COMPARISON OF THOR LX XVERSION AND DORSIFLEXION RESPONSE IN COMPONENT TESTS, SLED TESTS AND FULL VEHICLE CRASH TESTS.

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ABSTRACT

In December 2015 NHTSA announced the intention to introduce a new, modified USNCAP vehicle test protocol. Among other proposed changes NHTSA has announced the introduction of a new full vehicle crash test, frontal oblique, and the introduction of a new ATD - THOR. In the THOR, ankle xversion and dorsiflexion injuries may be predicted based on the bending moments calculated from the THOR lower tibia load cell readings. These readings are transformed to the ankle joint location, and corrected through inertia compensation from acceleration readings measured at the mid-shaft of the tibia.

This approach is subject to the following assumptions. First, the mid-shaft tibia mounted accelerometer is assumed to read the same acceleration as the ankle potentiometer block. Second, the mid-shaft tibia, distal tibia load cell, and ankle potentiometer block are assumed to move as a rigid body. Third, there must be no alternative load paths applying force or moment to the distal tibia between the tibia load cell and the ankle joint.

The goal of this study was to examine oblique crash tests performed by NHTSA to observe mechanisms of loading of the ankle and distal tibia to elucidate the validity of the ankle joint moment calculations. We examined 35 USNCAP oblique crash tests with THOR dummies seated in both the driver and the passenger seat. From each crash test, we compared the calculated ankle joint moments to the joint angles read. Results were also compared to a series of oblique sled tests and component tests using THOR.

The results indicate that there is often an inconsistency between the component/sled tests and full vehicle tests featuring THOR ATD when predicting ankle injuries. In several cases the calculated joint moment does not correspond with the ankle rotation angle expected from the biofidelity component requirements. This observation was made for both dorsiflexion and xversion.

A case by case analysis of data points located away from the biofidelity corridor revealed multiple mechanisms responsible for the lack of comparable results between the biofidelity requirements and full vehicle crash tests. First, in some cases an alternative load path was present, applying a load to the distal tibia between the ankle and the load cell. Second, in multiple cases there was an interaction between the mid shaft of the tibia and interior of the vehicle that resulted in a short duration spike in the recorded tibia acceleration. Due to the proposed inertial compensation, the spike in the acceleration was carried over into the ankle moment calculation resulting in artificial moment prediction when no ankle rotation was present. Third, in several tests data acquisition problems were observed in the NHTSA tests (spiking channels, lost channels, or polarity errors) that resulted in incorrect or incomplete moment calculations pushing the results away from the biofidelity requirements.

In conclusion, alternative load paths at the distal tibia, and acceleration spikes in the tibia can cause an inconsistency between the moment and angle read for the THOR LX ankle in crash tests. Thus, the ankle moment calculation should be verified prior to applying to injury risk prediction to ensure that the results are not artefactual.

INTRODUCTION

On December 16th 2015 NHTSA released a Request for Comments (RFC) announcing the intension to introduce another USNCAP update. In the RFC, among other changes, NHTSA announced the intention to introduce a new frontal oblique test, and the use of THOR 50th percentile male anthropomorphic test device in the frontal oblique and full frontal tests [1].

Frontal Oblique Crash Test

In 2009 NHTSA published a report titled "Fatalities in Frontal Crashes Despite Seat Belts and Air Bags–Review of All CDS Cases–Model and Calendar Years 2000-2007–122 Fatalities" [2]. The goal of this study was to identify why people were still dying in frontal crashes despite the introduction of the advanced protective measures (seatbelts, airbags, and crashworthy structures). The conclusions of this study were that many injuries or fatalities were attributed to the frontal crashes with poor structural engagement between the vehicle and its collision partner. These included corner impacts, impact with narrow objects, and heavy vehicle underrides [2].

Based on these results NHTSA suggested that "there is an opportunity for the agency to continue examining the oblique crash type that was identified as a frontal crash problem by NHTSA in 2009" [1]. This resulted in the introduction of the new frontal oblique test announced in 2015 USNCAP RFC.

NHTSA's frontal oblique test has been under development for multiple years [3, 4, 5, and 6]. NHTSA first initiated this research program by conducting a series of vehicle-to-vehicle crash tests to understand occupant kinematics, vehicle interaction, and damage patterns [3]. These tests were followed by barrier-to-vehicle tests using the MDB used in the FMVSS 214. These tests showed that a different design MDB is needed to reproduce the results from the vehicle-to-vehicle testing [4]. The design modification of the FMVSS214 barrier included wider face plate and an optimized honeycomb depth and stiffness, and the new barrier was referred to as the Oblique Moving Deformable Barrier (OMDB).

NHTSA's current draft for the frontal oblique test protocol specifies a 90kph OMDB impact into a stationary test vehicle with 15 deg angle and 35% overlap (Figure 5) [7]. NHTSA stated that the current test condition "has shown to be representative of a midsize vehicle-to-vehicle 15-degree oblique, 50-percent overlap test, resulting in a 56 km/h (35 mph) delta-V" [1].

THOR ATD

In the 1980s, the National Highway Traffic Safety Administration (NHTSA) initiated the development of an advanced frontal crash test dummy with improved biofidelity under frontal impact conditions. The design of the THOR-50M has been updated iteratively: the THOR Alpha (2001) [8], THOR-NT (2005) [9], THOR Mod Kit (2011~2013) [10], and THOR Metric (2014).

THOR-50M features several updates in design compared to previous dummies, such as improved anthropometry, and improved design of neck, chest, shoulder, spine, and pelvis [11]. THOR also features advanced instrumentation for additional body regions that were not considered with HIII dummy. The HIII-50M ATD currently used in the full frontal crash test is instrumented to predict injury risk in head (HIC, AIS 3+), chest (deflection, AIS 3+), neck (Nij, tension, compression, AIS 3+), and femur (axial force, AIS 2+). In contrast, in the 2015 USNCAP RFC announcment NHTSA proposed to utilize the THOR's advanced mesurment capabilities to expand number of evaluated body regions. Proposed body regions included head (HIC, BrIC, AIS 3+), neck (Nij, CNij, AIS 3+), chest (multipoint thoracic injury, AIS 3+), abdomen (dynamic abdominal deflection, AIS 3+), pelvis (acetabulum load, AIS 3+), upper leg (femur axial force, AIS 2+), lower leg (revised tibia index, distal tibia force, proximal tibia force, dorsiflexion moment, inversion/eversion moment, AIS 2+)

Among other changes THOR introduces a potential for predictive capability for injury assessment for lower extremities through the use of the THOR LX. THOR LX was envisioned as part of the development due to the biofidelity and instrumentation limitations of the lower leg of the Hybrid III dummy. The THOR-LX incorporates significantly improved biofidelity and expanded injury assessment capabilities [12] compared to the standard HIII lower extremity.

