Development of a Preliminary Response Corridor for Combined Loading of the Lumbar Spine

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ABSTRACT

As human travel evolves and new seating configurations are introduced, it is important to understand how these seating configurations impact injury risk. In recent years, the installation of passenger seats at an angle offset from the direction of travel (oblique seats) has gained popularity with airplane manufacturers. Existing seat safety standards were not created specifically for oblique seats, so it is unknown whether current standards provide the best level of protection for obliquely seated occupants. Previous Postmortem Human Surrogate (PMHS) tests have been conducted to investigate gross occupant kinematics in an oblique seating posture during a crash scenario. From this testing, severe lumbar spine injuries were produced through a combination of multi-axis bending and distraction. In an effort to better understand the loads associated with these injuries and how they differ from injuries in a forward-facing seat, an experimental isolated PMHS spine study was created. Eight PMHS isolated lumbosacral spines were tested in tension on an electrohydraulic piston while positioned in three separate postures: the spines naturally unloaded posture (neutral), flexed forward (flexed), and flexed and laterally bent 15° (oblique). With the sacrum fixed, a sub-failure tensile test to 4 mm of T12 displacement was conducted in each posture, followed by a tensile test to failure in the oblique posture (n=5) or flexed posture (n=3). Test specimens were isolated from T11/12 through the sacrum and were potted in Polymethyl methacrylate (PMMA). Both the T12/L1 and L5/S1 junctions were kept unrestricted. Retroreflective markers were used for motion analysis. Bolted to both the inferior and superior PMMA were 6 axis load cells. Force and moment data were collected. The inferior load cell was then attached to a novel positioning table, and the superior load cell was attached to the electrohydraulic piston. Using rigid body transformations, the inferior load cell data were transformed to anatomic loads at the center of the sacral end plate. Using the method developed by Lessley et al., a preliminary response corridor was created for the tensile force of the oblique failures. The oblique response corridor demonstrates a large difference when compared to the average tensile response in the flexed position as well as existing flexion-distraction injury literature. The upper bound of the corridor has a peak load and displacement of 4150 N at 13 mm. These values are 13% and 24% less, respectively, than the average peak load and displacement of the flexed position failures. The application of the corridor development method introduced by Lessley et al. proved to be an appropriate method to analyze the current data. The corridors were able to both retain the characteristic shape of the load curves, and demonstrate the differences between the two loading scenarios and previous literature.

INTRODUCTION

As human travel evolves and new seating configurations are introduced, it is important to understand how these seating configurations impact injury risk. In recent years, the installation of passenger seats at an angle offset from the direction of travel (oblique seats) has gained popularity with airplane manufacturers. Existing seat safety standards were not created specifically for oblique seats, so it is unknown whether current standards provide the best level of protection for obliquely seated occupants. Previous Postmortem Human Surrogate (PMHS) tests have been conducted to investigate gross occupant kinematics in an oblique seating posture using the prescribed emergency landing test conditions set forth by the FAA (Humm et al., 2015). From this testing, severe lumbar spine injuries were produced through a combination of multi-axis bending and distraction. In an effort to better understand the loads associated with these injuries and how they differ from injuries in a forward-facing seat, an experimental isolated PMHS spine study was created. Data from the isolated experimental tests suggests a significant difference in loading between spines failed in an obliquely bent position and spines failed in a flexed position. The objective of the current work is to apply a previously developed corridor creation method to the isolated spine experimental failure data to demonstrate differences in loading between the two failure conditions. Using this novel data to develop response corridors is crucial to creating validation criteria for ongoing and future computational modeling studies investigating the models response to oblique loading scenarios.

METHODS

Specimen Preparation

Unembalmed, PMHS, whole lumbar spines were used in testing. Test specimens were isolated from T12 to the sacrum and were cleared of surrounding musculature leaving ligamentous structures intact. The ends of the specimen were potted in polymethyl methacrylate (PMMA) in such a way that left both the T12/L1 and L5/S1 joints unrestricted. The inferior endplate of T12 and the sacral endplate were both positioned parallel to their respective PMMA potting using x-ray imaging. This allowed for easy and accurate measurement of spine bending during testing without the need for radiography. Custom pins were inserted into each vertebra to allow the attachment of 3 non-collinear motion capture markers. Markers were also taped to the potting on both ends as the PMMA prevented pins from being inserted into T12 and the sacrum. Once prepared and instrumented with the motion capture markers, specimens underwent a pre-test CT scan. Scans were used to aid in the identification of post-test injuries as well as in relating motion capture data to anatomic motion.

