THORACIC BIOFIDELITY ASSESSMENT OF THE THOR MOD KIT ATD

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Paper Number 13-0327

ABSTRACT

During the upgrade of the 50th percentile male THOR anthropomorphic test device (ATD) from the Alpha level to the NT level, the low-speed Kroell hub impact corridor was selected as the design requirement for blunt thoracic impact response. Although this requirement was reiterated during the development of the THOR Mod Kit, it has been documented that the response of the thorax does not meet the design requirement. There were three objectives to this study: first, to quantify the thoracic biofidelity of frontal impact ATDs; second, to demonstrate that the Mod Kit design level of the THOR ATD meets the intended the low-speed blunt thoracic impact biomechanical response requirement; and third, to evaluate the influence of the SD-3 shoulder design on the performance of the THOR ATD in blunt thoracic impact. Data were collected from low-speed (4.3 meters per second) blunt thoracic impact tests of several variations of 50th percentile male ATDs: Hybrid III, THOR-NT, THOR Mod Kit, and THOR Metric. The latter two THOR variations were tested both with and without an updated shoulder ("SD-3") used in the European Union's THORAX project demonstrator. The thoracic force-deflection responses were qualitatively compared to the existing low-speed thoracic impact response corridors: the Kroell corridor, based on internal deflection, and the Lebarbé corridor, based on external defelction. The THOR-NT and THOR Mod Kit responses showed force levels similar to the biomechanical response requirements, but deflections lower than desired. The repeatability array carried out on one THOR Mod Kit ATD showed no notable variations in force or deflection. Quantitative comparison of the ATD impact response to the biofidelity corridors was carried out using a biofidelity ranking system, which was used to demonstrate that the response of the THOR ATDs are not differentiable from the human subjects used to develop the corridors. The low-speed blunt thoracic impact response requirement for the THOR Mod Kit design level was met both qualitatively and quantitatively. The installation of the SD-3 shoulder influenced the resulting biofidelity ranking system results, but did not change the order of ranking of either the THOR Mod Kit or the THOR Metric ATDs. This study is limited by the volume, quality, and specificity of the PMHS data.

INTRODUCTION

The National Highway Traffic Safety Administration (NHTSA) has been researching advanced anthropometric test devices (ATDs) to succeed the Hybrid III ATD since the early 1980s (Haffner, 2001). The primary design objective of this research was to represent the response of automotive occupants in sophisticated restraint systems developed since the advent of the Hybrid III, such as force-limited three-point belts and air bags. This research has culminated in the development of the Test Device for Human Occupant Restraint (THOR), first as the THOR Alpha (Haffner, 2001) and later upgraded to the THOR-NT (Shams, 2005). Most recently, in coordination with the Society for Automotive Engineers (SAE) THOR Evaluation Task Group, a modification package ("Mod Kit") intended to enhance the biofidelity, repeatability, durability, and usability of the THOR was introduced (Ridella, 2011) and installed as an upgrade kit on the NHTSA-owned fleet of THOR-NT ATDs. One of the primary requirements of the Mod Kit upgrade was to ensure thoracic biofidelity as assessed by the low-speed Kroell blunt hub impact corridor. Although this design requirement was first implemented during the upgrade from THOR Alpha to THOR-NT and reiterated during the development of the THOR Mod Kit, it has been documented that the response of the thorax does not meet this design requirement (Ridella, 2011; Mueller 2011).

Subsequent to the development of the THOR Mod Kit, an upgrade to the Chalmers shoulder assembly known as the "SD-3" was developed through the European Union's THORAX project (Lemmen, 2012). This shoulder assembly is currently being evaluated to determine its suitability for inclusion in the THOR drawing package. One step in this evaluation is to install the shoulder on the THOR ATD and compare the response to both the standard shoulder response and to the biomechanical response requirement.

There are three objectives in the current study: first, to quantify the thoracic biofidelity of frontal impact ATDs; second, to demonstrate that the Mod Kit design level of the THOR ATD meets the intended the low-speed blunt thoracic impact biomechanical response requirement; and third, to evaluate the influence of the SD-3 shoulder design on the performance of the THOR ATD in blunt thoracic impact.

Figure 1. THOR Metric ATD

METHODS

The first objective of this study can be addressed using a biofidelity ranking system, but to implement such a system in this case, several steps were necessary to prepare the both the existing biofidelity corridors and the collected test data (Figure 2). First, since the biofidelity corridor used as the primary THOR design requirement ("Kroell") exists as a force-deflection characteristic, it was necessary to develop internal (skeletal) deflection and force time history data before the biofidelity ranking system could be implemented. This was carried out using a three degree-of-freedom "Lobdell" model fit to the response corridor. Then, for each ATD configuration, at least one blunt thoracic impact test was carried out. The measured thoracic response was compared to the Kroell corridor time histories using the biofidelity ranking system. Next, in order to develop the external deflection for comparison to the Lebarbé corridor, a Lobdell model was fit to the response of the blunt thoracic impact test. This process resulted in four measurements of thoracic impact response biofidelity for each ATD.

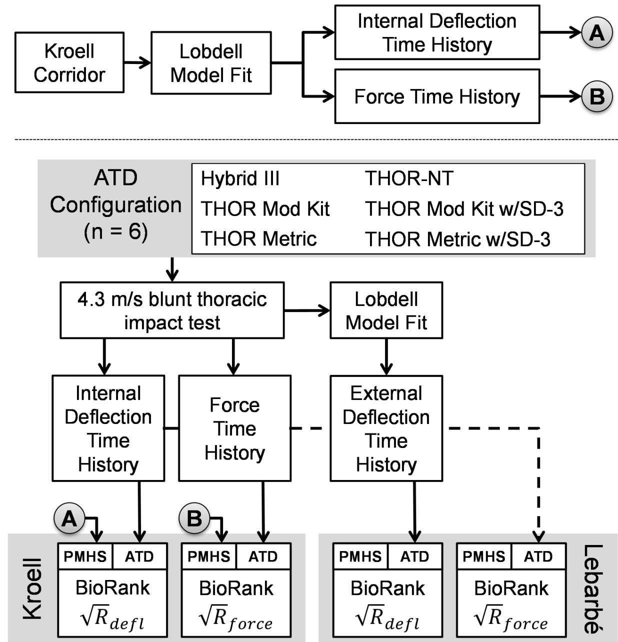

Figure 2. Methodology employed in this study to quantify biofidelity of thoracic impact response.

Blunt Thoracic Impact Tests

Low-speed blunt thoracic impact tests were carried on four different 50th percentile male ATDs: Hybrid III, THOR-NT, THOR Mod Kit, and THOR Metric. The THOR Mod Kit and the THOR Metric were tested both with the standard THOR-NT shoulder and with SD-3 shoulder, for a total of six configurations (Table 1). In each test, the response force imparted on the impact pendulum and the internal deflection time histories were recorded. In one test (THOR Mod Kit w/SD-3), high-speed video of the impact event was recorded from the side and film analysis was used to calculate external deflection by measuring the change in distance between the impactor face and the posterior aspect of the ATD starting at the time of first contact.

