,k),'k','LineWidth',2);
                    hold on %use to plot only loading for all curves
            end
        end
    end
end
clear temp
end
for f=2:5
    eval(strcat('temp=LevelsEach38Fit',num2str(f),'Y(:,m);'))
    if f==5

142
plot(DefFits,temp,'Color',colors18(f,:), 'LineWidth',2);
hold on
else
    plot(DefFits,temp,'Color',colors18(f-1,:), 'LineWidth',2);
hold on
end
clear temp
end

%title(strcat('Level ',num2str(m),' Ribs'))
xlim([0,35])
%ylim([-1000,9000])
xlabel('Deflection (%)')
ylabel('Strain (uS)')
clear range
end

%% Plot SD 1 rib with fits for each impact
range=L3;
for i=2:SVs
    for j=4:1:nIV(i)
        figure
        eval(strcat('temp=',SubjVars(i,:),ImpVars(j,:),';','))
        %Plot the S-D curve
        for k=range
            if GageCheck(i,j,k)==1
                plot(temp(:,2),temp(:,k),'k','LineWidth',2); hold on
                %use to plot full curve
                plot(temp(1:DefPeakTime(i,j),2),temp(1:DefPeakTime(i,j),k),'k','LineWidth',2); hold on %use to plot only loading for all curves
                plot(temp(Reach5Time(i,j):DefPeakTime(i,j),2),temp(Reach5Time(i,j):DefPeakTime(i,j),k),'k','LineWidth',2); hold on %use to plot only direct loading (after 5%) for all curves
            end
        end
        clear temp
    end
end

% %Plot the fits
for f=1:5
% eval(strcat('temp=',SubjVars(i,:),ImpVars(j,:),'Fit',num2str(f),'(:,range);'))
    if f==1
    plot(DefFits,temp,'Color',colors18(6,:), 'LineWidth',2); hold on
    elseif f==5

plot(DefFits,temp,'Color',colors18(f,:), 'LineWidth', 2); hold on
else
    plot(DefFits,temp,'Color',colors18(f-1,:), 'LineWidth', 2); hold on
end
clear temp
end

title(strcat(DataVars(range,:),' S-D and Fits'))
legend(SGVars,'location','eastoutside')
xlim([0,30])
ylim([-500,2000])
xlabel('Deflection (%)')
ylabel('Strain (uS)')

end
end

%% Plot SD response corridor
for m=4:5
    eval(strcat('range=Level', num2str(m), ';'))
    figure
    hold on

    patch([Corridors(1:CorridorEnd(m),Def);flipud(Corridors(1:CorridorEnd(m),Def))],
          [Corridors(1:CorridorEnd(m),m+6);flipud(Corridors(1:CorridorEnd(m),m+12))],
          [0.7 0.7 0.7]); % plot the corridor +/- SD
    plot(Corridors(1:CorridorEnd(m),Def),Corridors(1:CorridorEnd(m),m), 'k','LineWidth', 2) % plot the mean response

    %This portion adds the S-D curves with the corridor
    for i=SVs
        for j=1:nIV(i)
            eval(strcat('temp=', SubjVars(i,:), ImpVars(j,:), ';'))
            for k=range
                if GageCheck(i,j,k)==1
                    %plot(temp(:,2),temp(:,k),'k','LineWidth', 2); hold on %use to plot full curve
                    plot(temp(1:DefPeakTime(i,j),2),temp(1:DefPeakTime(i,j),k), 'r','LineWidth', 2); hold on %use to plot only loading for all curves
                end
            end
clear temp耐

end
end

% plot(Corridors(1:CorridorEnd(m),Def),Corridors(1:CorridorEnd(m),m ),'k','LineWidth',2) % plot the mean response