THOR LX Ankle

The design of ankle assembly of the THOR-LX was aimed to generate two main motions of the ankle: dorsi/plantarflexion and inversion/eversion (Figure 1). Unlike the ankle of the Hybrid III, which has a ball joint, the ankle assembly of the THOR-LX consists of two pin joints, named for their anatomical analogues: the talocrural joint and the subtalar joint. The goal of this design was to maintain simplicity in the design and independent control of the torque-angle response in the two rotation directions. A third rotary joint is present in the distal tibia to allow internal/external rotation. Dorsiflexion motion occurs in the talocrural joint. Inversion/eversion motion occurs in the subtalar joint [13].

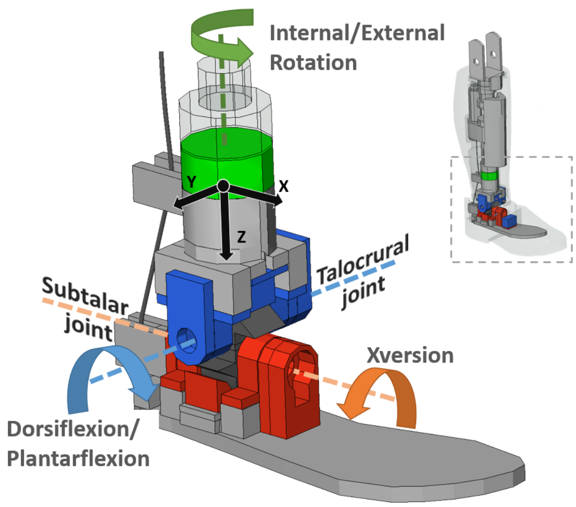

Figure 1: THOR LX talocrural and subtalar joint location [14].

A critical feature of both the talocrural and the subtalar joints is the ability to generate a non-linearly increasing torque with increasing joint rotation angle. This feature is accomplished with two stiffness elements in each joint - and internal element and an external element (Figure 2). The internal element is called a “Rosta” - a typical vibration damper unit which consists of a small, square, metal insert rotating within a square metal housing containing four elastomeric inserts located at the corners of the housing. These provide a continuously increasing resistive torque. The rostas are intended to provide only the initial part of the torque-angle response, the external elements, or bumpers, are intended to provide the resistance beyond initial response range, until the final range of motion. The external element modulates the contact between metal faces on the ankle structure using an elastomeric element, acting as a soft joint stop limiting the range of motion [13]. A summary on the intended range of motion of the THOR-LX ankle assembly is shown in Table 1.

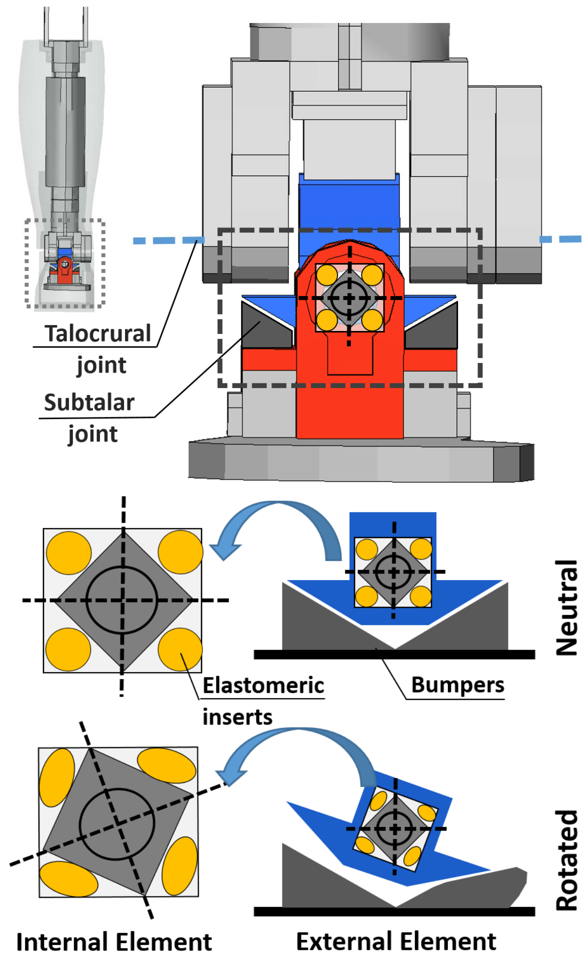

Figure 2: Internal and external stiffness element used to generate non-linear joint stiffness [14].

Table 1.
THOR LX design range of motion in each given direction [13].

	Range of motion
Dorsiflexion	0-45° (int.: 0°-25°, ext.: 25°-45°)
Plantarflexion	15°-60° (int.: 15°-45°, ext.: 45°-60°)
Inversion/Eversion	0 ~ 40° (int.: 0°-12°, ext.: 12°-40°)
Internal/External Rotation	0-10°

THOR LX Instrumentation. In addition to the advanced design features, the THOR-LX also introduces additional instrumentation to provide measures for the injury assessment. These include upper and lower tibia load cell, achilles cable load cell, tibia x and y accelerometers, foot triaxial accelerometer, and rotary potentiometers for dorsiflexion, xversion and internal rotation angle (Figure 3).

