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THOR-50M Durability Report

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| 16. Abstract This report documents the methods and results of qualification-type testing performed to evaluate the durability of the THOR 50th Percentile Male Dummy (THOR-50M). This evaluation concluded that the THOR-50M exhibited acceptable durability when exposed to elevated energy qualification-type tests. The durability assessment began with a baseline qualification test, and then the input energy levels were increased by 10 percent, 20 percent, and 30 percent prior to performing a final baseline test. The responses produced during the pre-durability baseline tests and post-durability baseline tests were evaluated against the qualification corridors, and the THOR-50M's durability was deemed acceptable where the dummy passed the qualification requirements, and didn't show visible signs of deterioration. | | | | | |
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1 BACKGROUND

The National Highway Traffic Safety Administration has actively supported the development of an advanced frontal crash test dummy that incorporates improved biofidelic features and significantly expanded instrumentation. The THOR-50M (Test Device for Human Occupant Restraint) represents an advanced frontal crash test 50th percentile male dummy for frontal impacts. The primary design objectives included:

- a) Biofidelity in mass, size, surface geometry, and dynamic response;
- b) Repeatability and reproducibility of performance;
- c) Durability - minimization of damage in severe test environments; and
- d) Incorporation of specific instrumentation relevant to injury assessment.

The design approach included a systematic evaluation of design requirements for each of these objectives. This study specifically addresses the durability design objective. Performing elevated energy qualification tests allows the agency to evaluate the durability of the THOR-50M design. Neck and upper leg component qualification tests, as well as full body qualification tests on the head, face, thorax, and abdomen, were conducted at increased energy levels. These increased energy levels were achieved by performing the qualification tests at higher velocities; tests included energy increases of approximately 10 percent, 20 percent and 30 percent above the qualification tests specified in the *THOR 50th Percentile Male (THOR-50M) Qualification Procedures Manual*.¹

2 OBJECTIVES

This study evaluates the durability of the THOR-50M in elevated energy qualification tests. The durability baseline tests for each body region were performed according to the procedures described in the *THOR-50M Qualification Procedures Manual*.² Baseline tests were run at the qualification speed and the durability tests were performed at speeds corresponding to energy level increases of 10 percent, 20 percent, and 30 percent. A final baseline test was performed at the prescribed standard qualification test velocity. The two baseline tests were compared to determine if deterioration in the components could be detected in the data. To allow for recovery of parts after impacts, the minimum wait time between tests followed the prescribed allowance in the Qualification Procedures Manual. When applicable, all testing was performed on the left side of the dummy. For these tests, unless otherwise noted, THOR-50M serial number DO9799 was used.

¹ NHTSA. (In press). *THOR 50th percentile male (THOR-50M) qualification procedures manual*, September 2018. Washington, DC: National Highway Traffic Safety Administration.

² Ibid.

When tested at the nominal qualification speeds, most of the qualification tests produce injury assessment metrics that either:

- A. Represent at least a 50 percent risk of injury based on previously published injury risk functions; or
- B. Have a magnitude greater than the mean plus one standard deviation of the NHTSA oblique vehicle tests (N =18).

There were two exceptions where the nominal qualification test speeds did not reach either of these targets: Upper Leg Impact and Heel Impact. In these conditions, qualification test speeds were increased even further until either of these targets were met.

Under most qualification procedures, dummy metrics increase with higher energy levels and thus represent overload conditions. For the case of the neck tests, however, neck loads show low sensitivity to increases in energy. For these tests, the input acceleration is governed by the crushing of aluminum honeycomb. Since it crushes at a constant force, raising the impact speed has much less of an effect on dummy loads than in tests where the dummy is struck by a pendulum probe directly. Nonetheless, the neck tests do serve to exercise the neck in overload conditions, as the higher speeds do result in greater head rotation.

3 ELEVATED ENERGY QUALIFICATION TEST DURABILITY

3.1 HEAD

3.1.1 Methodology

Durability tests were performed using the head qualification procedures described in the *THOR-50M Qualification Procedures Manual*.³ The head qualification test is a dynamic test performed to examine the force-time and acceleration-time characteristics of the head when impacted on the forehead with a 23.36 kg rigid impactor at 2.00 ± 0.05 m/s (Figure 3-1). For durability tests on the head, the test energy was elevated from the qualification baseline in increments of approximately 10 percent, to a maximum of approximately 30 percent, by increasing the test velocity (Table 3-1). After the 30 percent energy increase, another baseline test was conducted to ensure that there were no changes in response due to elevating the test energy level.