%plot lines for comparative data - Li 2010 Charpail 2005 Kemper 2011
if m==3
    %plot([0,LiDef(1)], [0,LiStrain(1)],'k','LineWidth',3)
    plot([0,LiDef(1)]+5, [0,LiStrain(1)],'k-.','LineWidth',3)
else if m==4
    %plot([0,LiDef(2)], [0,LiStrain(2)],'k','LineWidth',3)
    plot([0,LiDef(2)]+5, [0,LiStrain(2)],'k-.','LineWidth',3)
    scatter(LiDef(2)+5,LiStrain(2), 'k', 'LineWidth',1)
    for i=1:4
        plot([5,KempDef4(i)], [0,KempStrain4(i)],'b--', 'LineWidth',3)
        scatter(KempDef4(i),KempStrain4(i), 'b', 'LineWidth',1)
    end
else if m==5
    for i=1:4
        plot([0,CharpDef(i)]+5, [0,CharpStrain(i)],'g:','LineWidth',3)
    scatter(CharpDef(i)+5,CharpStrain(i), 'g', 'LineWidth',1)
    end
    for i=1:2
        plot([5,KempDef5(i)], [0,KempStrain5(i)],'b--', 'LineWidth',3)
        scatter(KempDef5(i),KempStrain5(i), 'b', 'LineWidth',1)
    end
else if m==8
    %plot([0,LiDef(3)], [0,LiStrain(3)],'k','LineWidth',3)
    plot([0,LiDef(3)]+5, [0,LiStrain(3)],'k','LineWidth',3)
end

% title(strcat('Level ',num2str(m),' Ribs'))
% legend('Li 2010', 'Li 2010 + toe','Current study')
xlim([0,35])
% ylim([-1000,5000])
xlabel('Deflection (%)')
ylabel('Strain (uS)')
clear range

end

%% S-D plots for comparison to F-D

figure
hold on
plot(CB1Imp6(1:DefPeakTime(1,6),2),CB1Imp6(1:DefPeakTime(1,6),5),
'b:','LineWidth',2);
plot(CB1Imp4(1:DefPeakTime(1,4),2),CB1Imp4(1:DefPeakTime(1,4),5),
'r--','LineWidth',2);
plot(CB1Imp3(1:DefPeakTime(1,3),2),CB1Imp3(1:DefPeakTime(1,3),5),
'k','LineWidth',2);
xlim([0,25])
xlabel('Deflection (%)')
ylabel('Strain (uS)')
Appendix C: Supplement to Chapter 4
Figure 47. Schematic of subject instrumentation for test 1

Table 15. Strain gage locations on the ribs for test 1

<table>
<thead>
<tr>
<th>Rib Level</th>
<th>Left Lateral</th>
<th>Left Posterior</th>
<th>Right Lateral</th>
<th>Right Posterior</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>5</td>
<td>X</td>
<td>X X</td>
<td>X X</td>
<td>X</td>
</tr>
<tr>
<td>6</td>
<td>X</td>
<td>X X</td>
<td>X X</td>
<td>X</td>
</tr>
<tr>
<td>7</td>
<td>X</td>
<td>X X</td>
<td>X X</td>
<td>X</td>
</tr>
<tr>
<td>8</td>
<td>X</td>
<td>X X</td>
<td>X X</td>
<td>X</td>
</tr>
<tr>
<td>9</td>
<td>X</td>
<td>X X</td>
<td>X X</td>
<td>X</td>
</tr>
<tr>
<td>10</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>
Figure 48. Schematic of subject instrumentation for test 2

Table 16. Strain gage locations on the ribs for test 2

<table>
<thead>
<tr>
<th>Rib Level</th>
<th>Left Lateral</th>
<th>Left Posterior</th>
<th>Right Lateral</th>
<th>Right Posterior</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>4</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>6</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>7</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>8</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>9</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>
In Table 17, each listed orientation direction is relative to the subject. For example, ‘Left’ refers to the occupant’s left.

<table>
<thead>
<tr>
<th>Location</th>
<th>Axis 1</th>
<th>Axis 2</th>
<th>Axis 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manubrium</td>
<td>Left</td>
<td>Down</td>
<td>Backward</td>
</tr>
<tr>
<td>T1</td>
<td>Right</td>
<td>Down</td>
<td>Forward</td>
</tr>
<tr>
<td>T4</td>
<td>Right</td>
<td>Down</td>
<td>Forward</td>
</tr>
<tr>
<td>T12</td>
<td>Right</td>
<td>Down</td>
<td>Forward</td>
</tr>
<tr>
<td>Sacrum</td>
<td>Right</td>
<td>Down</td>
<td>Forward</td>
</tr>
<tr>
<td>Pelvis</td>
<td>Down</td>
<td>Backward</td>
<td>Left</td>
</tr>
</tbody>
</table>

