

## **Repeatability and Reproducibility of Upper Thorax Responses of THOR-50M ATDs**

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### **ABSTRACT**

Anthropomorphic test device (ATDs) used for injury assessment are continuously being developed to enhance their biofidelity. For frontal crash testing, the Test device for Human Occupant Restraint (THOR-50M) ATD is being considered as the next injury assessment device in place of the current Hybrid III 50M (HIII-50M) ATD. Due to improved biofidelity and advanced instrumentation, the THOR-50M ATD has been developed to improve the assessment of injury measures in comparison to HIII-50M ATD. This study evaluated the THOR-50M ATD's repeatability and reproducibility (R&R) of the thorax, and compares the findings to that of the HIII-50M ATD.

The thorax deflection of THOR-50M and HIII-50M were measured respectively. For three THOR ATDs, the upper thorax qualification test was conducted three times by the present certification procedures. For five Hybrid III ATDs, the thorax impact test was conducted three times by the Low Speed Thorax Impact Test Procedure. The coefficient of variation (CV) of thorax deflection was calculated to evaluate the R&R in thorax response. In addition, the thorax deflection was converted into injury risk probability because the THOR-50M utilizes different risk curves, measurement equipment, and measurement points from the HIII-50M. In the HIII-50M ATD, the characteristics of ribs are certified as a way to improve the R&R. In order to investigate the effect of the characteristics of ribs on the THOR's upper thorax response, the ribs thickness was measured for three THOR ATDs. Moreover, a lumbar spine is one of the components that influence on THOR's upper thorax response. The bending stiffness was evaluated by lumbar spine flex joint bending test. Two THOR ATDs attached with the thickest and thinnest ribs were selected. The thorax deflection was measured by upper thorax qualification tests.

It was found that the CV of THOR-50M was larger than that of the HIII-50M. Also, it was found that the upper X-axis and Z-axis thorax deflection of the THOR-50M with the thinnest ribs was about 5 % larger than that of the THOR-50M with the thickest ribs. In the upper Z-axis thorax deflection, the difference between two ATDs attached with the same ribs was about 7%

The thorax of THOR-50M has more complex structure than that of HIII-50M, so the R&R of THOR-50M might be lower than that of Hybrid III in thorax response. It is believed that the THOR-50M's upper thorax deflection is influenced by rib cage stiffness which depend on the thickness of ribs. In order to improve R&R, it is recommended that rib thickness be certified, as is done for the HIII-50M. The bending stiffness of THOR's lumbar spine might have a contribution to increasing Z-axis deflection.

In conclusion, a certification method for guaranteeing rib characteristics is required for minimizing the variation of the upper X-axis and Z-axis thorax deflection. For future studies, the influence of other THOR-50M ATD components on the upper thorax deflection should be investigated.

## INTRODUCTION

As shown In the United States, though the number of fatalities decreased from 2005 to 2010, it is currently comparable to that of 7 years ago. Thorax injuries are one of the main causes of fatalities and severe injuries in auto traffic accident(Cuerden et. al. 2006), so addressing this issue is required to promote additional fatality reduction. Assessing injury values according to human body leads to develop the implementation of restraint systems and airbags and reduces the number of fatalities and severe injuries in car crashes. ATDs are used for assessing injury values in many countries and continuously being improved biofidelity and measurement capability.

In 1976, the HIII-50M ATD was first released. Currently, this is the device to assess the injury values in the frontal crash tests throughout the world (Foster et. al. 1977). The National Highway Traffic Safety Administration (NHTSA) of the U.S. acknowledged need for improved biofidelity and measurement capabilities of the Hybrid III (Backaitis et. al. 1979). NHTSA announced plan to develop an advanced crash test ATD in 1992. The THOR-50M ATD was launched in 1996, and subsequent design changes included the THOR Alpha in 2001 and the THOR NT in 2005(Martin et. al. 2007). In 2011, NHTSA updated the THOR NT to improve the usability, durability, and biofidelity (Ridella et. al. 2011). THOR-50M ATD is considered to be the next-generation injury assessment device in place of the current Hybrid III ATD.