Anthropomorphic Test Devices

The THOR-NT, which was built by GESAC, Inc., was based on the drawing package released in 2005. The THOR Mod Kit was originally built as a THOR-NT by GESAC, Inc., and then subsequently modified by Humanetics Innovative Solutions, Inc. to the Mod Kit build level (Ridella, 2011). The THOR Metric (Figure 1) was built by Humanetics to the same design as the THOR Mod Kit, except that it was built from scratch instead of upgrading a THOR-NT. While there are some detailed differences between the THOR Mod Kit and the THOR Metric, such as the imperial fasteners in the THOR Mod Kit compared to the metric fasteners in the THOR Metric, the performance requirements for both ATDs are based on the test conditions defined by the biomechanical response requirements and certification requirements of the THOR-NT (NHTSA, 2005a,b), with additional requirements specified during the development of the Mod Kit (Ridella, 2011).

Table 1. Test Objects

Identifier	Description
Hybrid III	As described in 49 CFR Part 572 Subpart E
THOR-NT	As described in THOR-NT technical data package (http://www.nhtsa.gov/Research/Biomechanics+&+Trauma/>> THOR-NT+Advanced+Crash+Test+Dummy)
THOR Mod Kit	As described in Ridella, 2011
THOR Mod Kit w/SD-3	As described in Ridella, 2011 except for the shoulder assembly. SD-3 shoulder assembly as described by Lemmen et al (2012) is installed
THOR Metric	As described in Ridella, 2011 but with the remaining components soft-converted (exact unit conversion without change in precision or physical configuration) to metric dimensions and metric fasteners used throughout
THOR Metric w/SD-3	As described in Ridella, 2011 but with the remaining components soft-converted to metric dimensions and metric fasteners used throughout. Additionally, SD-3 shoulder assembly as described by Lemmen et al (2012) is installed

Biomechanical Response Requirements

The Biomechanical Response Requirements for the THOR ATD (NHTSA, 2005a) specify two test conditions that were used as design requirements. The first condition is a blunt thoracic impact, which consists of a 23.4 kilogram pendulum with a 152.4 millimeter diameter flat face impacting the center of the sternum at 4.3 meters per second. The 6.7 meter-per-second impact was originally included in the design requirements, but this requirement was relaxed during the development of the Mod Kit. The 6.7 meter-per-second condition remains as a certification condition, but primarily to assess the durability of the ATD. The second condition describes a 15 degree oblique impact to the lower thorax using the same impactor characteristics.

Calculation of Thoracic Deflection

In the design of the THOR-NT, the thoracic deflection instrumentation is initially aligned with the coordinate system of the pendulum. However, this is not necessarily effective for rib strain estimation, as this effectively measures the change in distance between the 4^{th} rib and the 8^{th} thoracic vertebral body. In this arrangement, rotation of the ribs about the spine can be measured as deflection, but such deflection does not necessarily relate to rib strain. In the design of the THOR Mod Kit, the upper thorax deflection instrumentation was attached to the same spine segment as the rib attachment, which is thought to be a more accurate representation of rib strain, which in turn is believed to be a predictor of rib fracture (Forman, 2012)

However, this presents an additional layer of processing difficulty, as the coordinate system used to measure skeletal deflection on the THOR Mod Kit is not parallel to the impactor in the blunt thoracic impact test, thus may not record the total skeletal deflection. As previously presented (Shaw, 2012), the methodology to process the IR-TRACC chest deflection instrumentation presents the three-dimensional deflections in the coordinate system of the upper spine, which is roughly 20 degrees forward of vertical. During the blunt thoracic impact event, the THOR rib cage compresses towards and rotates downward about the upper spine. This results in compression of the chest along the axis of the impactor that is not captured by the upper spine local X-axis. To account for this, both the local X- and Z-axes of deflection in the upper spine coordinate system must be evaluated (Appendix A).

Biofidelity Ranking

The biofidelity ranking system ("Bio Rank" for short) calculation assesses the biofidelity of an ATD by comparing the dummy response to the mean cadaver response. To account for the potentially large variability in individual cadaver responses, Bio Rank calculates a cumulative variance between the dummy response and the mean cadaver response (DCV) and normalizes this value by the cumulative variance between the mean cadaver response and the mean plus one standard deviation cadaver response (CCV) (Rhule, 2002). For example, given a fixed dummy response, the DCV/CCV value would be higher for a narrow corridor of cadaver response corridor compared to a wide corridor of cadaver response. For the current effort, the $\sqrt{R}$ terms for deflection and force are presented both individually and combined to allow multiple levels of comparison. The biofidelity targets for the deflection and force time-histories are limited to the timeframe between 0 and 500 milliseconds, since the impactor is no longer in contact with the occupant. While the unloading portion of the event is important in that the unloading hysteresis is one representation of the viscoelastic properties of the occupant, including too much of the unloading portion could override response at peak force, which has a stronger relationship to injury risk.

Generation of Mean, +/- SD for Kroell Corridor

The design requirement for response to blunt thoracic impact for the THOR ATD was specified using the corridors known as the Kroell corridors, developed from several series of PMHS impacts in the early 1970s (Neathery, 1974). From these tests, a biofidelity corridor for low-speed (4.3 meters per second) blunt thoracic impact was developed through an oft-criticized “eyeball averaging” method, though subsequent reanalysis has not shown significant differences from this method (Lessley, 2004).

Since the Kroell corridor exists in the force-vs-deflection domain and not the time domain, the calculation of Bio Rank is not straight-forward. In order to achieve the time histories of force and deflection for the mean response, a simplified Lobdell model (Lobdell, 1973) was formulated (Figure 3). The simplified Lobdell model includes 8 variables and two constants (Table 2). This model was optimized to match the mid-points of the low-speed thoracic impact response corridor as defined in the THOR Biomechanical Response Requirements manual (Figure 4).

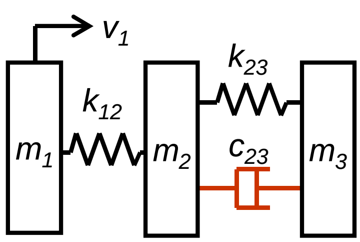

Figure 3. Simplified Lobdell model implemented in this study

Table 2. Variables in the Simplified Lobdell model of thorax response to blunt hub impact

Variable	Description
m_1	mass of impactor
m_2	mass of the sternum, anterior rib cage
m_3	mass of the remaining coupled mass of the body
k_{12}	stiffness of the skin/muscle in front of sternum
k_{23a}	stiffness of rib cage before k_{23s}
k_{23b}	stiffness of rib cage after k_{23s}
k_{23s}	inflection point of piecewise linear stiffness k_{23}
c_{23a}	viscous response of thorax compression
c_{23b}	viscous response of thorax extension
v_1	initial velocity of the impactor

The optimization was configured to minimize the objective function defined by the sum of the normalized distances from each target point (represented by red stars in each relevant plot) and the nearest point on the Lobdell model force-vs-deflection response. To ensure a global solution in the optimization, an initial design array was developed by generating 100,000 designs by randomizing variable values between 0.1 times and 10 times the values provided for the initial dummy targets (Lobdell, 1973). The design that demonstrated the best fit was then used as the input to a brute force optimization using the ranges defined by +/- 20% of each variable value.