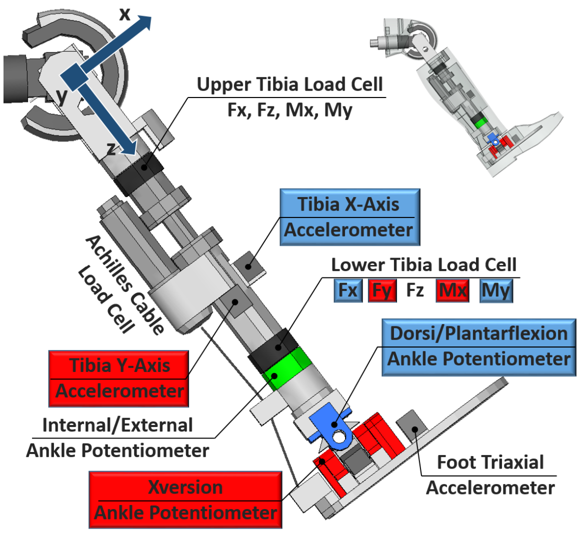

Figure 3: THOR LX instrumentation [15]

Dorsiflexion and Xversion injury measures. In the 2015 RFC NHTSA described injury risk functions designed to evaluate the risk of malleolar fractures and ankle ligament injuries through calculation of the dorsiflexion and xversion bending moments at the ankle [1]. Since the lower tibia load cell, used for ankle moment calculation, is located about 100mm away from ankle joint, the loads and moments measured at the lower tibia load cell need to be transformed to determine the section moments at the ankle. This means that the ankle moment calculation includes the moment recorded at the load cell, and as well as the recorded shear force acting on a predefined moment arm (distance between the load cell and the ankle joint). The calculation of ankle moment additionally includes an inertial compensation component that accounts for the mass block located between the lower tibia load cell and the ankle joint. Ankle dorsiflexion moment calculation is shown in Equation 1, and ankle xversion moment calculation in Equation 2.

$$M_{y(ankle)} = M_y - F_x D - \frac{m a_x D}{2} \qquad \textbf{(Equation 1)}$$

Where:
M_y - Y -axis moment measured at lower tibia load cell in Nm.
F_x - X-axis force measured at lower tibia load cell in N.
D - Distance between ankle joint and lower tibia load cell [0.0907m].
m - Mass between ankle joint and lower tibia load cell [0.72kg].
a_x - X-axis acceleration of the tibia in m/s^2

$$M_{x(ankle)} = M_x + F_y D + \frac{m a_y D}{2} \qquad \textbf{(Equation 2)}$$

Where:
M_x - X -axis moment measured at lower tibia load cell in Nm.
F_y - Y-axis force measured at lower tibia load cell in N.
D - Distance between ankle joint and lower tibia load cell [0. 1054m].
m - Mass between ankle joint and lower tibia load cell [0.72kg].
a_y - Y-axis acceleration of the tibia in m/s^2

It is important to note that the above formulations of ankle moments have been corrected and differ form of the ones published in the Appendix II of the 2015 RFC. The formulations published by NHTSA carried several errors. First, the xversion moment definition carried an erroneous polarity for shear force and acceleration. The above corrected definition assumes SAE J211 [16] sign convention. Second, the distance between the sensing plane of the lower tibia load cell and the ankle joint was assumed in the RFC to be equal for both loading directions. The correct distances were extracted from the draft of the THOR Qualification Manual [17] and included in the above definition.

Study Goals

As it represents a new potential tool for injury risk assessment, the goal of this study was to examine the dorsiflexion and xversion responses of the THOR LX ankle in available crash tests (frontal barrier and oblique MDB) to gain an understanding of the current state of performance in the fleet, and to identify any potential factors that may confound ankle injury prediciton using the THOR LX.

METHODS

NHTSA Crash Test Database

In December 2016 NHTSA's crash test database was queried for vehicle crash tests featuring THOR ATD. The search yielded 112 results, including research oblique OMDB to vehicle impacts, as well as frontal 100 percent overlap barrier crash tests. The frontal oblique test database included impacts to the driver's and passenger's side, with 35 and 20 percent overlap, and 7 and 15 degree impact angle. An in depth review of obtained data revealed that only 35 of the downloaded tests included complete channel count obtained from the THOR ATD data acquisition system. In the remaining tests, tibia accelerations, as well as lower tibia load cell Mx, My, Fx and Fy channels were not collected. Since these signals are necessary for calculating dorsiflexion and xversion moments at the ankle, any tests without the necessary channels were excluded from analysis (i.e., only the 35 tests with the complete data were included; Table 2). Among selected crash tests 14 were labeled as tests performed on "research vehicles", for which neither video nor data obtained for the vehicle is available to public on NHTSA's database website. However the data obtained by the equipment provided by NHTSA (the OMDB and the THOR) is made publicly available. Consequently, these tests provide additional data, useful for evaluating THOR LX performance in full vehicle crash test environment, even with incomplete vehicle and video information.

Table 2.
Vehicle crash tests selected for the evaluation of THOR LX ankle performance. Frontal-Vehicle-to-Barrier (FVtB) and OMDB-to-Vehicle (OMDBtV).

Test No.	Test Type	Vehicle	Model Year
9333	FVtB	Chevrolet Malibu	2015
9334	FVtB	Toyota Highlander	2015
9335	FVtB	Ford F-150	2015
9336	FVtB	Mazda 3	2015
9337	FVtB	Honda Fit	2015
9354	OMDBtV	Subaru Forester	2015
9476	OMDBtV	Chevrolet Malibu	2015
9477	OMDBtV	Chevrolet Malibu	2015
9478	OMDBtV	Ford F-150	2015
9479	OMDBtV	Ford F-150	2015
9480	OMDBtV	Toyota Highlander	2015
9481	OMDBtV	Toyota Highlander	2015
9482	OMDBtV	Honda Fit	2015
9483	OMDBtV	Volvo S60	2015
9572	OMDBtV	Honda Fit	2016
9573	OMDBtV	Chevrolet Malibu	2016
9574	OMDBtV	Nissan Rogue	2016
9585	OMDBtV	Toyota Sienna	2015
9586	OMDBtV	Chevrolet Tahoe	2016
9587	OMDBtV	Ford F-150	2016
9727	OMDBtV	Chevrolet Malibu	2015
9739	OMDBtV	Research vehicle	N/A
9740	OMDBtV	Research vehicle	N/A
9741	OMDBtV	Research vehicle	N/A
9742	OMDBtV	Research vehicle	N/A
9743	OMDBtV	Research vehicle	N/A
9744	OMDBtV	Research vehicle	N/A
9952	OMDBtV	Research vehicle	N/A
9953	OMDBtV	Research vehicle	N/A
9954	OMDBtV	Research vehicle	N/A
9955	OMDBtV	Research vehicle	N/A
9956	OMDBtV	Research vehicle	N/A
9957	OMDBtV	Research vehicle	N/A
9959	OMDBtV	Research vehicle	N/A
9960	OMDBtV	Research vehicle	N/A