³ Ibid.

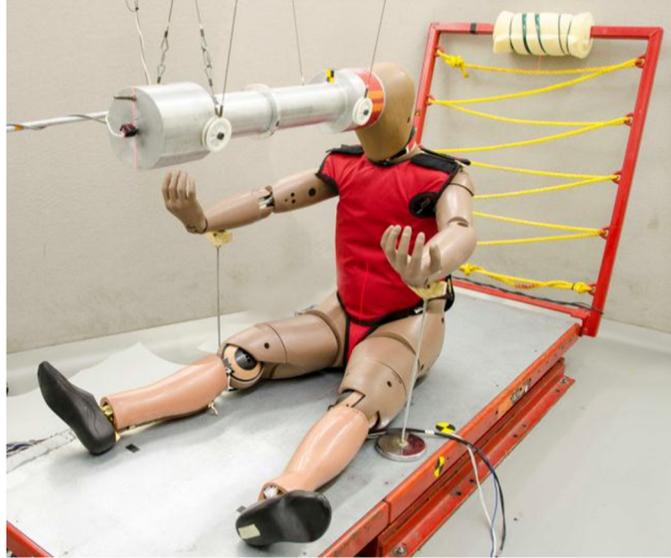


Figure 3-1. Head impact test setup

Table 3-1. Durability Test Velocities for Head Impact Tests

| Durability Test | Velocity (m/s) |
|---------------------|----------------|
| Initial Baseline | 2.01 |
| 10% Energy Increase | 2.12 |
| 20% Energy Increase | 2.18 |
| 30% Energy Increase | 2.27 |
| Final Baseline | 2.01 |

3.1.2 Results

For the baseline THOR-50M head qualification tests, the peak force and the peak head center of gravity (CG) resultant acceleration must be within the ranges provided in Table 3-2. Table 3-3, along with Figure 3-2 and Figure 3-3, illustrates the results of the durability tests.

Table 3-2. Head Impact Standard Qualification Response Requirements

| Parameter | Units | Specification | |
|-------------------------------------|-------|---------------|-------|
| | | Min. | Max. |
| Impact Velocity | m/s | 1.95 | 2.05 |
| Peak Probe Force | N | 5022 | 6138 |
| Peak Head CG Resultant Acceleration | g | 105.3 | 128.7 |

Table 3-3. Head Impact Durability Results

| Date | Test Number | Durability Description | Impact Velocity (m/s) | Peak Probe Force (N) | Head CG Resultant (G) |
|---------|-------------|------------------------|-----------------------|----------------------|-----------------------|
| 8-11-15 | 081115_15 | Initial Baseline | 2.01 | 5478 | 117.6 |
| 8-11-15 | 081115_16 | 10% Energy Increase | 2.12 | 5935 | 126.9 |
| 8-11-15 | 081115_17 | 20% Energy Increase | 2.18 | 6182 | 137.7 |
| 8-11-15 | 081115_18 | 30% Energy Increase | 2.27 | 6512 | 141.1 |
| 8-11-15 | 081115_19 | Final Baseline | 2.01 | 5579 | 117.5 |