Table 17. Orientation of each 6DX Pro motion block, relative to the subject

<table>
<thead>
<tr>
<th>Strain Gages</th>
<th>Location</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral aspect of left clavicle</td>
<td></td>
<td>Vishay Micro-Measurements</td>
</tr>
<tr>
<td>Sternum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lateral aspect of ribs 4-10 (left and right)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Posterior aspect of ribs 5-9 (left and right)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6DX Pro Motion Blocks</td>
<td>Manubrium</td>
<td>DTS</td>
</tr>
<tr>
<td>Spine: T1, T4, T12, Sacrum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pelvis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chestbands</td>
<td>Axilla (40-channel)</td>
<td>Humanetics</td>
</tr>
<tr>
<td>Xiphoid Process (59-channel)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6aω Tetrahedron</td>
<td>Head</td>
<td>Endevco, DTS</td>
</tr>
</tbody>
</table>

Table 18. Details of instruments used on PMHS 1
### Table 19. Details of instruments used on PMHS 2

<table>
<thead>
<tr>
<th>Location</th>
<th>Instrumentation</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain Gages</td>
<td>Lateral aspect of left clavicle</td>
<td>Vishay Micro-</td>
</tr>
<tr>
<td></td>
<td>Sternum</td>
<td>Measurements</td>
</tr>
<tr>
<td></td>
<td>Anterior aspect of ribs 2-10 (left) and 3-10 (right)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Posterior aspect of ribs 5-10 (left) and 5-8 (right)</td>
<td></td>
</tr>
<tr>
<td>6DX Pro</td>
<td>Manubrium</td>
<td>DTS</td>
</tr>
<tr>
<td>Motion Blocks</td>
<td>Spine: T1, T4, T12, Sacrum</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pelvis</td>
<td></td>
</tr>
<tr>
<td>Chestbands</td>
<td>Axilla (59-channel)</td>
<td>Humanetics</td>
</tr>
<tr>
<td></td>
<td>Xiphoid Process (40-channel)</td>
<td></td>
</tr>
<tr>
<td>6aω Tetrahedron</td>
<td>Head</td>
<td>Endevco, DTS</td>
</tr>
</tbody>
</table>

### Table 20. Details of instruments used on the test setup

<table>
<thead>
<tr>
<th>Location</th>
<th>Instrumentation</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sled Buck</td>
<td>Accelerometers (y-axis) x 2</td>
<td>Endevco</td>
</tr>
<tr>
<td>ASIS</td>
<td>Cylinder Accelerometers (y-axis) x 4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Frame Accelerometers (y-axis) x 2</td>
<td></td>
</tr>
<tr>
<td>3-point Belt</td>
<td>Load Cell (tensile force) x 4</td>
<td>Measurement Specialties</td>
</tr>
<tr>
<td>Airbag</td>
<td>Pressure transducers x 2</td>
<td></td>
</tr>
</tbody>
</table>
Vicon Marker Setup

- Tragion (L/R)
- Nasion
- Mental protuberance
- Infraorbitale (L/R)

- Acromion (L/R)
- Manubrium
- Sternum

= marker screwed in
= marker attached to the skin

Arm
- Proximal humerus
- Midshaft humerus
- Distal humerus
- Olecranon (elbow)

Forearm
- Radius styloid process (wrist)

Thigh
- Greater trochanter
- Mid-proximal femur, medially
- Mid-distal femur, laterally
- Medial epicondyle
- Lateral epicondyle

Leg
- Tibial tuberosity
- Medial malleolus

= marker screwed in
= marker attached to the skin

- Frame: 10
- Door: 5
- Seat: 5
- Seatbelt: 6
- Total: 26

Marker setups for the upper and lower limbs apply to both the left and right sides.

Figure 49. Vicon marker locations on the subject and the test structure
Injuries

A summary of the injuries sustained by the subjects was presented in the main body of the text, Table 6. Images of the various injuries are presented here.