Sled tests

The results from sled tests were used in this study in order to compare THOR LX performance between vehicle crash test and sled test environments. Eleven sled tests were performed using a reverse acceleration servo-hydraulic sled system. A vehicle buck based on a genericized representation of a production vehicle was used, oriented in an oblique configuration relative to the sled velocity vector. The THOR-M50 ATD was seated in the driver's seat in all reported sled tests.

Data Processing. The data necessary for calculating ankle dorsiflexion and xversion injury metrics was extracted from all vehicle crash tests selected for the analysis and processed following the SAE J211 guidelines [16]. Extracted moment and force signals were debiased and filtered with a channel frequency class (CFC) 600 Hz filter. Extracted accelerations were filtered using CFC 1000Hz filter. Ankle potentiometers signals were neither debiased nor filtered for the analysis.

RESULTS

Vehicle Crash Test Results
The available crash tests downloaded from NHTSA database (Table 2) were analyzed in terms of recorded ankle dorsiflexion and xversion responses. Only the driver data was analyzed for the Frontal-Vehicle-to-Barrier crash tests, since this is the only seating location where THOR M-50 is used. Both the driver and the passenger data (with THOR in each position) was analyzed for the OMDB-to-Vehicle tests.

For each test, the maximum recorded dorsiflexion moment was calculated using Equation 1, and plotted against the corresponding dorsiflexion angle recorded at the time of peak moment (Figure 4). Thirty oblique and 5 frontal crash tests resulted in a total of 130 data points (2 legs per occupant, 2 occupants per oblique test, 1 occupant per frontal test).

To provide a reference for the expected performance of the THOR LX ankle, the peak-moment/angle datapoints from the crash tests were compared to the biofidelity requirement corridor for dorsiflexion, as well as typical dorsiflexion certification responses for the THOR LX (Figure 4). The biofidelity requirements were obtained from Crandall et al. 1996 [18]. A typical certification response in dorsiflexion was obtained from the dynamic ball of the foot impact, published during the development process of the THOR LX [19].

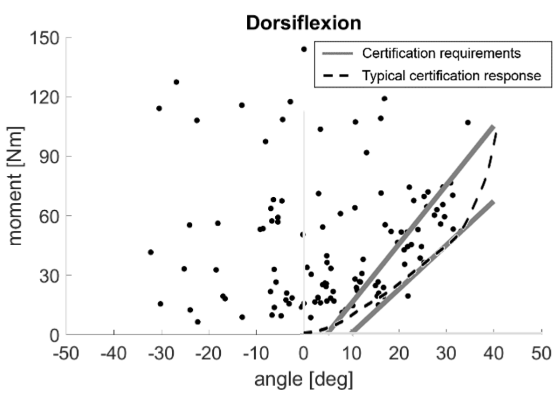

Figure 4: Maximum calculated dorsiflexion moment vs corresponding dorsiflexion angle observed in crash tests, compared to the certification corridor for the THOR LX and a typical certification response

Likewise, for each test the maximum and minimum recorded xversion moment was calculated using Equation 2, and plotted against corresponding xversion angle recorded at the time of max/min moment (Figure 5). Thirty oblique and 5 frontal crash tests resulted in a total of 260 data points (2 readings per leg [max and min], 2 legs per occupant, 2 occupants per oblique test, 1 occupant per frontal test).

As with dorsiflexion, the max/min datapoints for xversion were compared to the certification targets and a typical certification response for the THOR LX (Figure 5). Design biofidelity requirements were obtained from Jaffredo et al. 2000 [20]. A typical certification response in xversion was obtained from the quasi-static inversion tests, published during the development process of THOR LX [19].

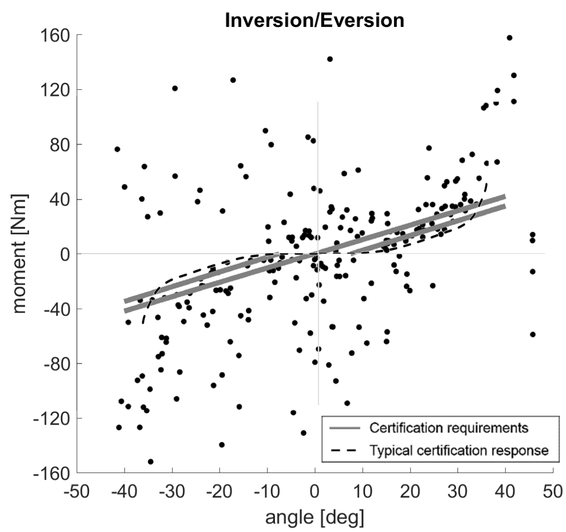

Figure 5: Maximum and minimum calculated xversion moment vs corresponding xversion angle observed in crash tests, compared to the biofidelity targets and a typical certification response for the THOR LX.

Sled Test Results
A similar analysis was performed on the data available from the sled tests series. The maximum dorsiflexion moment (Figure 6) and maximum and minimum xversion moments (Figure 7) were calculated using Equation 1 and 2, and plotted against the corresponding dorsiflexion and xversion angles. Eleven sled tests resulted in a total of 22 data points (2 legs per occupant, 1 occupant per sled test) for dorsiflexion and 44 data points (2 readings per leg [max and min], 2

legs per occupant, 1 occupants per sled test) for xversion. The biofidelity requirements, as well as the typical certification responses described above were also plotted for both dorsiflexion (Figure 6) and xversion (Figure 7).