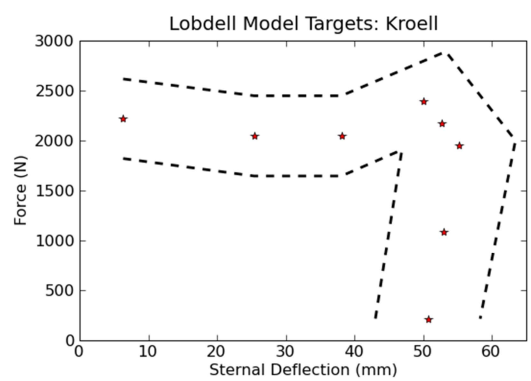

Figure 4. 4.3 meters per second blunt thoracic impact response requirement (NHTSA, 2005a) in dashed black line, along with optimization target points (red stars).

The mean response was then scaled in the deflection and force axes by 15% (as described in Neathery, 1974) to create the upper and lower boundaries of the force and deflection time-histories for use in the Bio Rank calculation.

Generation of Mean, +/- SD for Lebarbé Corridor

In support of the International Standards Organization (ISO) Frontal Biofidelity Specification

International Task Force (ISO/TC22/SC12/WG6), new biomechanical response targets were developed in the low-speed blunt thoracic impact condition (Lebarbé, 2012). These targets have since been adopted by the European Union's THORAX project, which aims to develop a thoracic impact response demonstrator which has been installed on a THOR ATD. The development of this corridor included a different normalization process, along with additional newer data sets, compared to the Kroell corridor. Since this corridor was developed by calculating the mean and standard deviations of the force and deflection time-histories, it is suitable for evaluation using Bio Rank. Nonetheless, a Lobdell model was optimized to the Lebarbé corridor to allow an apples-to-apples comparison with the Kroell corridor (Figure 5).

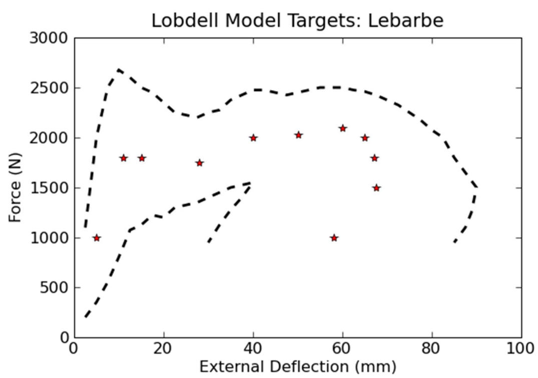

Figure 5. 4.3 meters per second blunt thoracic impact response target (Lebarbé, 2012) in dashed black line, along with optimization target points (red stars).

Estimation of External Deflection for THOR (based on THOR-K SD3 tests)

The two targets for blunt thoracic impact response differ in that the Kroell target is based on skeletal deflection, while the Lebarbé target is based on external deflection. Both the certification requirements and the biomechanical response requirements for the THOR ATD (NHTSA, 2005a,b) specify that internal (skeletal) deflection shall be measured. As such, a comparison to the Lebarbé target is not possible. To address this issue, a series of blunt thoracic impact tests were conducted, using both the THOR Mod Kit and the THOR Mod Kit with the SD-3 shoulder installed, which employed high-speed video to track the external deflection in addition to internal deflection measured by the thoracic IR-TRACC instrumentation.

Ideally, the external deflection measured should be related to the internal deflection by some transfer function. However, due to various nonlinearities, this cannot be calculated by a simple shifting and/or scaling of the internal deflection. Therefore, to address this issue, a Lobdell model was fit to the response of the THOR internal response the same way it was fit to the Kroell corridor, except this time the deflection time-history was used as the target. Once optimized to recreate the skeletal deflection using the differential motion of m_2 and m_3, the model can be used to predict external deflection based on the differential motion of m_1 and m_3. The quality of this prediction can be evaluated using the THOR Mod Kit with SD-3 test condition, where both internal and external deflections were measured.

RESULTS

Repeatability

For all of the ATDs included in this study, local repeatability (same ATD, same laboratory, consecutive tests) was excellent (Figure 6). Since the repeatability was good, the Bio Rank subsequent calculations were carried out using just one of the sets of test results for each ATD, since calculating an average of the response time-histories could result in smoothing or filtering of the responses if the timing was not identical, resulting in non-physical nonlinearities.

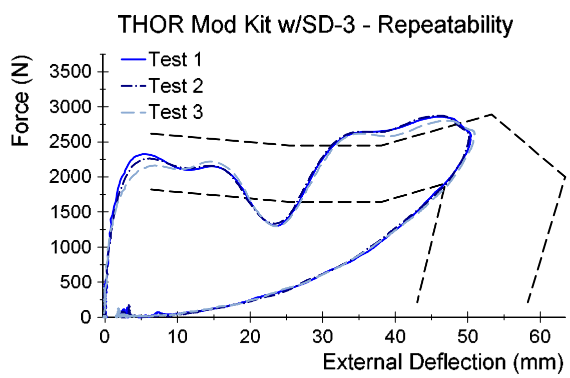

Figure 6. Three consecutive repeated blunt thoracic impact tests on a THOR Mod Kit w/SD-3 shoulder (S/N 16).

Response to Blunt Hub Impact

In a blunt thoracic impact with a 23.4 kilogram impactor at 4.3 meters per second, compared to the Kroell internal deflection corridor the Hybrid III shows the stiffest response, with a peak force about 1,000 Newtons higher than the corridor and a peak deflection 10 millimeters less than the peak of the lower boundary of the corridor (Figure 7). The THOR-NT response (Figure 8) is stiffer than the THOR Mod Kit response (Figure 9), which is in turn stiffer than the THOR Metric response (Figure 10). When installed on the THOR Mod Kit, the SD-3 shoulder resulted in a similar peak deflection as the standard shoulder, while some of the local peaks in force have been smoothed out. When installed on the THOR Metric, there peak deflection is reduced by roughly five millimeters, and the local peaks in force are similarly smoothed out.

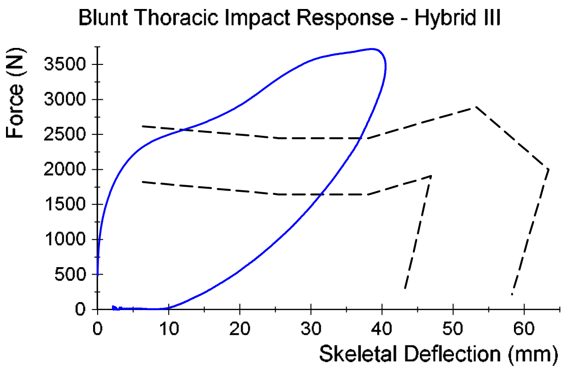

Figure 7. Force-deflection response of the Hybrid III under 23.4kg, 4.3m/s blunt thoracic impact.