THOR-50M ATD has enhanced biofidelity and additional capabilities to measure injury values. By using biomechanical data, some components of THOR (such as, face, neck, shoulder, thorax, thoracic spine, abdomen, pelvis, and femurs) have been redesigned to simulate the human body in response to impact loading (Rangarajan et al., 1998, Xu et al., 2000). In the thorax, the structure has been improved dramatically. THOR-50M ATD's thoracic spine consists of a flexible rubber link, while the Hybrid III's thoracic spine is rigid from the lumbar spine to the neck. The THOR-50M ATD's rib cage has been redesigned to approximate human rib geometry and structure (Greg et. al. 2004). In addition, new measurement equipment has been adopted to better evaluate deflection of THOR-50M's thorax.

Deflection of the thorax is measured by the sternal potentiometer in the Hybrid III, while it is measured directly by light reflective displacement meter which called the Infrared Telescoping Rod for Assessing of Chest Compression (IR-TRACC) in the THOR-50M. The IR-TRACC enables to measure the 3D

compression of the ribs, and is located at four points of thorax in THOR-50M (Kazuhiro et. al. 2006).

For ATDs, the basic performance repeatability and reproducibility (R&R) is assessed by certification procedures. Using ATDs with sufficient R&R enables manufacturers to evaluate automobile crash performance which aids development of the body structure and restraint systems. The repeatability of THOR-50M prototype was evaluated in sled tests and compared to that of HIII-50M ATD. The response of THOR-50M prototype in some restraint modes are no less repeatable than that of Hybrid III in sled tests. However, THOR's response is not as repeatable as in the thorax qualification test (Lan et. al. 2000). On components test, THOR's thorax is needed to improve R&R in order to assess injury values exactly and be spread widely. In Hybrid III, the characteristics of ribs are certificated as one of the way to improve R&R (Okubo et. al. 2009). The effect of rib characteristics on the THOR-50M thorax response has not been studied in this manner.

This paper reports on the evaluation of R&R by conducting thorax qualification test. The thorax deflection of THOR-50M ATD's were compared with that of HIII-50M ATD's for each risk curve. In addition, the components of THOR-50M's thorax (such as ribs and a lumbar spine) were studied to assess their influence on the thorax response.

## METHODS

For THOR-50M, the upper thorax qualification test was conducted using the THOR 50th Percentile Male (THOR-50M) Qualification Procedure Manual DRAFT (NHTSA 2016). Figure 1 (a) shows setup of upper thorax test. In this test, a probe with a mass of  $23.36 \pm 0.02$  kg and a  $152.40 \pm 0.25$  mm diameter rigid disk impact interface (the same equipment used in a similar qualification test for the Hybrid III 50th percentile male ATD) contacts the ATD at mid-sternum level at  $4.30 \pm 0.05$  m/s. By reading each tilt sensor, the angle of T6 and Pelvis was set at the qualification setup parameters (T6:  $X = 0 \pm 0.5^\circ$ ,  $Y = -4 \pm 1^\circ$ , Pelvis:  $X = 0 \pm 0.5^\circ$ ,  $Y = 15 \pm 1^\circ$ ). Figure 2 shows the polarity of T6 and Pelvis.