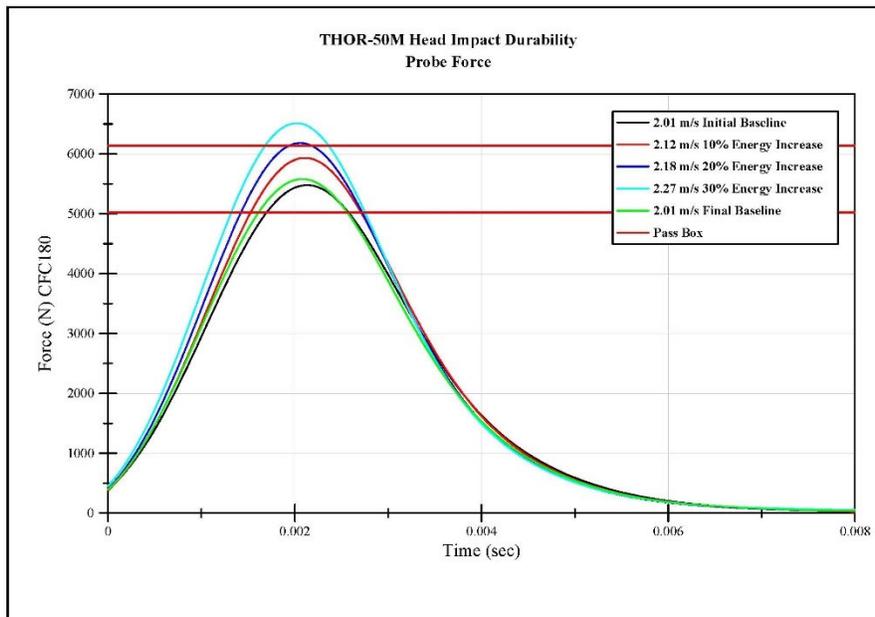


Figure 3-2. Probe force for head durability tests

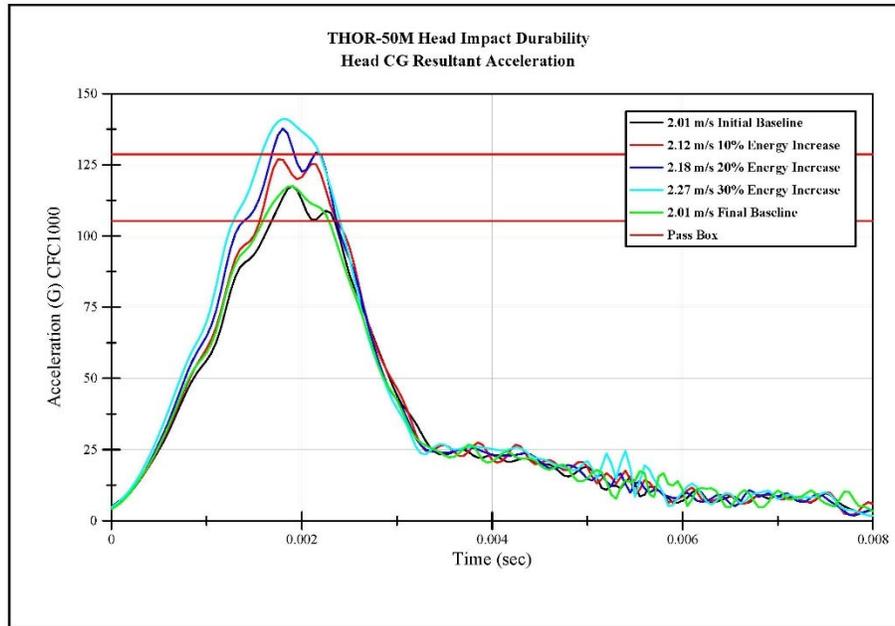


Figure 3-3. Head CG resultant acceleration for head durability tests

3.1.3 Discussion

The final baseline test results showed that the head returned to specification values for both peak probe force and head resultant CG after the increased energy tests. No visible damage to the head was observed post-testing. Results indicate that the head displays acceptable durability.

3.2 FACE

3.2.1 Methodology

Durability tests were performed using the face qualification procedures described in the *THOR-50M Qualification Procedures Manual*.⁴ The face rigid disk qualification test examines facial impact response to loading by a rigid 152.7 mm diameter circular disk face of a 13.00 kg impactor at a velocity of 6.73 ± 0.05 m/s (Figure 3-4).

⁴ Ibid.

During the repeatability and reproducibility testing on the THOR-50M face, it was observed that peak probe force and the head CG resultant acceleration increased with each subsequent qualification test.⁵ This meant that the face foam would need to be replaced after several tests since the probe force and resultant CG acceleration resulted in values above the specifications. As such, for the face impact durability tests, the test energy was elevated from just below the qualification baseline to approximately 30 percent, for a series of three tests (Table 3-4) to determine if multiple elevated energy tests would result in failing specification values. After the three 30 percent increased energy tests, another baseline test was conducted to ascertain any changes in response due to elevating the test energy level. THOR-50M serial number DO9798 was used for these tests.