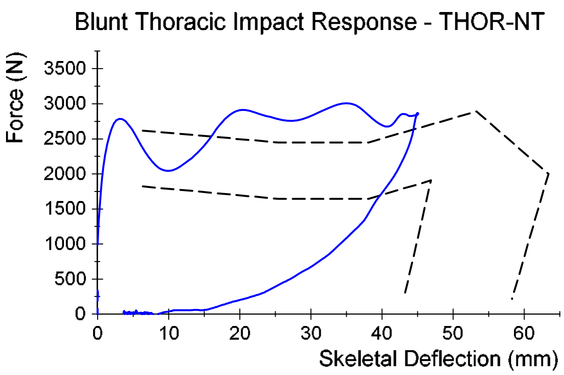

Figure 8. Force-deflection response of the THOR-NT under 23.4kg, 4.3m/s blunt thoracic impact.

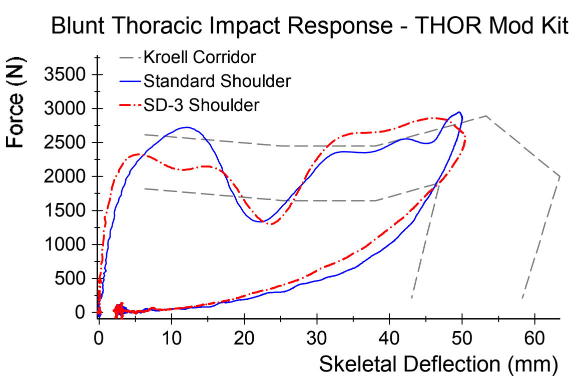

Figure 9. Force-deflection response of the THOR Mod Kit with and without the SD-3 shoulder under 23.4kg, 4.3m/s blunt thoracic impact.

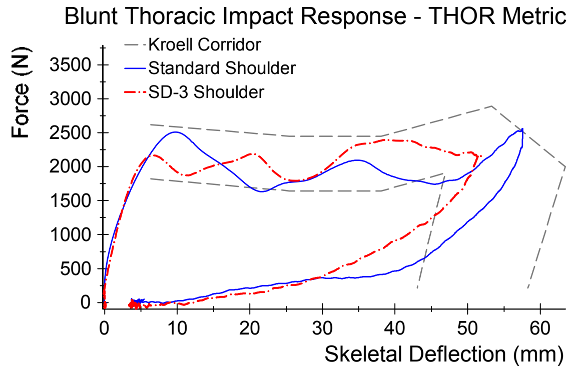

Figure 10. Force-deflection response of the THOR Metric with and without the SD-3 shoulder under 23.4kg, 4.3m/s blunt thoracic impact.

Generation of Mean, +/- SD for Kroell Corridor

The optimized Lobdell model of blunt thoracic impact achieved good qualitative and quantitative agreement with the center of the Kroell corridor (Figure 11). The scaled upper and lower boundaries generally conformed to the boundaries of the original Kroell corridor, though naturally the sharp creases were not able to be represented with the simple Lobdell model. The resulting skeletal deflection and force time-histories (Figure 12) were similar in shape to those of the Lebarbé targets (Figure 13). Note that both deflection time-histories show a very narrow corridor width at the onset of force and deflection, though only the Kroell force time-history narrows at the end of the force time-history

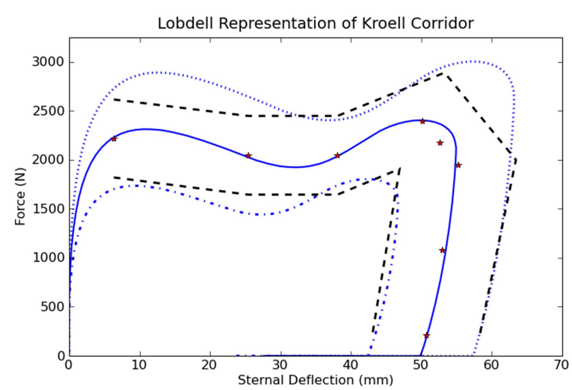

Figure 11. Lobdell model response that best fits the center of the Kroell corridor.

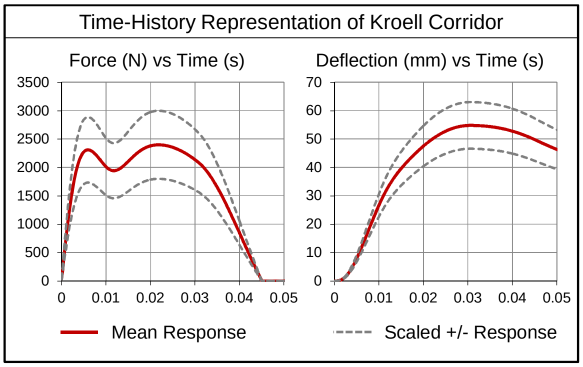

Figure 12. Representation of the force (left) and skeletal deflection (right) components of the Kroell corridor as a time-histories for use in Bio Rank calculations.

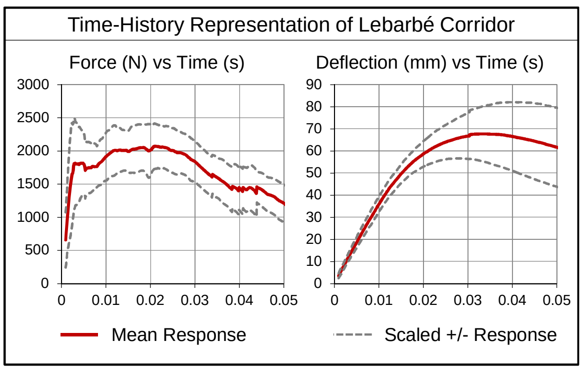

Figure 13. Representation of the force (left) and external deflection (right) components of the Lebarbé corridor as a time-histories for use in Bio Rank calculations.

Comparing the Lobdell model fits of the Kroell and Lebarbé corridors, the parameters resulting in optimal fit to the corridor centerline were noticeably different for the two conditions (Appendix B). However, the Kroell response, when represented in the same external deflection basis as the Lebarbé response, fits within the plus or minus standard deviation corridor for a majority of the response (Figure 14).

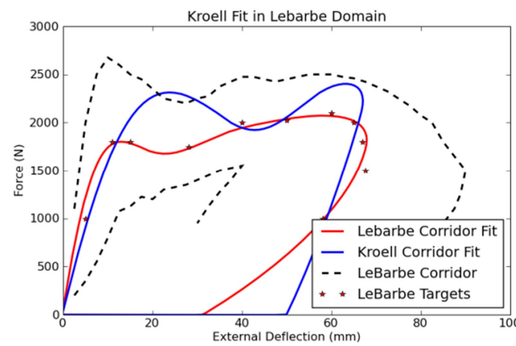

Figure 14. Lobdell model response that best fits the Lebarbé corridor mean response.

Estimation of External Deflection for THOR (based on THOR-K SD3 tests)

For each of the tests for which external deflection was not explicitly measured during a test with high-speed video, the external deflection was determined by first fitting a Lobdell model to the measured sternal deflection, then outputting the impactor-to-spine deflection predicted by this Lobdell model. To validate this methodology, the external deflection measured during the test of the THOR Mod Kit with SD-3 was compared to the Lobdell model prediction (Figure 15). The peak deflection predicted by the model is 60.5 millimeters, compared to 75.3 millimeters measured during the test. It should be noted that this measured deflection is based on post-processing of high-speed video data, which introduces numerous error sources including images resolution, lens distortion, and synchronization of test data and video data.