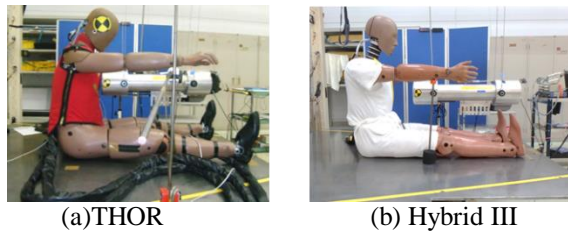


Figure 1. Setup of the thorax qualification test

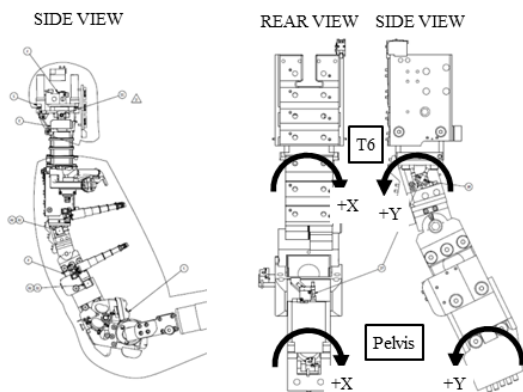


Figure 2. Polarity of T6 and Pelvis tilt sensor

For HIII-50M ATD, the thorax impact test was conducted by Low Speed Thorax Impact Test Procedure for the Hybrid III 50th Male ATD (SAE International 2007). Figure 1 (b) shows setup of thorax impact test. The probe condition such as size, mass, and speed was same as that of THOR ATD. The ribs both longitudinally and laterally were adjusted to  $\pm 0.5^\circ$  and the pelvis angle was adjusted to  $13 \pm 2^\circ$ .

Table 1 shows thorax qualification test matrix. For three THOR and five Hybrid III ATDs, thorax deflection was measured three times by each certification procedure. In order to distinguish the three THOR ATDs, they were named THOR Aa, THOR Bb, THOR Cc. For example, the body and rib cage that THOR Aa has was defined as THOR A and Rib cage a. Similarly five Hybrid III ATDs were named HY III A, HY III B, HY III C, HY III D, HY III E, HY III F.

Table 1. Thorax qualification test matrix

| TEST Number | ATD name | Body name | Rib cage name | ATD               | Number of test |
|-------------|----------|-----------|---------------|-------------------|----------------|
| 1           | THOR Aa  | THOR A    | Rib cage a    | THOR-50M 50thMale | 3              |
| 2           | THOR Bb  | THOR B    | Rib cage b    | THOR-50M 50thMale | 3              |
| 3           | THOR Cc  | THOR C    | Rib cage c    | THOR-50M 50thMale | 3              |
| 4           | HY III A | -         |               | HIII-50M ATD      | 3              |
| 5           | HY III B | -         |               | HIII-50M ATD      | 3              |
| 6           | HY III C | -         |               | HIII-50M ATD      | 3              |
| 7           | HY III D | -         |               | HIII-50M ATD      | 3              |
| 8           | HY III E | -         |               | HIII-50M ATD      | 3              |
| 9           | THOR Ac  | THOR A    | Rib cage c    | THOR-50M 50thMale | 3              |
| 10          | THOR Ca  | THOR C    | Rib cage a    | THOR-50M 50thMale | 3              |

As criterion for evaluating the R&R, the coefficients of variation (CV) value of the deflection was calculated by Equation 1. The CV is the ratio of the standard deviation of the peaks over the mean of peaks, which is commonly used in the ATD R&R analysis (J.Foster 1977). The calculated CV was rated according to table 2 (NTHSA 2006).

$$CV \text{ Value (\%)} = \frac{1S.D.}{\text{Average}} \quad \text{(Equation 1)}$$

Table 2. Rating for the R&R in qualification tests

| CV       | Index        |
|----------|--------------|
| 0 – 5%   | Excellent    |
| > 5– 8%  | Good         |
| > 8– 10% | Acceptable   |
| > 10%    | Unacceptable |

Equations 2 shows THOR-50M's risk curve and Equation 3 shows HIII-50M's risk curve for thorax deflection. The thorax deflection was converted into injury risk probability because the THOR is different from the Hybrid III with regards to risk curves, the measurement equipment, and the measurement points.