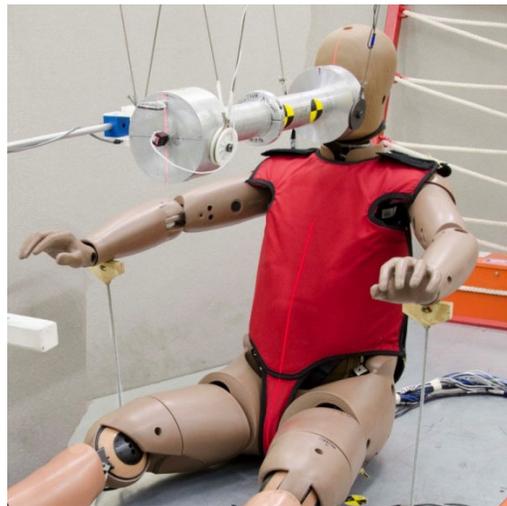


Figure 3-4. Face impact test setup

Table 3-4. Durability Test Velocities for Face Impact Tests

| Durability Test | Velocity (m/s) |
|------------------------|-----------------------|
| Initial Baseline | 6.68 |
| 30% Energy Increase | 7.64 |
| 30% Energy Increase | 7.65 |
| 30% Energy Increase | 7.65 |
| Final Baseline | 6.68 |

⁵ NHTSA. (In press). *THOR-50M Repeatability and Reproducibility of Qualification Tests*, June 2019. Washington, DC: National Highway Traffic Safety Administration.

3.2.2 Results

For the standard THOR-50M face qualification tests, the peak force and the peak head CG resultant acceleration must be within the ranges provided in Table 3-5. Table 3-6, along with Figure 3-5 and Figure 3-6, illustrates the results of the durability tests.

Table 3-5. Face Rigid Disk Impact Qualification Response Requirements

| Parameter | Units | Specification | |
|-------------------------------------|-------|---------------|------|
| | | Min. | Max. |
| Impact Velocity | m/s | 6.68 | 6.78 |
| Peak Probe Force | N | 6378 | 7796 |
| Peak Head CG Resultant Acceleration | g | 124 | 152 |

Table 3-6. Face Impact Durability Results

| Date | Test Number | Durability Description | Impact Velocity (m/s) | Peak Probe Force (N) | Head CG Resultant (G) |
|----------|-------------|------------------------|-----------------------|----------------------|-----------------------|
| 12-06-17 | 171206-3 | Initial Baseline | 6.68 | 6146 | 116 |
| 12-07-17 | 171207-5 | 30% Energy Increase | 7.64 | 9047 | 183 |
| 12-11-17 | 171211-1 | 30% Energy Increase | 7.65 | 9827 | 205 |
| 12-12-17 | 171212-1 | 30% Energy Increase | 7.65 | 10574 | 218 |
| 12-13-17 | 171213-1 | Final Baseline | 6.68 | 8048 | 161 |