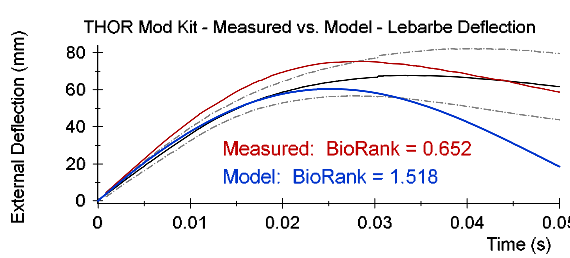

Figure 15. Comparison of the measured and predicted external deflection (and force-deflection response) of the THOR Mod Kit with SD-3 ATD.

The same trends in relative stiffness that appear in the Kroell corridor comparison (Figure 7 through Figure 10) are repeated in the Lebarbé corridor comparison (Figure 16 through Figure 19). Note that these responses present the force and external deflection time-histories predicated by the Lobdell model. Qualitatively, out of the ATDs included in this study the response of the THOR Metric with the SD-3 shoulder is the closest to meeting both the Lobdell (Figure 10) and the Lebarbé (Figure 19) corridors.

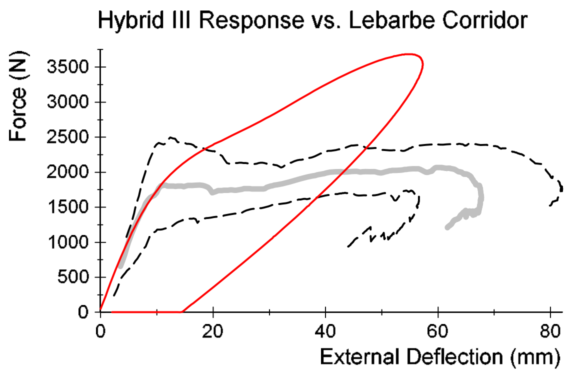

Figure 16. Force vs. external deflection response of the Hybrid III under 23.4kg, 4.3m/s blunt thoracic impact.

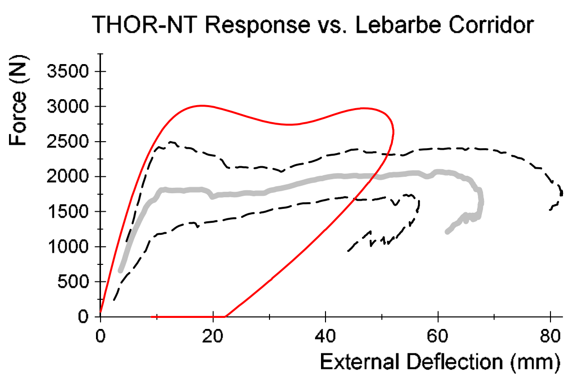

Figure 17. Force vs. external deflection response of the THOR-NT under 23.4kg, 4.3m/s blunt thoracic impact.

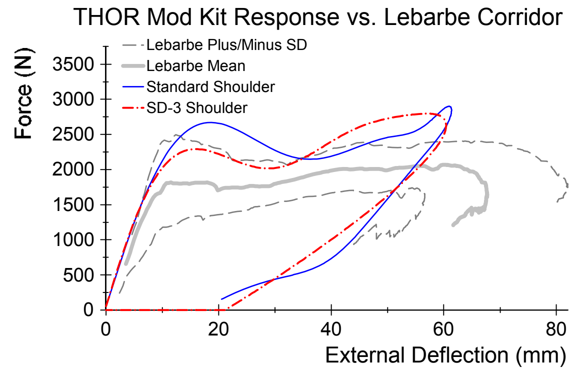

Figure 18. Force vs. external deflection response of the THOR Mod Kit with and without the SD-3 shoulder under 23.4kg, 4.3m/s blunt thoracic impact.

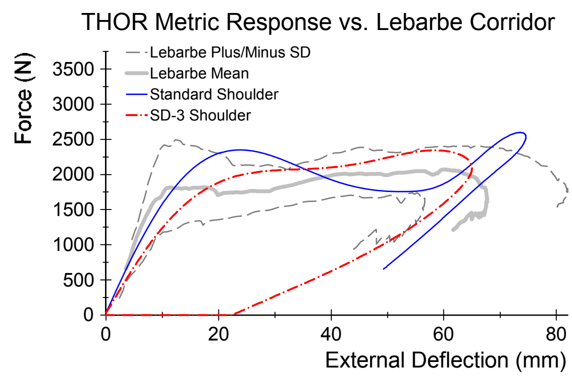

Figure 19. Force vs. external deflection response of the THOR Metric with and without the SD-3 shoulder under 23.4kg, 4.3m/s blunt thoracic impact.

Bio Rank

A Lobdell model was optimized to fit the force vs. skeletal deflection response of the Kroell 4.3 meters per second blunt thoracic impact response biofidelity corridor to allow the Bio Rank calculation of the individual force and deflection time histories measured in certification tests carried out for each of the ATDs included in this study. For the Bio Rank evaluation using the Kroell corridor as the biomechanical response basis (Table 3), the measured skeletal deflection was used (either the chest slider on the Hybrid III, the CRUX on the THOR-NT, or the IR-TRACC on the remaining THORs). For the Bio Rank evaluation using the Lebarbé corridor as the biomechanical response basis, the deflection used for all of the ATD responses was the external deflection output from a Lobdell model that was fit to the measured internal deflection (Table 4).

In the case of the THOR Mod Kit w/SD-3, the Bio Rank $\sqrt{R}_{defl}$ could be calculated for both the measured external deflection and the external deflection calculated using the Lobdell model fit to the ATD. In this condition, $\sqrt{R}_{defl}$ for the measured and predicted external deflections were 0.652 and 1.518, respectively. This discrepancy is likely due to the 20% difference noted in the peak external deflection calculated using the Lobdell model and the measured external deflection from the test of the THOR Mod Kit w/SD-3 (Figure 15).

In every Bio Rank calculation except for the $\sqrt{R}_{defl}$ for the Lebarbé corridor comparison, the THOR Metric with the SD-3 shoulder had the lowest $\sqrt{R}$, indicating the most biofidelic response. All of the THOR Mod Kit and Metric responses demonstrated $\sqrt{R}$ values below 2.0, suggesting that the ATD responds as much like the target corridor as would another human subject (Rhule, 2002).