THOR

$$P(AIS \geq 3) = 1 - e^{-\left(\frac{R_{max}}{59.865}\right)^{2.7187}} \quad \text{(Equation 2)}$$

Hybrid III

$$P(AIS+ \geq 3) = \frac{1}{1 + e^{(10.5456 - 1.568 * (Chest-Def.[mm])^{0.462})}} \quad \text{(Equation 3)}$$

In order to investigate the effect of the characteristics of ribs on the upper thorax response, the thickness of all THOR's ribs were measured. Figure 3 shows the von Mises stress distribution of ribs in the upper thorax qualification test. The von Mises stress was calculated by the computer simulation using Humanetics THOR 50th Metric LS-DYNA Model Version 1.0. At the time of peak thorax deflection, the von Mises stress is distributed on the edge side of ribs. Therefore, the ribs thickness of the edge side was measured. Figure 4 shows the measurement points of rib thickness, and Table 3 shows the angle for specifying the measurement points.  $\alpha$  was midangle between Line a and the horizontal line. Line a passed the Point a which showed the edge of ribs. For one rib, the thickness of 4 points was measured. The average thickness between L1 and R1, L2 and R2 was calculated respectively.

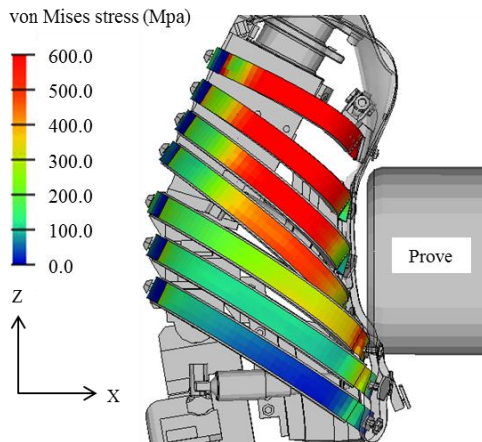


Figure 3. von Mises stress distribution at the time of peak deflection

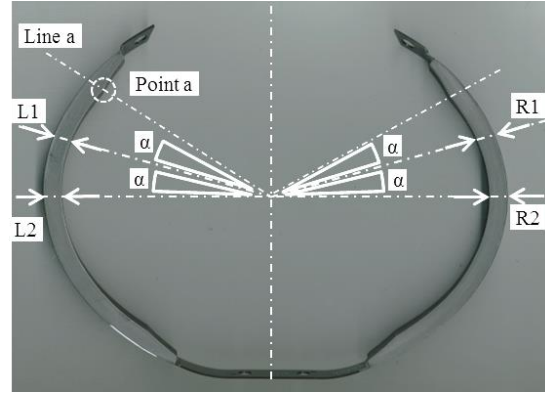


Figure 4. Measurement point of ribs thickness

Table 3.  
The angle for specifying the measurement points of ribs thickness

| Rib order | $\alpha$ |
|-----------|----------|
| 1st       | 25°      |
| 2nd       | 25°      |
| 3rd       | 30°      |
| 4th       | 35°      |
| 5th       | 25°      |
| 6th       | 30°      |
| 7th       | 15°      |

The lumbar spine is one of the components that influence THOR's thorax response except for ribs. For the lumbar spines of THOR A and THOR C, its bending stiffness was evaluated by referencing lumbar spine flex joint bending test (FTSS 2006) as shown in Figure 5. LUMBAR SPINE FLEX JOINT ASSEMBLY attached a rigid iron plate with bolts was fixed on the floor. The initial position of the assembly was adjusted to  $0 \pm 1^\circ$ . A wire threaded through the top of the iron plate was pulled from the initial position to  $15 \pm 1^\circ$  at a rate of 1-2°/second by load cell. The tensile load was measured every five degrees, and the flexion bending moment was calculated by Equation 4. M is bending moment, F is the force reading the load cell, and 0.305m is the length of plate.



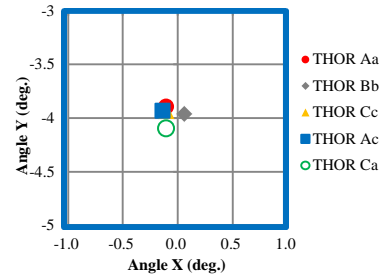
Figure 5. Lumbar spine flex joint bending test