Test 1

Figure 50. Overview of left side rib fractures
Figure 51. Left second rib

Figure 52. Left third rib
Figure 53. Left fourth rib

Figure 54. Left ribs 2-4, pleural surface
Figure 55. Left sixth rib

Figure 56. Overview of right side showing location of R4 injury
Figure 57. Right fourth rib cutaneous

Figure 58. Right fourth rib pleural
Figure 59. Sternum

Figure 60. Left radius

Figure 61. Left ulna
Test 2

Figure 62. Overview of left side posterior rib fractures

Figure 63. Left fourth rib posterior cutaneous
Figure 64. Left fifth rib posterior cutaneous

Figure 65. Left sixth rib posterior cutaneous
Figure 66. Left seventh rib posterior cutaneous

Figure 67. Left eighth rib posterior cutaneous
Figure 68. Overview of left side anterior rib fractures

Figure 69. Left third rib anterior cutaneous, two fractures
Figure 70. Left fourth rib anterior cutaneous

Figure 71. Left fifth rib anterior cutaneous
Figure 72. Left sixth rib anterior cutaneous

Figure 73. Left seventh rib anterior cutaneous
Figure 74. Left ribs 3-5, fractures on 3-5 anterior and 4-5 posterior

Figure 75. Left sixth rib pleural, anterior and posterior fractures
Figure 76. Left ribs 7-8 pleural, fractures on 7 anterior and 7-8 posterior

Figure 77. Overview of right side anterior rib fractures
Figure 78. Right third rib anterior cutaneous

Figure 79. Right third rib anterior pleural
Figure 80. Right fourth rib anterior cutaneous

Figure 81. Right fourth rib anterior pleural
Figure 82. Right fifth rib anterior cutaneous

Figure 83. Right fifth rib anterior pleural
Figure 84. Right sixth rib anterior cutaneous

Figure 85. Right sixth rib anterior pleural
Figure 86. Right seventh rib anterior cutaneous

Figure 87. Right seventh rib anterior pleural
Figure 88. Left clavicle distal fracture
Figure 89. Left fibula proximal fracture
Figure 90. Spleen laceration
Comparisons Between Test 1 and Test 2

There were several things that looked different between the two tests, including input, response, and injuries.

Sled Pulse

The HYGE sled fired about 10 ms later in test 2 than in test 1.

Figure 91. Velocity of the sled for test 1 and test 2

ASIS Cylinder 1

Cylinder 1 of the ASIS is the most critical to this study, as it directly interacts with the thorax. In test 2, cylinder 1 compensated for the lack of sled acceleration and still pretty closely matched the acceleration and velocity profiles for the first 21 ms. Cylinder 1 then overshot the previous velocity.
Figure 92. Acceleration and velocity of ASIS cylinder 1 for test 1 and test 2

**Intrusion Distance**

Due to the combination of two factors [1) the Cylinder 1 making up for the sled not firing and 2) Cylinder 1 oversooting], a much higher door intrusion was observed in test 2 than in test 1. The difference in intrusion really shoots up during the previously described overshoot period, beginning at 26 ms.

Figure 93. Intrusion distance of the door relative to the sled for test 1 and test 2 (left). Difference in door intrusion distance between the two tests (right).
Occupant Motion Relative to Seat

Although the sled fired late in test 2, the velocity of the occupant’s thorax was nearly identical through the first 18 ms of both tests. This occurred because, in the case of the sled firing, the occupant simply slid across the seat and did not move relative to the ground.

Figure 94. Velocity of the sled and of the occupant thorax for test 1 and test 2

Intrusion Rate Relative to Occupant

The occupant-relative intrusion rate is the difference in velocity between the intruding door and the occupant thorax. It provides a measure of what input is actually being experienced by the occupant. Both the intrusion rate (relative to the sled) and the occupant-relative intrusion rate are shown in Figure 95. The peak intrusion rate relative to the occupant is the same in both tests, the only difference being that it occurred later in
test 2. At the time of fractures in test 2 (19-21 ms) the relative intrusion rate was lower than it had been in test 1.