Table 3. Bio Rank calculation using the Kroell corridor as the force and deflection target

Biomechanical Basis: Kroell			
ATD	$\sqrt{R}_{defl}$	$\sqrt{R}_{force}$	$\sqrt{R}_{avg}$
Hybrid III	2.648	1.844	2.246
THOR-NT	1.865	1.052	1.459
THOR Mod Kit	1.030	1.024	1.027
THOR Mod Kit w/SD-3	1.256	0.973	1.115
THOR Metric	0.266	1.267	0.767
THOR Metric w/SD-3	0.581	0.905	0.743

Table 4. Bio Rank calculation using the Lebarbé corridor as the force and deflection target

Biomechanical Basis: Lebarbé 2012			
ATD	$\sqrt{R}_{defl}$	$\sqrt{R}_{force}$	$\sqrt{R}_{avg}$
Hybrid III	2.364	2.923	2.644
THOR-NT	2.327	1.968	2.148
THOR Mod Kit	1.518	1.514	1.516
THOR Mod Kit w/SD-3	1.621	1.438	1.530
THOR Metric	0.495	0.985	0.740
THOR Metric w/SD-3	1.049	0.769	0.909

DISCUSSION AND LIMITATIONS

It is no surprise that in the low-speed blunt thoracic impact condition that was used as a primary design requirement for the THOR ATD, its biofidelity when assessed in the same condition shows improvement over the Hybrid III, for which the primary thoracic impact response requirement was a high-speed (6.7 meters per second) blunt thoracic impact. On the other hand, the quantification of biofidelity implemented in this study demonstrates that the THOR-NT blunt thoracic response is less biofidelic than the THOR Mod Kit design level, which is important because the same design requirement was used for the THOR-NT during the upgrade from the THOR Alpha version, yet the response of the THOR-NT would not be considered biofidelic under evaluation in the same condition.

When installed on the THOR Mod Kit or the THOR Metric, the SD-3 shoulder does not appreciably improve or degrade the biomechanical response in the blunt hub impact. The SD-3 was designed more for biofidelic range of motion and shoulder belt interaction than for blunt hub impact response, so this outcome was not unexpected since this increased range of motion assumedly results in the mass of the shoulders and arms being less coupled to the thorax. This assumption is supported by the Lobdell models fit to the THOR Mod Kit and THOR Metric with and without the SD-3 shoulder, as the variable m_3 indicates that the coupled mass of the thorax is lower with the SD-3 shoulder than with the standard shoulder (Appendix B). There are other variable differences as well, but it is difficult to compare directly since the value of variable k_{23s}, the switch between the piecewise linear stiffness of the rib cage, is markedly different.

Overall, the THOR Metric resulted in the lowest Bio Rank values of any of the frontal impact ATDs included in this study. Addition of the SD-3 shoulder to the THOR Metric resulted in some differences in the individual $\sqrt{R}$ values, as in both corridor comparisons the deflection values increased but the force values decreased. However, the average $\sqrt{R}$ values for both the Kroell and Lebarbé corridor comparisons for the Metric THOR with the SD-3 shoulder were below 1.0, suggesting that the response is indiscernible from the response of a human subject used to develop the biofidelity corridors.

The performance of the THOR under the low-speed blunt thoracic impact condition does not alone demonstrate sufficient biofidelity of the ATD, since this condition is not necessarily representative of the type of loading that the occupant may undergo during as a motor vehicle occupant during a frontal or oblique crash. One way to assess the thoracic biofidelity under such conditions is through an isolated sled test representing shoulder belt loading to the thorax, as carried out in the “Gold Standard” condition at the University of Virginia (Shaw, 2013). Preliminary results show that the chest deflection measured using the THOR Mod Kit w/SD-3 were more PMHS-like than those of the Hybrid III, though there were some localized differences in the response of the loaded shoulder and associated upper chest quadrant, as well as differences in the chest deflection measurement locations between the Hybrid III and the PMHS.

There is a second thoracic impact response requirement in the THOR Biomechanical Response Requirements manual (NHTSA, 2005a): oblique impact to the lower thorax, based on tests carried out by Yoganandan et al (1997). The THOR manual includes mean and plus/minus standard deviation responses for both the force and deflection time-histories (NHTSA 2005a, Figures 21 and 22). This deflection time-history appears to be related to processed chestband deflection, though the force and deflection time-histories are only presented for one subject in the source referenced by the manual. The manual later states that the external deflection in the THOR tests was taken from a linear potentiometer measuring the impactor displacement, which is not ideal since it does not account for the spine moving away from the impact interface. Due to this lack of information, the oblique thoracic impact condition was not included in the present study.

There are several limitations to this study that are worth noting, mostly relating to the implementation of the Lobdell model. Though it has not been demonstrated herein, it is acknowledged that the optimization of the Lobdell model returns a non-unique solution. Specifically, the value of the variable k_{12}, which represents the stiffness of the impactor-to-chest response, could significantly influence the relationship between internal and external deflection. However, changes to k_{12} also influence the initial peak (between 0 and 10 millimeters of deflection) of the response, so care was taken in selecting the validation points to ensure that this portion of the response was captured. Nonetheless, it is understood that the predicted external deflection is not a single solution, thus the values of the Bio Rank $\sqrt{R}_{defl}$ in the Lebarbé condition should be used with caution.

FUTURE WORK

One of the potential applications of the THOR ATD is the assessment of injury risk in small overlap and oblique vehicle crash tests (Saunders, 2012). Since oblique loading of the thorax by the shoulder belt or steering wheel rim is possible in this test condition, it is important that the biomechanical response of the thorax in oblique loading is assessed. To confirm the biofidelity of the ATD, the THOR will be exercised in the same condition as the oblique thorax loading conditions referenced in the THOR Biomechanical Response Requirements manual.

CONCLUSIONS

Using the previously-developed Bio Rank methodology to assess frontal impact ATD thoracic biofidelity as defined using both the Kroell and the Lebarbé biomechanical response bases, the THOR Metric ATD demonstrates the best qualitative agreement with the available biofidelity corridors and resulted in a favorable quantitative biofidelity assessment compared to the Hybrid III and previous versions of the THOR ATD. Using the quantitative biofidelity ranking system, the THOR Mod Kit and Metric ATDs result in $\sqrt{R}$ values below 2.0, indicating that the ATDs respond as much like the target corridor as would another human subject. It was further demonstrated that the THOR Metric ATD showed the best overall thoracic impact response biofidelity. The installation of the SD-3 shoulder assembly resulted in better qualitative agreement and similar quantitative agreement with the biomechanical response corridors.

ACKNOWLEDGEMENTS

The authors would like to express appreciation for the contributions of the NHTSA Vehicle Research and Test Center staff including, but not limited to, Bruce Donnelly, Kevin Moorhouse, Alena Hagedorn, Jim Stricklin, Patrick Biondillo, and Dave Walker.

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APPENDIX A. THORAX DATA PROCESSING

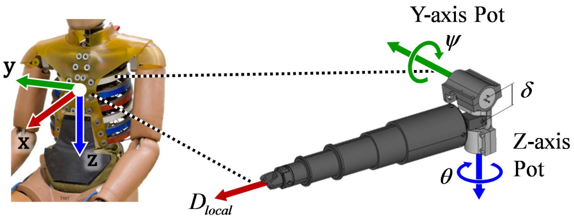


Figure A1. Diagram of the IR-TRACC configuration in the upper thorax of the THOR Mod Kit.