$$M = F \times 0.305 \text{ (N*m)} \quad \text{(Equation 4)}$$

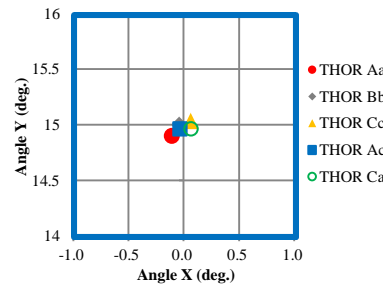
Rib cages were exchanged to investigate the effect of the characteristics of ribs on the upper thorax deflection. At the 3rd rib equipped with the top of IR-TRACCs, the difference of thickness was largest between Rib cage a and Rib cage c. Thin ribs probably lead to reduce stiffness of the rib cage. Therefore, all THORAX ELLIPTICAL RIBS and THORAX ELLIPTICAL RIB STIFFENERS were exchanged between THOR Aa and THOR Cc. The effects were evaluated by the upper thorax qualification test similarly. This test matrix is shown in Table 1. The tests were conducted three times at each condition.

## RESULTS

For three THOR-50M and five HIII-50M ATDs, the thorax qualification test was conducted three times respectively according to each procedure. Figure 6 shows the initial angles of tilt sensors at the upper thorax qualification test in THOR-50M ATD. In all tests, the angles of LTS and Pelvis were within the blue line that shows the specified range of the procedure. The CV value was calculated to evaluate the R&R in the thorax response of THOR and Hybrid III ATDs. Figure 7 shows the CV of the THOR's and Hybrid III's thorax deflection in thorax qualification test. For the THOR-50M ATD, the CV of THOR Bb and TOTAL were good although that of all Hybrid III were excellent. The R&R of THOR was lower than that of Hybrid III for the thorax qualification testing. As shown in Figure 8, THOR's and Hybrid III's thorax deflections were converted into injury risk probability. The largest difference of injury risk was calculated respectively for all tests. The injury risk variation for THOR-50M ATD's was about 8.4%, although that of HIII-50M ATDsIII was 0.6%. Therefore, THOR is required to improve the R&R in thorax qualification test.