Test Setup and Procedure

Eight spines were tested in tension on an electrohydraulic piston (MTS, Eden Prairie, MN) while subjected to three distinct postural preloads through the use of a custom positioning device. The postures were the spines naturally unloaded posture (neutral), flexed forward (flexed), and flexed and laterally bent 15° (oblique). The superior end of the spine was attached to the piston actuator and the inferior end was attached to the positioning table. 6 axis load cells (Sunrise Instruments, Canton, MI) were attached to both the superior and inferior PMMA between the potting and the test fixture. A 3D motion capture system (Vicon, Oxford, UK) was used to track the movement of each vertebra. A uniaxial accelerometer was also attached to the piston to corroborate test displacement and velocity. Load cell, piston, and accelerometer data were collected at 20 kHz, and motion capture data were collected at 1 kHz.

Prior to testing, spines were attached to the piston and manually manipulated to determine the subject specific terminal flexion angle. This was done by manually flexing the inferior end of the spine to a reading of 30 Nm of flexion as measured by the T12 load cell. Spines were then allowed to hang in their natural, unstressed position, and the positioning table was attached while minimizing loading. Once attached to the table, spines underwent 20 cycles of cyclic preconditioning to 3 mm of distraction conducted at 1 Hz. The spines then underwent one sub failure tensile test of 4 mm in each of the three test positions (neutral, flexed, and oblique). Spines were then failed in tension in either the flexed or oblique position by a displacement of 30 mm. An acceptable failure was determined as a predominately soft tissue injury at the L5/S1 level. This created five oblique position failures and three flexed position failures.

Data Analysis and Corridor Development

Custom MATLAB (MathWorks, Natick, MA) scripts were used to process the data. Data were filtered according to SAE J211 specifications and laboratory best practices. Instrumented CT scans allowed the relation of motion capture markers to anatomic landmarks through the use of 3DSlicer software (Fedorov et al., 2012). These relationships were used to transform load cell data to anatomic loads at the center of the sacral endplate through the use of rigid body transformations. The data from the oblique failure tests were used to create injury response corridors. Corridors were created using the method developed by Lessley et al. that accounts for standard deviations in both the independent and dependent variables (Lessley et al. 2004). This method is applicable to time independent data, which was an important factor in its selection as the data of interest are displacement based.

The first part of the analysis concerns the development of a characteristic average response. This averaging technique allows the data to maintain load response trends that provide a more accurate representation of the characteristic shape than a simple average does (Lessley et al., 2004). A variation of the method developed by Lessley et al. was used for this step. The original procedure calls for each raw displacement curve to be divided by its individual maximum displacement. Here, each total column displacement curve was divided by the displacement corresponding to the maximum tensile force (Figure 1). The location of maximum tensile force was determined to be the point of ultimate failure of the spine and was thus the location of maximal importance. Each spine was tested to a total column displacement (T12 relative to sacrum) of 30 mm, but each spine failed at a different amount of displacement less than 30 mm. This same normalized displacement curve was applied to all three loads of interest: the tensile force (z-force), flexion moment (y-moment), and lateral bending moment (x-moment). Meaning, x- and y-moment displacement curves were also normalized to the location of the maximum z-force. This allowed the relationships between the peak moment timing and peak force timing to remain intact for each specimen.

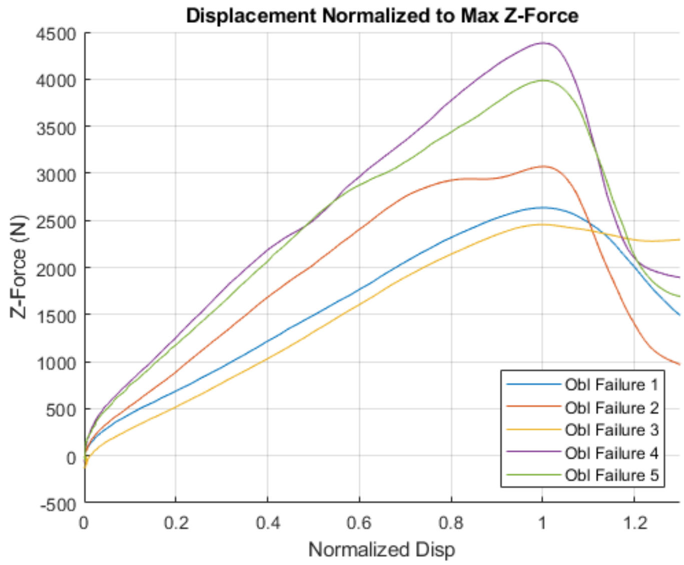

Figure 1: Z-force VS displacement normalized to the location of peak z-force for each oblique failure test.