Upper Chest (IR-TRACC below pot; See Figure A1)

$$X_{US} = D_{local} \cos\theta \cos\psi + \delta \sin\psi \qquad \text{Eq. A1}$$

$$Y_{US} = D_{local} \sin\theta \qquad \text{Eq. A2}$$

$$Z_{US} = -D_{local} \cos\theta \sin\psi + \delta \cos\psi \qquad \text{Eq. A3}$$

Lower Chest (IR-TRACC above pot)

$$X_{LS} = D_{local} \cos\theta \cos\psi - \delta \sin\psi \qquad \text{Eq. A4}$$

$$Y_{LS} = D_{local} \sin\theta \qquad \text{Eq. A5}$$

$$Z_{LS} = -D_{local} \cos\theta \sin\psi - \delta \cos\psi \qquad \text{Eq. A6}$$

where:

D_{local}	=	Position of the anterior attachment point of the IR-TRACC tube relative to the attachment origin at the Z-axis potentiometer
θ	=	Angle time-history of Z-axis rotational potentiometer
ψ	=	Angle time-history of Y-axis rotational potentiometer
δ	=	Offset between centers of Z-axis and Y-axis potentiometers
XYZ_{US}	=	X, Y, or Z component relative to upper spine coordinate system
XYZ_{LS}	=	X, Y, or Z component relative to lower spine coordinate system

Pendulum coordinate system correction

$$\phi_{US} = -17 + \phi_{LTS} \qquad \text{Eq. A7}$$

$$\phi_{US,PEND} = \phi_{PEND} - \phi_{US} = \phi \qquad \text{Eq. A8}$$

$$X_{PEND,L} = X_{US,L} \cos\phi - Z_{US,L} \sin\phi \qquad \text{Eq. A9}$$

$$X_{PEND,R} = X_{US,R} \cos\phi - Z_{US,R} \sin\phi \qquad \text{Eq. A10}$$

$$\bar{X}_{PEND} = \frac{X_{PEND,L} + X_{PEND,R}}{2} \qquad \text{Eq. A11}$$

$$\bar{X}_{PEND,REL} = \bar{X}_{PEND} - \bar{X}_{PEND}(0) \qquad \text{Eq. A12}$$

where:

ϕ_{US}	=	Angle of the upper thoracic spine in the lab coordinate system
ϕ_{PEND}	=	Angle of the pendulum in the lab coordinate system (0˚)
ϕ_{LTS}	=	Y-axis angle measured by the lower thoracic spine tilt sensor
ϕ	=	Angle of transformation from US to PEND
$[X,Z]_{US,[L,R]}$	=	Left- and right-side upper spine X- and Z-axis position
$X_{PEND,[L,R]}$	=	Left- and right-side X-axis deflection in pendulum coordinate system
$\bar{X}_{PEND}$	=	Average of left- and right-side X-axis deflection in pendulum coordinate system
$\bar{X}_{PEND,REL}$	=	Relative X-axis deflection in pendulum coordinate system
$\bar{X}_{PEND}(0)$	=	Average of left- and right-side X-axis deflection in pendulum coordinate system at the time of initial impactor contact with the chest

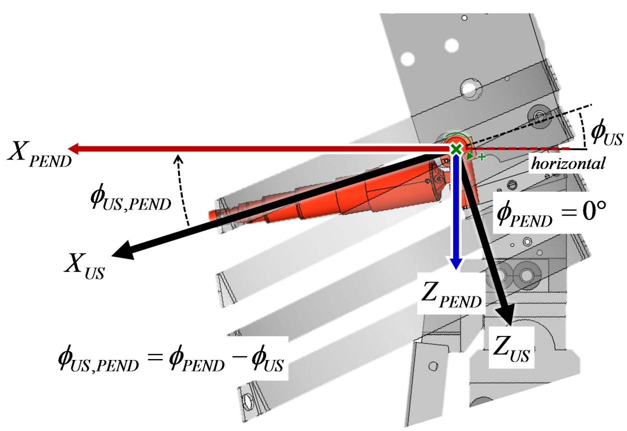


Figure A2. Schematic of the upper spine coordinate system relative to the pendulum coordinate system

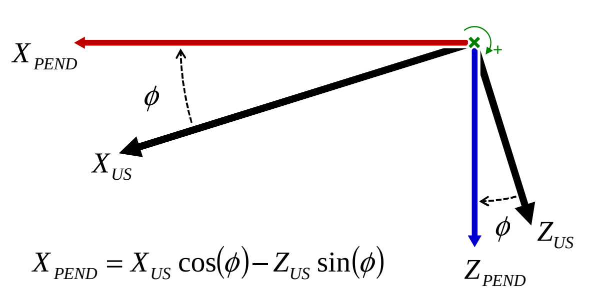


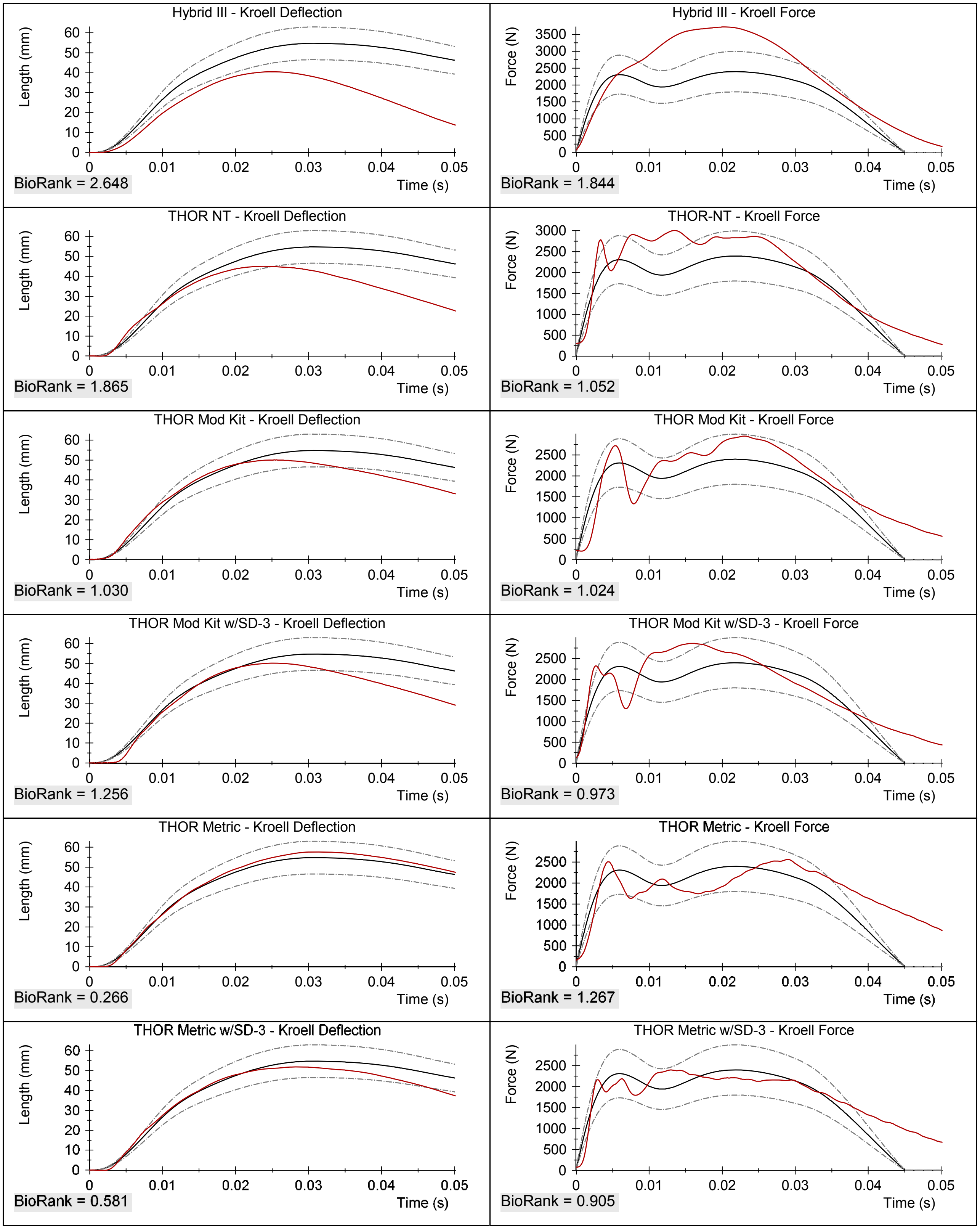
Figure A3. Representation of upper spine coordinate system components relative to the X-axis of the pendulum coordinate system