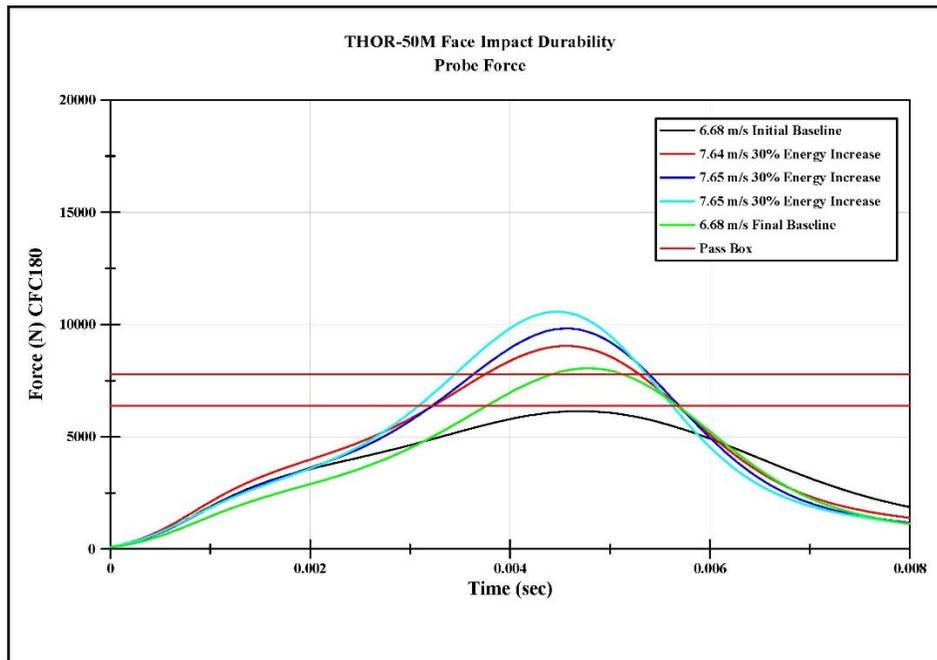


Figure 3-5. Probe force for face impact durability tests

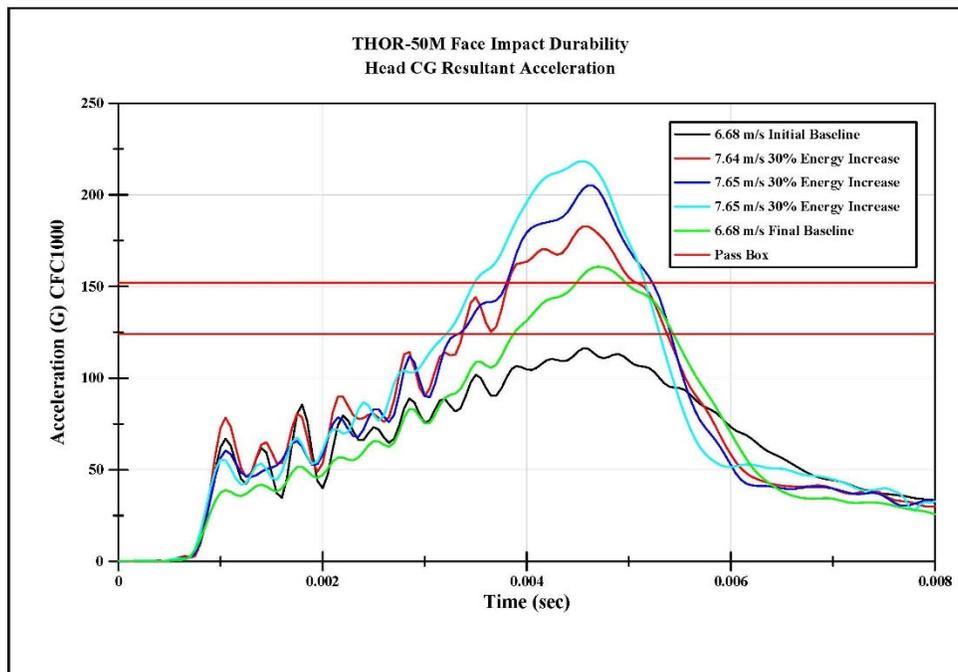


Figure 3-6. Head CG resultant acceleration for face impact durability tests

3.2.3 Discussion

Despite the fact that the initial baseline tests were slightly below the specification corridors, the final baseline test results showed that the face exceeded the specification values for peak probe force and peak head CG resultant acceleration after the increased energy tests. No visible damage to the face was observed post-testing. Results indicate that the face has a limited number of impacts where it remains within the corridor; this result was also observed in the repeatability and reproducibility tests.⁶

The face foam is constructed of Confor foam, which is a memory foam that necessitates an extended recovery period after a dynamic impact. To ensure optimal recovery of the face foam, all face impacts to the THOR-50M are performed after the foam has recovered outside of the head skin for at least 24 hours, as specified in the *THOR-50M Qualification Procedures Manual*.⁷ Other than the considerations mentioned above, no additional steps were performed to condition the face foams between tests.

⁶ Ibid.

⁷ Ibid.

Even for recovery periods of 24 hours or longer, it was found that the face foam never completely recovered to its pretested condition; this was also observed in the *THOR-50M Repeatability and Reproducibility of Qualification Tests*.⁸ However, the R&R results show that the face foams remain within the qualification corridors for approximately ten subsequent impacts; this suggests that the face foams have a limited lifespan before requiring replacement, but do provide clearly failing qualification results when the life of the foam is exhausted.

Nonetheless, we are satisfied with the performance of the face and are content with simply replacing the foam at a rate of approximately seven impacts. In repeated qualification tests, the foam is effectively the only energy absorbing element and there is only a small, gradual increase in the impact force. This small deterioration in the foam is unlikely to have a noticeable effect on the results of a subsequent vehicle test because in a vehicle test more energy will likely be absorbed by a vehicle interior component relative to the rigid, qualification impact probe.