Having normalized the displacement data, the force and moment data were interpolated to define values at common normalized deflection values. Data were then averaged at each common deflection value for the three loads of interest. The final step in the characteristic average development was scaling the normalized displacement points by the average displacement at failure for each specimen. This created an average response that maintained the characteristic behavior of each individual failure response, which the simple average failed to do (Figure 2).

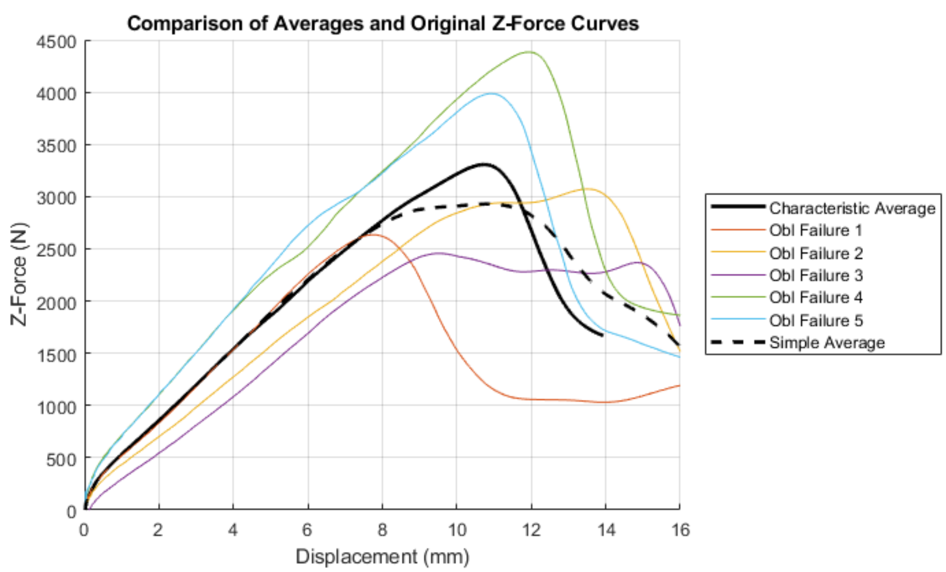

Figure 2: A comparison of the z-force VS displacement of characteristic average, simple average, and individual responses.

With the characteristic average created, the corridor could be developed around it. The first step of this was to calculate the standard deviation (S.D.) of the load for each common normalized displacement point on the characteristic average curve. Step two was to go back to the raw data and normalize load curves by the maximum load value (Figure 3). Unlike with displacement, each load curve (z-force, x-moment, y-moment) was normalized according to its own maximum value. Interpolation was then used to get displacement values at common normalized load values. After this, the standard deviation in deflection was found for each normalized load value. This step, as noted by Lessley, can cause issues with overestimating the standard deviations due to the presence of multiple displacement values for a single load value (Lessley et al., 2004). To avoid this, each inflection point was used to create data sections that prevented the S.D. data from becoming erroneously large.

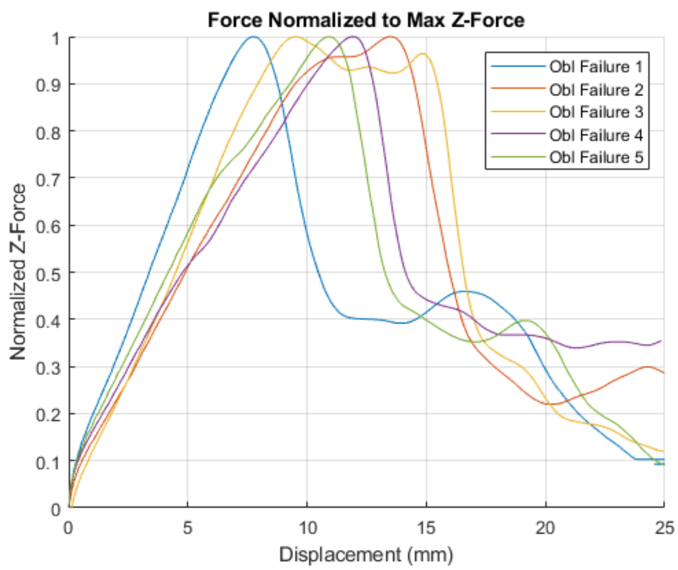

Figure 3: Normalized z-force VS displacement for each oblique failure test.