Figure 95. Door intrusion rate relative to the sled and relative to the occupant for test 1 and test 2

_Airbag Pressure_

The pressure in the airbag was very similar between the two tests for the upper sensor. However, the lower sensor shows a peak value 21% higher than on test 1, and the timing of the peak corresponds to the timing of the first rib fractures.
Figure 96. Airbag pressure readings for both ports on test 1 and test 2

*Seatbelt Load Cells*

The seatbelt load cells showed a number of similarities between the two tests, as well as a few differences. Values of the initial peak were similar across the two tests, but the tension at the anchor end was very different.

Figure 97. Seatbelt load cell data for test 1 (left) and test 2 (right)
Test 1 Strain and Strain Rate Data

Strain and strain rate data from PMHS 1 are presented here. Table 21 contains the names given to each strain gage in the data processing. Those names then appear in the title for each plot contained in Figure 98 and Figure 99.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clav</td>
<td>Distal Clavicle</td>
<td>CSG2_L05</td>
<td>L5 Lateral</td>
</tr>
<tr>
<td>Sternum</td>
<td>Sternum</td>
<td>CSG2_L06</td>
<td>L6 Lateral</td>
</tr>
<tr>
<td>CSG1_L05</td>
<td>L5 Posterior</td>
<td>CSG2_L07</td>
<td>L7 Lateral</td>
</tr>
<tr>
<td>CSG1_L06</td>
<td>L6 Posterior</td>
<td>CSG2_L08</td>
<td>L8 Lateral</td>
</tr>
<tr>
<td>CSG1_L07</td>
<td>L7 Posterior</td>
<td>CSG2_L09</td>
<td>L9 Lateral</td>
</tr>
<tr>
<td>CSG1_L08</td>
<td>L8 Posterior</td>
<td>CSG2_L10</td>
<td>L10 Lateral</td>
</tr>
<tr>
<td>CSG1_L09</td>
<td>L9 Posterior</td>
<td>CSG2_R04</td>
<td>R4 Lateral</td>
</tr>
<tr>
<td>CSG1_R05</td>
<td>R5 Posterior</td>
<td>CSG2_R05</td>
<td>R5 Lateral</td>
</tr>
<tr>
<td>CSG1_R06</td>
<td>R6 Posterior</td>
<td>CSG2_R06</td>
<td>R6 Lateral</td>
</tr>
<tr>
<td>CSG1_R07</td>
<td>R7 Posterior</td>
<td>CSG2_R07</td>
<td>R7 Lateral</td>
</tr>
<tr>
<td>CSG1_R08</td>
<td>R8 Posterior</td>
<td>CSG2_R08</td>
<td>R8 Lateral</td>
</tr>
<tr>
<td>CSG1_R09</td>
<td>R9 Posterior</td>
<td>CSG2_R09</td>
<td>R9 Lateral</td>
</tr>
<tr>
<td>CSG2_L04</td>
<td>L4 Lateral</td>
<td>CSG2_R10</td>
<td>R10 Lateral</td>
</tr>
</tbody>
</table>

Table 21. Naming scheme for strain gages on PMHS 1, as presented in Figure 98 and Figure 99
Figure 98. Strain plots for PMHS 1 (26 plots)
Figure 98 continued
Figure 98 continued

continued
Figure 98 continued
Figure 98 continued
Figure 99. Strain rate plots for PMHS 1 (26 plots)
Figure 99 continued
Figure 99 continued
Figure 99 continued