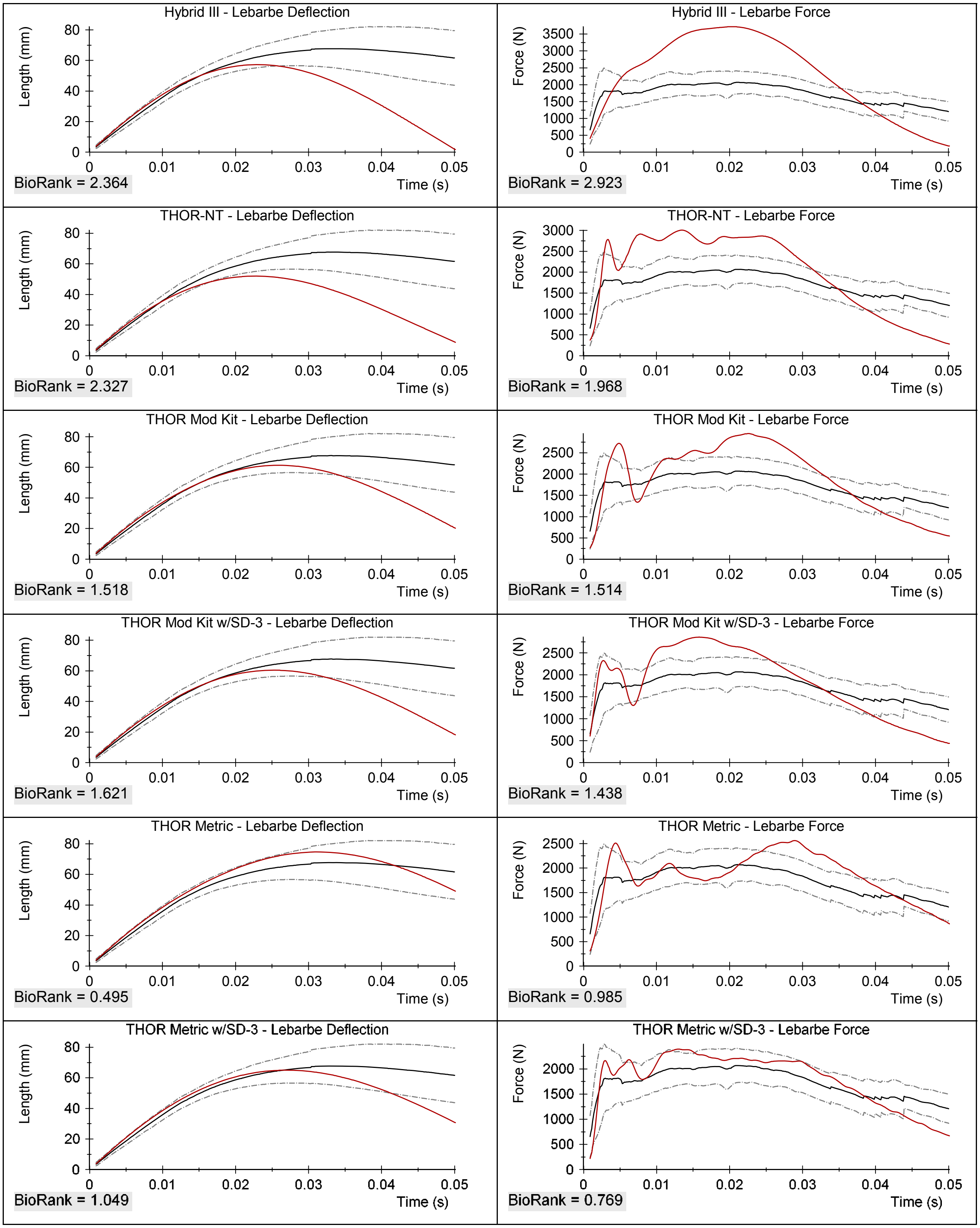
APPENDIX B. LOBDELL MODEL PARAMETERS

Lobdell model parameters for the conditions presented in this study.

Model Identifier \ **Variable / Units**	m_2 kg	m_3 kg	k_{12} N/m	k_{23a} N/m	k_{23b} N/m	c_{23a} Ns	c_{23b} Ns	k_{23s} m
Kroell Mean Response	0.85	32.66	180000	8400	61600	520	2490	0.0231
Lebarbé Mean Response	0.35	28.20	270000	29300	100100	350	510	0.0640
Hybrid III	0.53	48.32	220000	87100	81900	500	610	0.0202
THOR-NT	0.74	36.04	330000	39000	76100	660	490	0.0220
THOR Mod Kit	0.99	36.52	250000	39100	129700	460	300	0.0408
THOR Mod Kit w/SD-3	0.64	33.79	260000	34400	59400	420	410	0.0160
THOR Metric	1.04	40.73	180000	16900	105900	460	190	0.0434
THOR Metric w/SD-3	0.84	26.24	140000	44300	33100	400	540	0.0325

APPENDIX C. BIO RANK RESULTS




Hybrid III - Lebarbe Deflection
Length (mm)
Time (s)
BioRank = 2.364
Hybrid III - Lebarbe Force
Force (N)
Time (s)
BioRank = 2.923
THOR-NT - Lebarbe Deflection
Length (mm)
Time (s)
BioRank = 2.327
THOR-NT - Lebarbe Force
Force (N)
Time (s)
BioRank = 1.968
THOR Mod Kit - Lebarbe Deflection
Length (mm)
Time (s)
BioRank = 1.518
THOR Mod Kit - Lebarbe Force
Force (N)
Time (s)
BioRank = 1.514
THOR Mod Kit w/SD-3 - Lebarbe Deflection
Length (mm)
Time (s)
BioRank = 1.621
THOR Mod Kit w/SD-3 - Lebarbe Force
Force (N)
Time (s)
BioRank = 1.438
THOR Metric - Lebarbe Deflection
Length (mm)
Time (s)
BioRank = 0.495
THOR Metric - Lebarbe Force
Force (N)
Time (s)
BioRank = 0.985
THOR Metric w/SD-3 - Lebarbe Deflection
Length (mm)
Time (s)
BioRank = 1.049
THOR Metric w/SD-3 - Lebarbe Force
Force (N)
Time (s)
BioRank = 0.769