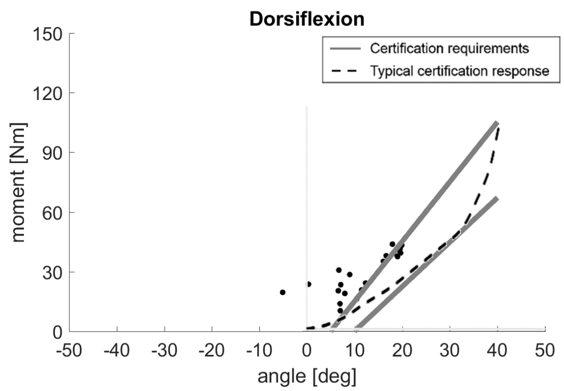

Figure 6: Sled test maximum calculated dorsiflexion moment vs corresponding dorsiflexion angle.

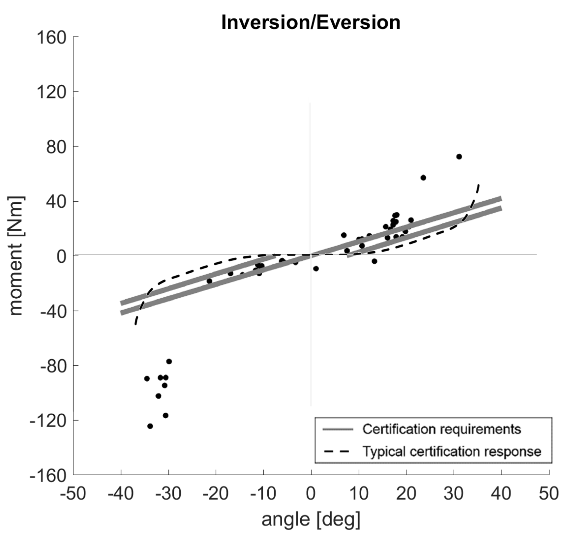

Figure 7: Sled test maximum and minimum calculated xversion moment vs corresponding xversion angle.

DISCUSSION

Component vs Sled vs Crash Test Results

The results presented above show a discrepancy between the expected moment-angle performance of the THOR LX ankle (described in the certification targets and typical certification responses) and the moment-angle relationship observed in the full vehicle crash tests. Both, dorsiflexion and xversion moments appear to be inconsistent with the recorded dorsiflexion/xversion angles. Figure 4 shows several test cases where a calculated dorsiflexion moment reaches a maximum value at the time when ankle joint is in plantarflexion (upper left quadrant of the graph in Figure 4). Similarly, Figure 5 shows several test cases where a maximum xversion moment occured during the negative ankle rotation, and vice versa (upper left and lower right quadrant in Figure 5, respectively). As a consequence, both the dorsiflexion (Figure 4) and xversion (Figure 5) results show a number of data points located away from the expected performance curves established for THOR LX.

On the other hand, the sled test results were clustered around the biofidelity requirements and component certification performance curves (Figure 12 and Figure 13). In few sled test cases the THOR LX instrumentation recorded a positive dorsiflexion moment with the ankle joint potentiometer recording none or little dorsiflexion rotation. This was due to the fact that at low loads to the ankle joint, the ankle moment calculation was dominated by the noise of the acceleration signal. At higher loads the effect of the noise was overshadowed by the contribution of the shear force and bending moment components of the ankle joint moment calculation.

In-Depth Crash Test Review

Small performance differences are often expected between different types of test modes (component vs. sled vs. full vehicle tests). For example, the component tests are performed on stationary test rigs, consequently excluding the inertia compensation component in the calculations. As a result the acceleration term is not present in the ankle moment equation used in the component certification tests [17]. However, the analysis presented above suggests that there is a large discrepancy between the performance of THOR LX in full vehicle crash tests compared to both sled and component tests. In order to understand the difference between those test modes, an in-depth case by case review was performed to identify potential mechanisms of the differences. A case by case analysis revealed that in several of the full-vehicle crash tests the THOR LX data featured problems that artificially influenced the calculation of the maximum and minimum ankle moment values. After a review of all the test data, the mechanisms for potentially artificial readings were subdivided into two separate categories:

- Data aquisition (DAQ) problems
- Confounding mechanical influences

DAQ problems. In several tests of the tests downloaded from the NHTSA database there were problems with the data acquisition systems which influenced the calculated ankle moments. These included dropped channels, channel spikes, and inverted polarity on several recorded channels.

Figure 8 shows an example of data that experienced DAQ problems. It depicts the results obtained for the passenger right foot in dorsiflexion, for test 9476. The figure shows the components of the ankle moment calculation associated with lower tibia load cell moment, force and tibia acceleration expressed in terms of their bending moment contribution. The resulting calculated dorsiflexion moment is shown at the top graph in the figure. The time history of the recorded dorsiflexion angle is shown in the plot at the bottom. The red dot indicated the time of peak calculated dorsiflexion moment.

As can be seen in Figure 8 the shear force channel (F_x) drops out at approximately 62 ms. Since the shear force was occurring in such a way that it was subtracting away from the translated moment, when the shear force channel drops out the calculated moment artificially jumped up in magnitude.

Since all three components, load cell bending moment, shear force and acceleration are critical for the calculation of the ankle moment, erroneous readings in any of these signals can result in substantial error in the ankle moment calculation. It is often the case that a shear load applied to the base of the foot will results in both bending moment and a shear force recorded at the lower tibia load cell, and both of these will cancel each other during the ankle moment calculation. An example of such loading conditions is shown in Figure 8. The shear force and bending moment balance each other out throughout the whole tests, except the portion of the signal where shear force records an erroneous value.

This in turn drives the ankle moment calculation up and results in an erroneous maximum ankle moment calculation. As a result the THOR LX predicted, in this case, around 50Nm of dorsiflexion moment at 0deg ankle rotation.