continued

189
Test 2 Strain and Strain Rate Data

Strain and strain rate data from PMHS 1 are presented here. Table 22 contains the names given to each strain gage in the data processing. Those names then appear in the title for each plot contained in Figure 100 and Figure 101.
<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clav</td>
<td>Distal Clavicle</td>
<td>L9P</td>
<td>L9 Posterior</td>
</tr>
<tr>
<td>Sternum</td>
<td>Sternum</td>
<td>L10P</td>
<td>L10 Posterior</td>
</tr>
<tr>
<td>L2A</td>
<td>L2 Anterior</td>
<td>R3A</td>
<td>R3 Anterior</td>
</tr>
<tr>
<td>L3A</td>
<td>L3 Anterior</td>
<td>R4A</td>
<td>R4 Anterior</td>
</tr>
<tr>
<td>L4A</td>
<td>L4 Anterior</td>
<td>R5A</td>
<td>R5 Anterior</td>
</tr>
<tr>
<td>L5A</td>
<td>L5 Anterior</td>
<td>R6A</td>
<td>R6 Anterior</td>
</tr>
<tr>
<td>L6A</td>
<td>L6 Anterior</td>
<td>R7A</td>
<td>R7 Anterior</td>
</tr>
<tr>
<td>L7A</td>
<td>L7 Anterior</td>
<td>R8A</td>
<td>R8 Anterior</td>
</tr>
<tr>
<td>L8A</td>
<td>L8 Anterior</td>
<td>R9A</td>
<td>R3 Anterior</td>
</tr>
<tr>
<td>L9A</td>
<td>L10 Anterior</td>
<td>R10A</td>
<td>R10 Anterior</td>
</tr>
<tr>
<td>L10A</td>
<td>L5 Posterior</td>
<td>R5P</td>
<td>R5 Posterior</td>
</tr>
<tr>
<td>L5P</td>
<td>L6 Posterior</td>
<td>R6P</td>
<td>R6 Posterior</td>
</tr>
<tr>
<td>L6P</td>
<td>L7 Posterior</td>
<td>R7P</td>
<td>R7 Posterior</td>
</tr>
<tr>
<td>L7P</td>
<td>L8 Posterior</td>
<td>R8P</td>
<td>R8 Posterior</td>
</tr>
</tbody>
</table>

Table 22. Naming scheme for strain gages on PMHS 2, as presented in Figure 100 and Figure 101
Figure 100. Strain plots for PMHS 2 (29 plots)
Figure 100 continued
Figure 100 continued
Figure 100 continued

continued
Strain Rate – Test 2

Figure 101. Strain rate plots for PMHS 2 (29 plots)

continued
Figure 101 continued

continued
Figure 101 continued
Figure 101 continued
Figure 101 ccontinued

![Graphs showing strain rate over time for RTP, R8A, R8P, R9A, and R10A.]
% Make the two data sources have the same time range (cut SP data)
TimeKT=KT_raw(:,1);
TimeSP=SP_raw(:,1);
LengthData=size(TimeKT,1);
TimeStart=TimeKT(1);
TimeEnd=TimeKT(LengthData);
SPStartIndex=find(TimeSP-TimeStart > -0.00002,1);
SPEndIndex=find(TimeSP-TimeEnd > -0.00002,1);
SP_raw_temp=SP_raw;
SPcols=size(SP_raw,2);
clear SP_raw;
SP_raw=SP_raw_temp(SPStartIndex:SPEndIndex,:);

CB_AxX_temp=CB_AxX;
clear CB_AxX
CB_AxX=CB_AxX_temp(SPStartIndex:SPEndIndex,:);
CB_AxY_temp=CB_AxY;
clear CB_AxY
CB_AxY=CB_AxY_temp(SPStartIndex:SPEndIndex,:);
clear SP_raw_temp

%% Combine the two data sets into one
AllData_raw=[KT_raw,SP_raw(:,2:SPcols)];
clear KT_raw SP_raw SPcols
nV=size(AllData_raw,2)-2; %number of data variables (col 1 is time, col 2 is trigger)

%% Arrage the data into usable variables
varNames=char('SledCY','SledCYRD','AsisAcc1','AsisAcc2','AsisAcc3','AsisAcc4','AsisFrUp','AsisFrLo','ABPresUp','ABPresLo','SbLCDring','SternumSG','ClavSG','L2A','L3A','L4A','L5A','L6A','L7A','L8A','L9A','L10A','L5P','L6P','L7P','L8P','L9P','L10P','R3A','R4A','R5A','R6A','R7A','R8A','R9A','R10A','R5P','R6P','R7P','R8P','TetraF1AccT','TetraF1AccR','TetraF1ARSL','TetraF2AccT','TetraF2AccR','TetraF2ARSL','TetraF3AccT','TetraF3AccR','TetraF3ARSL','SbLCShoulder','SbLCBuckle','SbLCAnchor','...
DxVarNames=char('DxMan', 'DxT1', 'DxT4', 'DxT12', 'DxS1', 'DxPel');