With the S.D. found for both load and deflection at each data point on the average curve, the four “extreme values” for each point were calculated. The values correspond to the points created from the four possible combinations of each data point and its respective standard deviations in both directions. From there, the curves created by the four extreme values were plotted and the highest and lowest points on the curves were used to create cohesive upper and lower bounds to the curve (Figure 4). Due to the difficulty in interpolating the independent variable, some numerical errors do occur, which can be seen as inconsistencies in the corridor bounds. Because of limited test data, corridors were not created for the flexed failure position. Only the characteristic average response will be included for flexed failures.

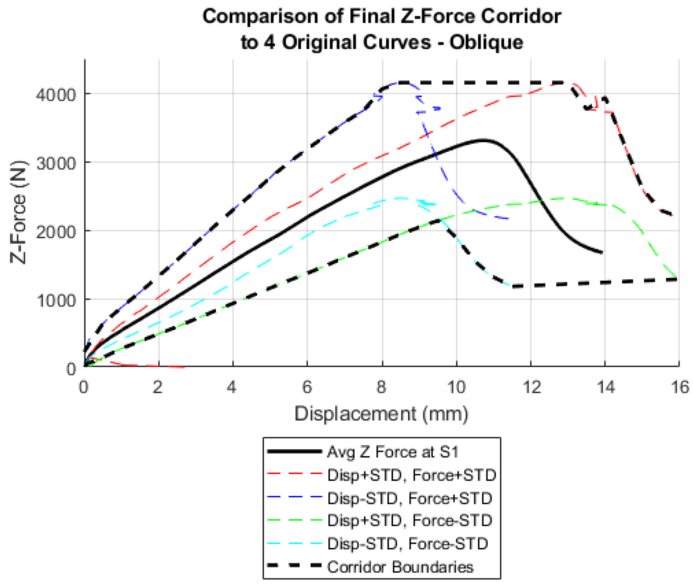

Figure 4: Comparison of final corridor boundaries to “extreme value” curves.

RESULTS

The upper bound has a ceiling of 4150 N, with a displacement range of 8.5 to 13 mm (Figure 5). The lowest estimated point of failure is 2136 N at 9.5 mm. Peak average response is 3306 N at 10.74 mm.

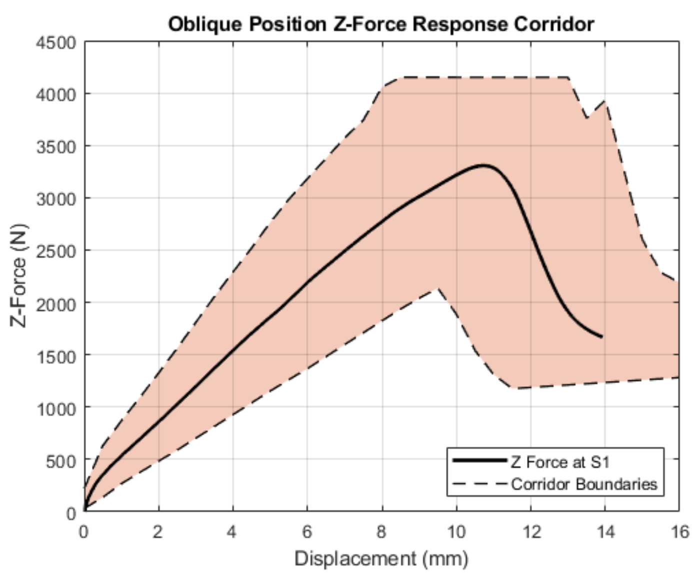

Figure 5: Response corridor for z-force of spines failed in an obliquely bent position.

Average peak values for the flexed condition were 4775 N at 17.03 mm. The upper bound of the oblique corridor has a peak load and displacement of 4150 N at 13 mm. These values are 13% and 24% less, respectively, than the average peak load and displacement of the flexed position failures (Figure 6). The maximum force from the upper bound is 5.7% less than the lower severity dynamic test from Neumann et al., and 20% less than the higher severity dynamic test (Neumann et al. 1995).