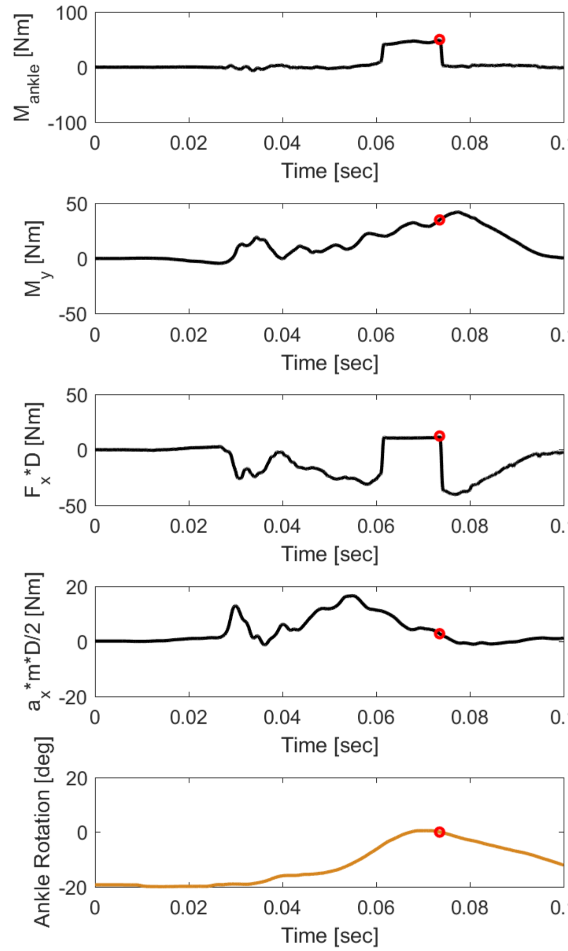

Figure 8: Calculated ankle moment components and angle. Test 9476, passenger right foot, dorsiflexion.

In addition to test 9476, several other cases containing other DAQ errors were discovered in the analyzed crash test data. A detailed list of all the tests containing this type of error, along with the error description is available in the Appendix A.

Confounding Mechanical Influences. Two assumptions are necessary for Equation 1 and Equation 2 to be valid in calculating resultant ankle moment.

First, any external loads acting through the ankle are assumed to act below the articulating ankle joint. These loads are transferred through the ankle joint and recorded by the lower tibia load cell. As a result it is assumed that no alternate load is applied to the distal tibia below the lower tibia load cell.

Second, it is assumed that THOR LX assembly acts as a rigid body, and that the accelerations recorded at the mid-shaft tibia may be used for ankle assembly inertial compensation for the ankle moment. However, the tibia accelerometers are located approximately 180mm from the ankle joint assembly (Figure 3).

During the in depth review, several tests showed mechanical phenomena that violated one or both of the assumptions described above. In several cases the pedal, knee bolster, or tunnel impacted into the distal tibia of the THOR-LX, resulting in an external load applied at a location between the ankle and the load cell. This violates the first assumption described above, as it represents application of a load through an alternate load wherein the recorded load is not reflective of the load passing through the ankle.

Figure 9 and Figure 10 show an example of such a test. It depicts the results obtained for the driver right foot in dorsiflexion for test 9574. In this particular case, as the toepan deformed the brake pedal impacted driver's right lower leg above the ankle joint assembly, between the ankle and the load cell. This event was recorded by the THOR DAQ at 0.04sec after the impact, and resulted in spikes in all three moment calculation components. Consequently, the THOR LX perceived a maximum dorsiflexion moment using the loads that did not pass through the ankle joint. As a result the maximum dorsiflexion moment was measured at a different time than the maximum dorsiflexion angle.

Figure 9: Still frames extracted from test 9574 at 0.030, 0.035, 0.040 and 0.045sec after the impact.

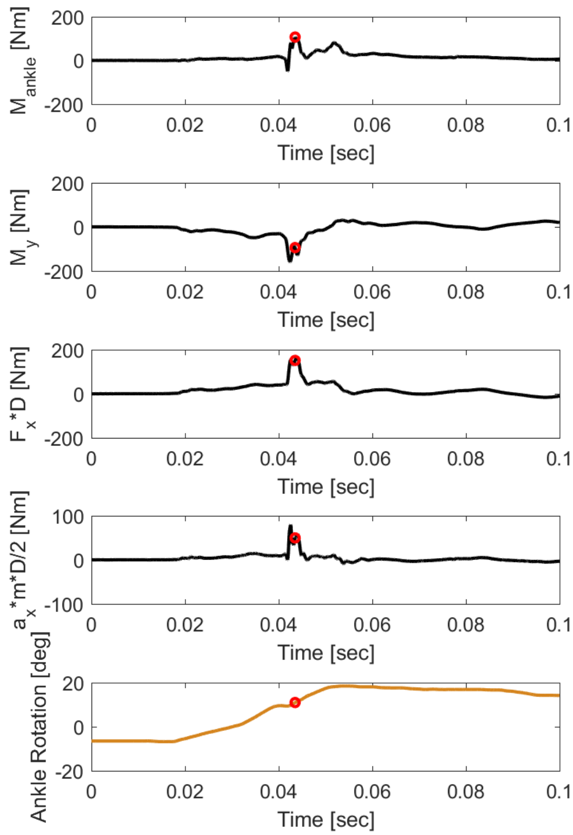

Figure 10: Calculated ankle moment components and angle. Test 9574, driver, right foot, dorsiflexion.

In several cases local mid-shaft tibia impacts resulted in accelerometer spikes that were carried onto the ankle moment calculation influencing the results. Some of the observed spikes were associated with the tibia impacting the knee bolster, and in some cases they were a result of a knee airbag deployed into the tibia in the vicinity of the accelerometer.

Figure 11 shows a sample case where a knee airbag deployment influenced the accelerometer signal. It depicts the results obtained for the driver right foot in xversion, for test 9481. In this given test the knee airbag deployed at about 0.02sec, and came in contact with the mid-shaft tibia region. This impact resulted in high amplitude, short duration acceleration, which in turn dominated the calculated xversion ankle moment. As a result, the maximum and minimum xversion moment was erroneously calculated at a time when there was no perceivable change in ankle xversion orientation.