% Create variable names for raw, filtered, and corrected data
addRaw=repmat(char('Raw'), nV, 1);
addF=repmat(char('F'), nV, 1);
addC=repmat(char('C'), nV, 1);
varNamesRaw=strcat(varNames, addRaw);
varNamesF=strcat(varNames, addF);
varNamesC=strcat(varNames, addC);

Time=AllData_raw(:,1);
Trigger=AllData_raw(:,2);
for i=1:nV  % This (i) cycles through each variable
    vT=varNamesRaw(i,:);
    eval(strcat(vT, '=AllData_raw(:,', num2str(i+2), ');'));
end

Data Processing

% Define basic processing variables

% Variable locations within varNames (88 variables)
AllDataVars=1:nV;
SledVars=[1,2];
AsisVars=3:8;
AsisLCVars=0;
AsisAccVars=3:8;
AbPressVars=[9,10];
LCVars=[11,50:52];
SGVars=12:40;
TetraVars=41:49;
DXVars=53:88;
ManVars=53:58;
T1Vars=59:64;
T4Vars=65:70;
T12Vars=71:76;
S1Vars=77:82;
PelVars=83:88;
SubjVars=12:88; %Strain Gages, Tetrahedron, 6DX
NotSGVars=[1:11,41:88]; %Everything but the SGs
:85]; %All accelerometers

% Chestband left and right sides
CB_Ax_sides=[26,2];
CB_Xi_sides=[15,29];

% Chestband front
CB_Ax_Strnm=53;
CB_Xi_Strnm=31;

%Ranges within varNames which group strain gages by %location
SGLVars=14:28; %Left side SGs
SGRVars=29:40; %Right side SGs
SGPVars=[23:28,37:40]; % 30% SGs - Posterior
SGAVars=[14:22,29:36]; % 90% SGs - Anterior

% Points of significance in time
Init=1:200;
Act=4001;
TimeOfInterest=Act-1000:Act+6000;
TimeOfInterestSize=size(TimeOfInterest,2);
TimeOfInterestStart=Time(TimeOfInterest(1));
TimeOfInterestEnd=Time(TimeOfInterest(TimeOfInterestSize));
%PreAct=Act-205:Act-5;

%InitV=1:20;
%PreImpV=975:999;
%ImpV=1001;

dt=1/20000;
%dTV=1/1000;
ChestBreadth_Ax=264; %mm seated with CB on; 234mm lying down
ChestBreadth_Xi=255; %mm seated with CB on; 235mm lying down
ChestBreadth=259; %mm seated with CB on; 234mm lying down
% Filter the data
%Has been updated for EIS

% Set up the second-order butterworth filters for CFC
60,180,600,1000
[b_CFC60,a_CFC60]=butter(2,100*2*dt);
b_CFC180,a_CFC180]=butter(2,300*2*dt);
b_CFC600,a_CFC600]=butter(2,1000*2*dt);
b_CFC1000,a_CFC1000]butter(2,1650*2*dt);
% [bfV,afV]=butter(2,0.6);

% Filter the data
for i=SledVars
    eval(strcat(varNamesF(i,:), '=filtfilt(b_CFC60,a_CFC60,', varNamesRaw(i,:), ');
    )
end
for i=AsisVars
    eval(strcat(varNamesF(i,:), '=filtfilt(b_CFC180,a_CFC180,', varNamesRaw(i,:), ');
    )
end
for i=AbPressVars
    eval(strcat(varNamesF(i,:), '=filtfilt(b_CFC180,a_CFC180,', varNamesRaw(i,:), ');
    )
end
for i=LCVars
    eval(strcat(varNamesF(i,:), '=filtfilt(b_CFC60,a_CFC60,', varNamesRaw(i,:), ');
    )
end
for i=SGVars
    eval(strcat(varNamesF(i,:), '=filtfilt(b_CFC1000,a_CFC1000,', varNamesRaw(i,:), ');
    )
end
for i=TetraVars
    eval(strcat(varNamesF(i,:), '=filtfilt(b_CFC1000,a_CFC1000,', varNamesRaw(i,:), ');
    )
end
for i=DXVars
    eval(strcat(varNamesF(i,:), '=filtfilt(b_CFC180,a_CFC180,', varNamesRaw(i,:), ');
    )
end