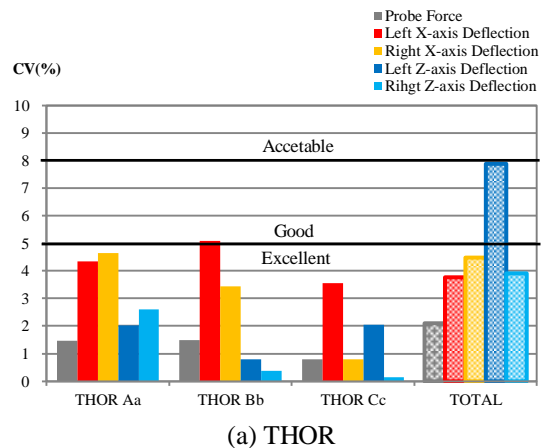


(a) T6

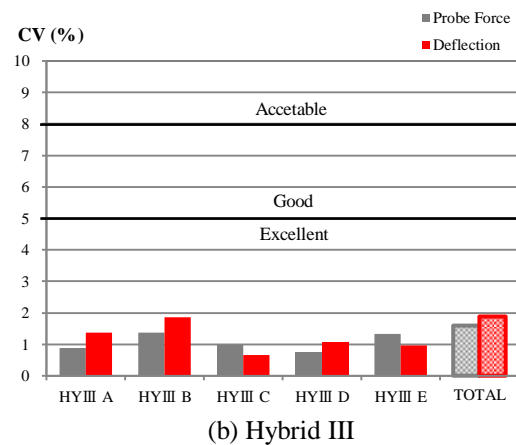


(b) Pelvis

Figure 6. Initial angles of tilt sensor



(a) THOR



(b) Hybrid III

Figure 7. CV value of thorax deflection in thorax qualification test

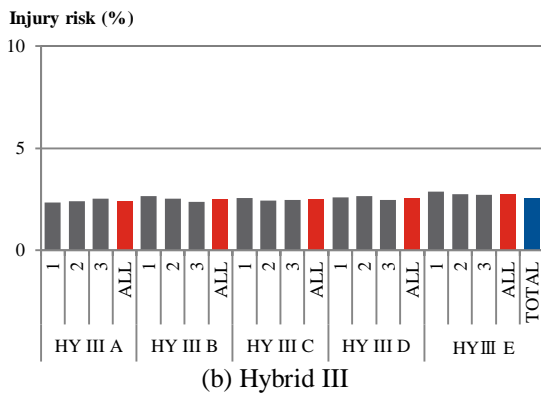
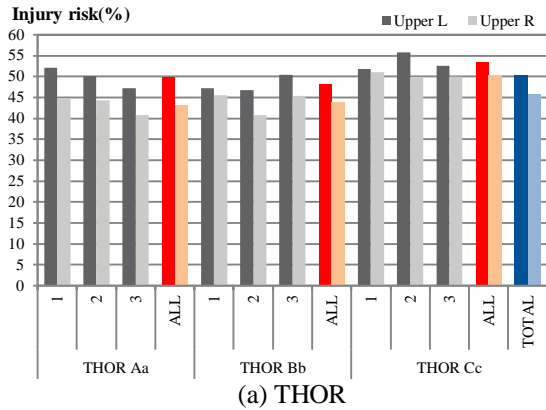


Figure 8. Injury risk in THOR's and Hybrid III's thorax qualification test

In order to investigate how the characteristics of ribs influence on the upper thorax response, the thickness of all THOR ATDs ribs were measured. Figure 9 shows the average thickness of the 3rd rib. L1 & R1 and L2 & R2 refer to the average between L1 and R1, L2 and R2. At the L1 & R1 and L2 & R2 points, it was observed that the thickness of Ribs cage c was approximately 0.7 and 0.4 millimeters thinner than that of Rib cage a.

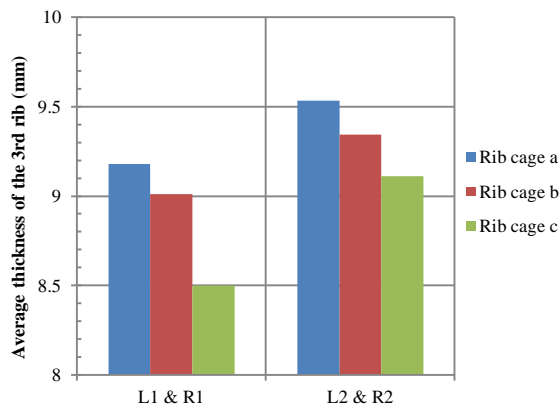


Figure 9. Rib thickness of THOR

For components other than the rib cage, the lumbar spine might have an effect on the THOR-50M ATD's thorax response. Therefore, a lumbar spine flex joint bending test was conducted to evaluate the flexion bending moment. Figure 10 shows that the flexion bending moment of LUMBAR SPINE FLEX JOINT ASSEMBLY and bending angle. At 10 degrees (which is the initial angle of lumbar spine in upper thorax qualification test), the bending moment of THOR C was about 2.8 N · m greater than that of THOR A. Therefore, THOR C's LUMBAR SPINE FLEX JOINT ASSEMBLY had high flexion bending stiffness.