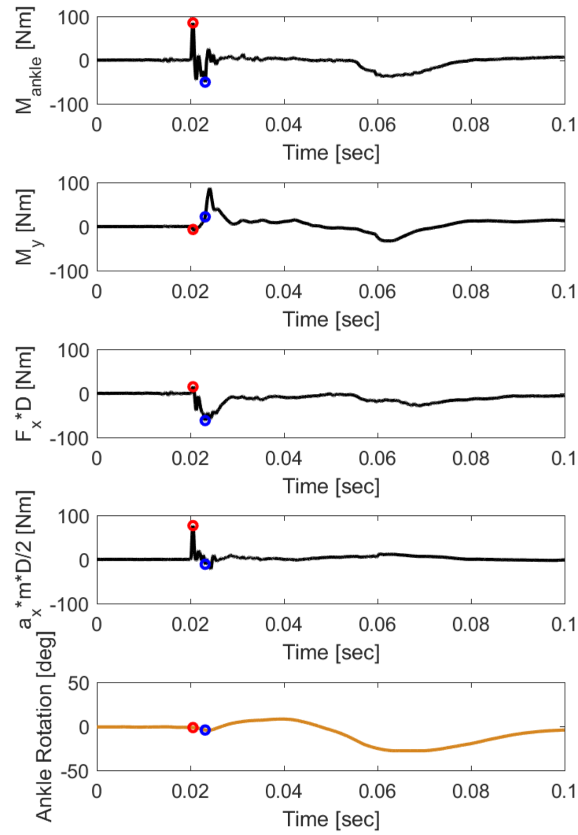

Figure 11: Calculated ankle moment components and angle. Test 9481, driver, right foot, xversion.

Several other cases exhibited similar confounding mechanical phenomena that resulted in erroneous ankle moment calculations. A detailed list of all the tests containing this type of error, along with the error description is available in the Appendix A.

Reduced data set

The entire dataset was reviewed on a case-by-case basis, and all cases that had either DAQ problems or were identified to show artificially confounding mechanics were eliminated from the data set. Additionally all of the tests performed on research vehicles (Table 2) were also excluded from the reduced data set since no video was available for their in depth review.

A total of 148 ankle measures (20 for frontal and 128 for oblique) for both dorsiflexion and xversion were reviewed in detail. Descriptions of the channel by channel data review, as well as the underlying cause for elimination from the data set are listed in Appendix A. Table 3 shows the breakdown of the reviewed data. Out of 148 reviewed ankle measures 11% (16) displayed problems associated with the data acquisition, and 18% (27) were classified as tests violating one of the two THOR LX mechanical assumptions, thus displaying incorrect THOR LX mechanics.

Table 3.
The summary of the in-depth review of the available crash test data.

Free of error	105	71%
DAQ problems	16	11%
Incorrect mechanics	27	18%
Total	**148**	**100%**

Following the in-depth review and exclusion of data with DAQ problem or artificially confounding mechanics, the reduced data set was again plotted in terms of the maximum dorsiflexion moment and max/min xversion moment vs corresponding angle. Figure 12 shows the dorsiflexion data set, and Figure 13 shows the xversion data set.

After eliminating the data with apparent DAQ issues and THOR-LX mechanics problems, the remaining data clustered around the expected performance curves. As a result, the scatter of the quality-controlled crash test data closely resembles the results obtained from the available sled tests.

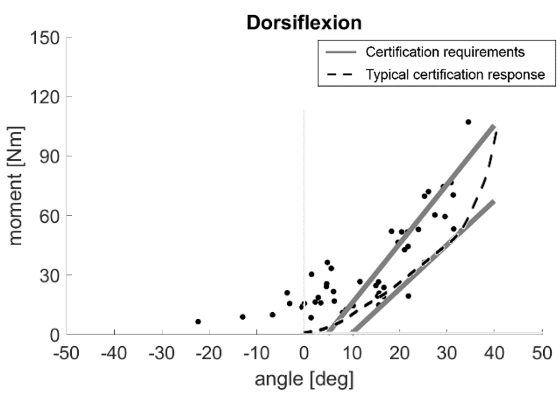

Figure 12: Maximum dorsiflexion moment vs corresponding dorsiflexion angle from the crash tests. Reduced, quality-controlled crash test data.

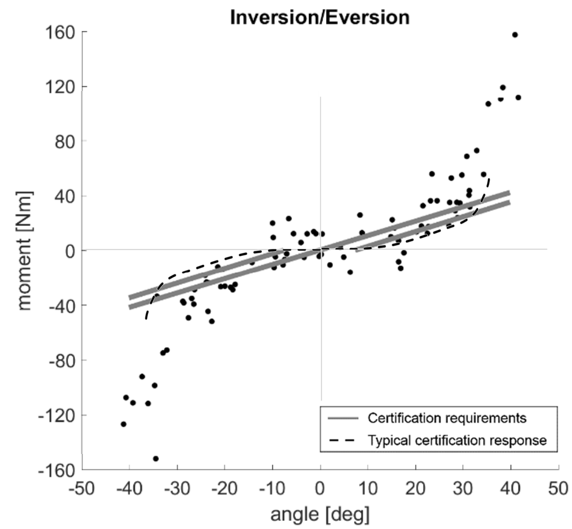

Figure 13: Maximum and minimum calculated xversion moment vs corresponding xversion angle from the crash tests. Reduced, quality-controlled crash test data.

CONCLUSIONS

This study examined the range of performance and potential confounding issues for the ankle moment-angle response for the THOR-LX in publicly available vehicle crash tests. After comparing peak moment-angle responses, a case by case analysis of data points located away from the expected component performance curves revealed multiple mechanisms that may confound the calculation of ankle moments for the THOR LX in crash tests.

First, in some cases the pedals, IP, or tunnel struck the distal tibia between the tibia load cell and the ankle, resulting in a reading in the load cell not reflective of the moment passing through the ankle (an alternative load path).

Second, in multiple cases there was an interaction between the mid shaft of the tibia and interior of the vehicle (including, in some cases, interaction with a deploying knee airbag) that resulted in a short duration spike in the tibia acceleration. Due to the inertial compensation present in the current formulation, the spike in the acceleration was carried over into the ankle moment calculation resulting in an artificial spike in the ankle moment calculation when no ankle rotation was present.

Third, in several cases data acquisition problems were observed (spiking channels, lost channels, or polarity errors) that resulted in incorrect or incomplete moment calculations drawing the results away from the expected performance.