CB_AxX=filtfilt(b_CFC60,a_CFC60,CB_AxX);
CB_XiX=filtfilt(b_CFC60,a_CFC60,CB_XiX);
CB_AxY=filtfilt(b_CFC60,a_CFC60,CB_AxY);
CB_XiY=filtfilt(b_CFC60,a_CFC60,CB_XiY);

%% Correct any bias and polarity issues
%Has been updated for ESI

% Unbias all data
for i=1:nV
eval(strcat(varNamesC(i,:),'(:,1)=' varNamesF(i,:),') - mean(varNamesF(i,:),'(Init));'))
end
% for i=1:nVV
%   for j=1:nIV
%     eval(strcat(varNamesVC(i,:),'(:,j)=' varNamesVF(i,:),'(:,j) - mean(varNamesVF(i,:),'(InitV,j));'))
%   end
% end

% Correct polarities
% RamPotC=-RamPotC;
% RamAccC=-RamAccC*9.81; %Convert acceleration to m/s^2
% LCF3C=-LCF3C;
for i=SGVars
  eval(strcat(varNamesC(i,:),'=-',varNamesC(i,:),';'))
end

% Convert accelerometer units to m/s^2
for i=AccelVars
  eval(strcat(varNamesC(i,:),'=9.81*',varNamesC(i,:),';'))
end

%% Copy the filtered, corrected data into the variables without suffixes
% Has been updated for EIS
for i=1:nV
  eval(strcat(varNames(i,:),'=',varNamesC(i,:),';'))
end

%% Calculate Strain Rate
% This has been updated for EIS
for i=SGVars
  eval(strcat(varNames(i,:),'Rate=diff(',varNames(i,:),'/(10^6))/dt ;'))
end

%% Integrate all Accels to Velocities and Positions
% This has been updated for ESI
for i=AccelVars
  eval(strcat(varNames(i,:),'I1(1:Act,1)=0;')) % m/s Set all pre-trigger velocities to 0
eval(strcat(varNames(i,:),'I1(Act:LengthData,1)=cumtrapz(Time(Act:LengthData),','varNames(i,:),'(Act:LengthData));')) %m/s

eval(strcat(varNames(i,:),'I2=cumtrapz(Time,','varNames(i,:),') %m
end

%% Calculate resultant accelerations and velocities for each 6DX
%This has been updated for ESI
for j=1:6
    for i=1:LengthData
        eval(strcat(DxVarNames(j,:),'Res(i,1)=sqrt(((','DxVarNames(j,:),'A1(i))^2)+(''
DxVarNames(j,:),'A2(i))^2)+(''
DxVarNames(j,:),'A3(i))^2));')
        eval(strcat(DxVarNames(j,:),'I1Res(i,1)=sqrt(((','DxVarNames(j,:),'
A1I1(i))^2)+(''
DxVarNames(j,:),'A2I1(i))^2)+(''
DxVarNames(j,:),'A3I1(i))^2));'
end
end

%Identify peak acceleration values
for j=1:6
    eval(strcat(DxVarNames(j,:),'Peak=max(','DxVarNames(j,:),') Res;'))
    eval(strcat(DxVarNames(j,:),'I1Peak=max(','DxVarNames(j,:),') I1Res)
end

%% Calculate chest deflection
%This has been updated for ESI
CB_Ax_Breadth(:,1)=CB_AxY(:,CB_Ax_sides(2))-CB_AxY(:,CB_Ax_sides(1));
ChestDef_AxLat(:,1)=CB_Ax_Breadth(Act)-CB_Ax_Breadth;

CB_Xi_Breadth(:,1)=CB_XiY(:,CB_Xi_sides(2))-CB_XiY(:,CB_Xi_sides(1));
ChestDef_XiLat(:,1)=CB_Xi_Breadth(Act)-CB_Xi_Breadth;

ChestDef_AxAP(:,1)=CB_AxX(Act,CB_Ax_Strnm)-CB_AxX(:,CB_Ax_Strnm);
ChestDef_XiAP(:,1)=CB_XiX(Act,CB_Xi_Strnm)-CB_XiX(:,CB_Xi_Strnm);
ChestDef_6DXAP(:,1)=(DxManA3I2+DxT4A3I2)*1000; %mm