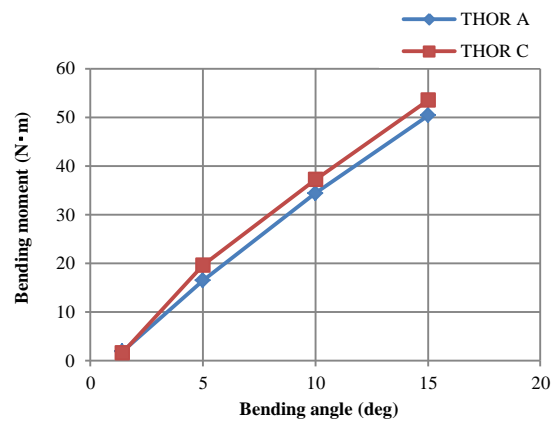
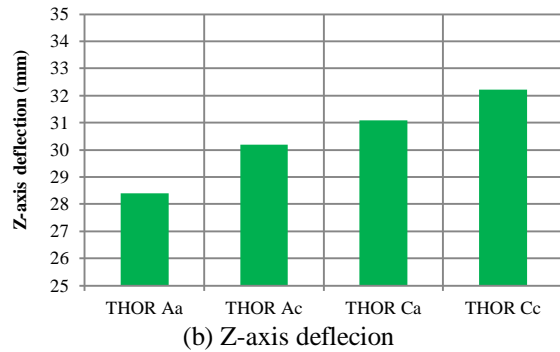
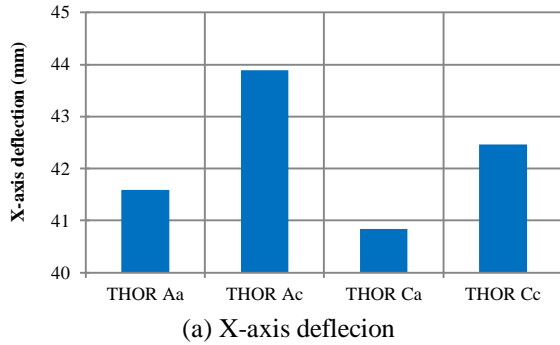
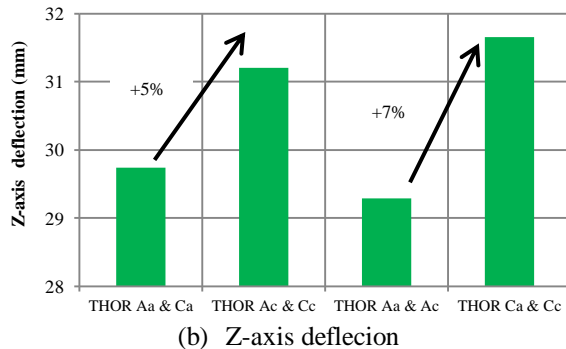
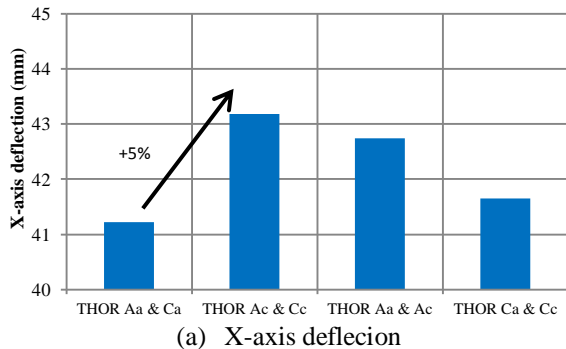


Figure 10. Bending moment in lumbar spine flex joint bending test

In the third rib, the thickness of Rib cage c was thinner than that of Rib cage a. Therefore, the Rib cage a and c were exchanged in each ATD and thorax qualification tests were conducted on them. The average of three tests was calculated between upper left and right thorax deflection. Figure 11-1 shows the thorax deflection of THOR in X-axis and Z-axis. Figure 11-2 (a) and (b) show X-axis and Z-axis deflection. THOR Aa & Ac refers to the average deflection between THOR Aa and THOR Ac. In the same rib cage, X-axis and Z-axis deflection of THOR Ac & Cc was about 5% greater than that of THOR Aa & Ca, regardless of other components. In the same body, the average Z-axis deflection of THOR Ca & Cc was about 7% greater than that of THOR Aa & Ac, regardless of rib cages. Therefore, the characteristics of rib cages have a big influence on X-axis and Z-axis thorax deflection and the characteristics of components except for a rib cage have a big influence on Z-axis thorax deflection.