In conclusion, in full vehicle crash tests calculation of the dorsiflexion and xversion moments in the ankle of the THOR LX can be confounded by alternative load paths (between the distal tibia load cell and the ankle), spikes in the mid-tibia accelerometer, or data acquisition problems that cause spiking or dropout of any of the constituent data channels. Careful quality control is necessary when using the THOR LX in full vehicle crash tests to ensure accurate capture and interpretation of the moments in the ankle.

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APPENDIX A

Table A1

Channel by channel data review of THOR LX ankle performance in the available crash tests. The mechanisms for potentially artificial readings were subdivided into two separate error categories: DAQ problems (1), and confounding mechanical influences (2).

Test #	Occupant	Leg	Mech.	Error Category		Type of recorded problem	Underlying cause of a problem
				1	2		
9333	Driver	Right	DF		X	Moment spike	Unknown
			XV	X		Acceleration spike	
		Left	DF				
			XV				
9334	Driver	Right	DF		X	Acceleration spike	KAB - accelerometer impact
			XV	X		Inverted polarity	
		Left	DF		X	Acceleration spike	KAB - accelerometer impact
			XV		X	Acceleration spike	KAB - accelerometer impact
9335	Driver	Right	DF				
			XV	X		Acceleration spike	
		Left	DF				
			XV				
9336	Driver	Right	DF				
			XV				
		Left	DF				
			XV				
9337	Driver	Right	DF				
			XV				
		Left	DF				
			XV				
9354	Driver	Right	DF	X		Inverted polarity	
			XV		X	Acceleration spike	KAB - accelerometer impact
		Left	DF	X		Acceleration spike	
			XV	X		Acceleration spike	
	Pass.	Right	DF				
			XV	X		Force spike	
		Left	DF				
			XV				
9476	Driver	Right	DF	X		Acceleration spike	
			XV				
		Left	DF				
			XV		X	Shear force spike	Left side tunnel impact
	Pass.	Right	DF	X		Force zero signal	
			XV				
		Left	DF				
			XV				
9477	Driver	Right	DF				
			XV				
		Left	DF		X	Acceleration spike	KAB - accelerometer impact
			XV		X	Acceleration spike	KAB - accelerometer impact
	Pass.	Right	DF				
			XV				
		Left	DF				
			XV				

Table A1 (continued)

Test #	Occupant	Leg	Mech.	Error Category		Type of recorded problem	Underlying cause of a problem
				1	2		
9478	Driver	Right	DF				
			XV		X	Acc, force, mom, spike	Pedal Impact
		Left	DF	X		Force spike	
			XV	X		Force spike	
	Pass.	Right	DF				
			XV	X		Inverted polarity	
		Left	DF				
			XV				
9479	Driver	Right	DF				
			XV				
		Left	DF		X	Acceleration Spike	Knee bolster impact
			XV		X	Acceleration Spike	Knee bolster impact
	Pass.	Right	DF				
			XV				
		Left	DF	X		Force/Moment spike	
			XV				
9480	Driver	Right	DF		X	Acceleration Spike	KAB - accelerometer impact
			XV		X	Acceleration Spike	KAB - accelerometer impact
		Left	DF	X		Force spike	
			XV		X	Acceleration Spike	KAB - accelerometer impact
	Pass.	Right	DF				
			XV				
		Left	DF				
			XV				
9481	Driver	Right	DF		X	Acceleration Spike	KAB - accelerometer impact
			XV		X	Acceleration Spike	KAB - accelerometer impact
		Left	DF		X	Acceleration Spike	KAB - accelerometer impact
			XV		X	Acceleration Spike	KAB - accelerometer impact
	Pass.	Right	DF				
			XV				
		Left	DF				
			XV				
9482	Driver	Right	DF				
			XV				
		Left	DF				
			XV				
	Pass.	Right	DF				
			XV				
		Left	DF				
			XV				
9483	Driver	Right	DF				
			XV				
		Left	DF				
			XV		X	Shear force spike	Pedal impact
	Pass.	Right	DF				
			XV				
		Left	DF				
			XV				

Table A1 (continued)

Test #	Occupant	Leg	Mech.	Error Category 1	Error Category 2	Type of recorded problem	Underlying cause of a problem
9572	**Driver**	**Right**	DF				
			XV				
		Left	DF				
			XV	X		Force spike	
	Pass.	**Right**	DF				
			XV				
		Left	DF				
			XV				
9573	**Driver**	**Right**	DF				
			XV				
		Left	DF				
			XV		X	Acc, Force spike	KAB impact, tunnel impact
	Pass.	**Right**	DF				
			XV				
		Left	DF				
			XV				
9574	**Driver**	**Right**	DF		X	Acc, Force, Mom spike	Brake pedal impact
			XV		X	Acc, Force, Mom spike	Brake pedal impact
		Left	DF				
			XV				
	Pass.	**Right**	DF				
			XV				
		Left	DF				
			XV				
9585	**Driver**	**Right**	DF				
			XV		X	Acc, Force spike	Brake pedal impact
		Left	DF				
			XV				
	Pass.	**Right**	DF				
			XV				
		Left	DF				
			XV				
9586	**Driver**	**Right**	DF		X	Acc, Force, Mom spike	Mid-tibia knee bolster impact
			XV		X	Acc, Force, Mom spike	Mid-tibia knee bolster impact
		Left	DF		X	Acc, Force, Mom spike	Mid-tibia knee bolster impact
			XV		X	Acc, Force, Mom spike	Mid-tibia knee bolster impact
	Pass.	**Right**	DF				
			XV				
		Left	DF				
			XV				
9587	**Driver**	**Right**	DF				
			XV				
		Left	DF				
			XV				
	Pass.	**Right**	DF				
			XV				
		Left	DF				
			XV	X		Force spike	

Table A1 (continued)

Test #	Occupant	Leg	Mech.	Error Category		Type of recorded problem	Underlying cause of a problem
				1	2		
9727	Driver	Right	DF				
			XV				
		Left	DF				
			XV				
	Pass.	Right	DF				
			XV				
		Left	DF				
			XV				
			XV				