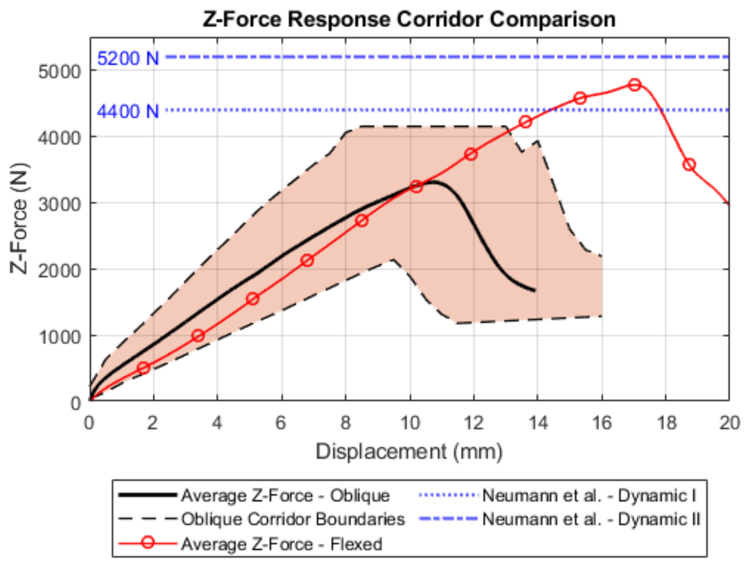

Figure 6: Comparison of oblique corridor to flexion-distraction failure values.

DISCUSSION

The use of response corridors is an important tool to demonstrate the range of responses that can be seen from a given loading scenario. These corridors provide an important reference against which load responses from other scenarios can be compared. Experimentally, this can be used to compare the response between two different test conditions to evaluate the similarities in loading. For the given analysis, the oblique response corridor for a spine failed in combined flexion, lateral bending, and tension is compared to the average response of a spine failed in combined flexion and tension. The oblique response corridor demonstrates a large difference when compared to the average tensile force response in the flexed position as well as existing flexion-distraction injury literature. Not only is there a considerable difference between loads at failure, but also between the amount of column displacement at failure. As seen in the results, the maximum point on the upper oblique corridor boundary shows 13% less force and 24% less displacement at failure as compared to the flexed position average response. Moreover, the peak average oblique response demonstrates a 31% decrease in force and a 37% decrease in displacement. Both the average responses and corridor demonstrate the large differences that exist between lumbar spines failed in quasi-static oblique bending and tension as compared to quasi-static flexion and tension.

Given the novelty of the current work, there is minimal literature which can appropriately be compared to the corridor. Work conducted by Neumann et al. in 1995 does offer some comparison. Neumann tested lumbar spine functional spinal units (FSUs) to failure through dynamic flexion-distraction using two different pulse severities – Dynamic I (less severe) and Dynamic II (more severe) (Neumann et al., 1995). Failure patterns similar to the current work were seen in the way of tensile injuries to the posterior and middle columns of the FSU. Neumann found average peak tensile loads of 4.4 kN (Dynamic I) and 5.2 kN (Dynamic II) for the two levels of test severity. Both average tensile force at failure values lie outside of the oblique upper corridor bound, and on either side of the average peak tensile force found in the flexed position from the current study. The data from Neumann et al. offers an interesting comparison. Although the loading mechanism was slightly different, test severities were comparable to those used in the current study. The current study employed quasi-static bending and dynamic tension and the work by Neumann involved both dynamic bending and tension. Despite the differences in bending load application, similar responses were seen in regards to the average tensile force in the flexed position of the current study. This further strengthens the finding that loading in the oblique position is substantially different from that in the flexed position.

While the applied corridor method has shown to provide a load response that represents the data well, and demonstrates differences among test positions, it is not without limitations. The major limitation of the study is the small sample size for each test condition. Given more data, the corridor would likely provide increased confidence in its ability to define the predicted load response. Additionally, the use of standard deviations for both the dependent and independent variables could lead to an overestimate of corridor size. This point does, however, strengthen the conclusions about the difference in loading between the two test conditions. Even with the possibility of an overestimated corridor, demonstrable differences between the two conditions remain.

CONCLUSIONS

The application of the corridor development method introduced by Lessley et al. proved to be an appropriate method to analyze the current data. The corridors were able to both retain the characteristic shape of the load curves, and demonstrate the differences between the two loading scenarios and previous literature. Given the novelty of the test data, the creation of response corridors is an important outcome that can be used as a comparison for future experimental work as well as computational models. Future work will be the creation of corridors for multiple load metrics. These corridors will then be used in a novel validation study of a previously developed finite element model.

ACKNOWLEDGEMENTS

This material is the result of work supported with resources from the Federal Aviation Administration (grant FAA-17G002) and use of facilities at the Zablocki VA Medical Center, Milwaukee, WI. Any views expressed in this article are those of the authors and not necessarily representative of the supporting organizations. An additional thank you goes to Justine Bales for her instrumental work in data collection.

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