**Figure 11-1. Deflection in thorax qualification test**



**Figure 11-2. Deflection in thorax qualification test**

## DISCUSSION

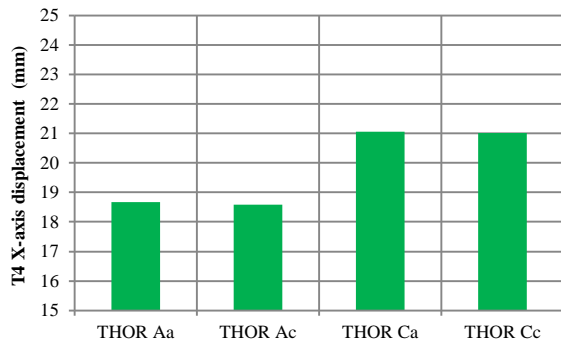
As shown in Figure 7, the R&R of the THOR-50M ATD was worse than that of Hybrid III in thorax qualification test. The reason is that the thorax of THOR has more complex structure, such as the flexible spine and the rib top connected by THORAX OUTER BIB which is soft, than that of HIII-50M ATD. In addition, the THOR's spine consists of several flexible components and sensors to measure injury values.

As shown in Figure 11-2(a) and (b), X-axis and Z-axis thorax deflection of the ATD attached with Rib cage c was about 5% greater than that of Rib cage a. As shown in Figure 9, the thickness of Rib cage c was thinner than that of Rib cage a at the 3rd rib equipped with the top of IR-TRACCs. Therefore, the difference of thorax deflection might be caused by the rib cage stiffness depended on the rib thickness. In order to improve the R&R, rib stiffness should be certified. A mass drop test similar to that used for the Hybrid III might be appropriate for this qualification.

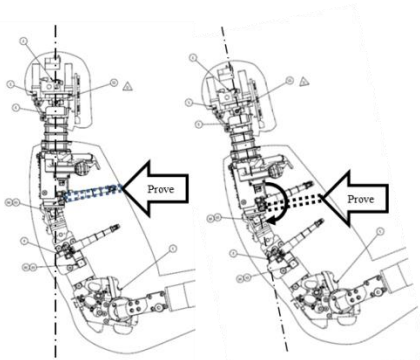
Additionally, figure 11-2(b) shows that the deflection of THOR Ca & Cc was about 7% greater than that of THOR Aa & Ac. It is believed that some components other than rib cage influence Z-axis deflection. Figure 12 shows the T4 X-axis displacement at the time of peak Z-axis deflection. THOR Aa & Ac refers to the average displacement between THOR Aa and THOR Ac. T4 X-axis displacement of THOR Ca & Cc was 2.5mm greater than that of THOR Aa & Ac. As shown in Figure 10, the flexion moment of THOR C was greater than that of THOR A at 10 degrees, which is the initial angle of lumbar spine in upper thorax qualification test. Figure 13 shows the schematic of thorax response in upper thorax qualification test. Increasing the bending spine at peak Z-axis deflection causes the IR-TRACCs to rotate in the Y-axis. The high bending stiffness of lumbar spine might increase the rotating spine. Therefore, the high bending stiffness of lumbar spine might have a contribution to increasing Z-axis deflection.

In a future study, it is necessary to confirm the effect of the lumbar spine flexion moment on thorax deflection. As the ribs, the lumbar spine certification based on bending stiffness may be required.





**Figure 12. T4 X-axis displacement at the peak Z-axis deflection in THOR's upper thorax qualification test**



**Figure 13. The Schematic of thorax response in THOR's upper thorax qualification test**

## CONCLUSION

Using several thorax qualification tests, the following conclusions were obtained.

For three THOR and five Hybrid III ATDs, the thorax deflection was measured three times by each certification procedure. On the thorax response, the R&R of THOR-50M ATD was lower than that of HIII-50M ATD.

The X-axis and Z-axis thorax deflection of the THOR ATD correlates with the rib cage stiffness and rib cage stiffness was shown to correlate with rib thickness. Therefore, it is important that the ribs thickness was controlled to enhance the reproducibility in thorax response.

The Z-axis thorax deflection of the THOR is correlated with the rotating spine, regardless of the rib thickness. The rotating spine is correlated with bending stiffness of lumbar spine. In order to further

explore opportunities for R&R enhancements, future studies should study the effect of lumbar spine characteristics as well as other ATD components.

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