3.3 NECK FLEXION

3.3.1 Methodology

Durability tests were performed using the neck flexion qualification procedures described in the *THOR Qualification Procedures Manual*. The flexion tests resemble the Hybrid III head-neck pendulum test defined in CFR Title 49, Part 572, Subpart E with 152.4 mm (6") aluminum honeycomb used to decelerate the pendulum from an impact velocity of 5.00 ± 0.05 m/s (Figure 3-7). For the flexion durability tests, the head/neck assembly was rigidly attached at the lower neck load cell to the bottom of the head-neck pendulum; the pendulum was decelerated from the specified speed during contact with a Hexcel aluminum honeycomb (or equivalent). For durability tests on the neck in flexion, the test energy was elevated from the qualification baseline in increments of approximately 10 percent, to a maximum of approximately 30 percent, by increasing the test velocity (Table 3-7). After the 30 percent energy increase, a final baseline test was conducted to ascertain no changes in response were observed due to elevating the test energy level.

⁸ Ibid.

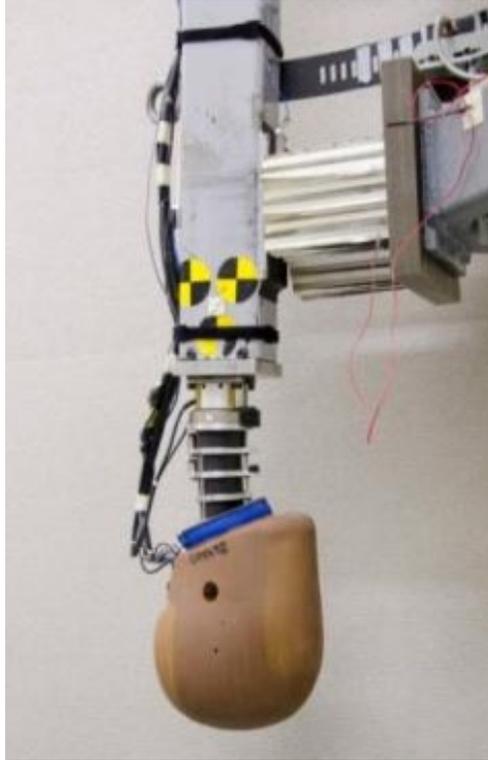


Figure 3-7. Neck flexion test setup

Table 3-7. Durability Test Velocities for Neck Flexion Tests

| Durability Test | Velocity (m/s) |
|---------------------|----------------|
| Initial Baseline | 5.04 |
| 10% Energy Increase | 5.24 |
| 20% Energy Increase | 5.48 |
| 30% Energy Increase | 5.65 |
| Final Baseline | 5.00 |

3.3.2 Results

For the THOR-50M neck flexion baseline qualification tests, the neck flexion responses must be within the ranges provided in Table 3-8. Table 3-9, along with Figure 3-8 through Figure 3-11, illustrates the durability test results.

Table 3-8. Neck Flexion Standard Qualification Response Requirements

| Parameter | Units | Specification | |
|---|-------|---------------|-------|
| | | Min. | Max. |
| Impact Velocity | m/s | 4.95 | 5.05 |
| Peak Upper Neck M_y | N-m | 27.9 | 34.1 |
| Peak Upper Neck F_z most positive value prior to 40 ms | N | 774 | 946 |
| Peak Head Angular Velocity ω_y (relative to earth) | deg/s | -2172 | -1777 |
| Peak Head Rotation (relative to pendulum) | deg | -71.0 | -58.1 |

Table 3-9. Neck Flexion Durability Results (EB6005)

| | | 171023-7 | 171023-12 | 171023-14 | 171023-16 | 171024-1 |
|---|-------|------------------|---------------------|---------------------|---------------------|----------------|
| | | Initial Baseline | 10% Energy Increase | 20% Energy Increase | 30% Energy Increase | Final Baseline |
| Date | | 10-23-17 | 10-23-17 | 10-23-17 | 10-23-17 | 10-24-17 |
| Impact Velocity | m/s | 5.04 | 5.23 | 5.48 | 5.65 | 5.00 |
| Peak Upper Neck M_y | N-m | 32.0 | 33.1 | 33.1 | 33.7 | 31.0 |
| Peak Upper Neck F_z most positive value prior to 40 ms | N | 825 | 921 | 1006 | 985 | 824 |
| Peak Head Angular Velocity ω_y (relative to earth) | deg/s | -1849 | -1946 | -1964 | -1924 | -1864 |
| Peak Head Rotation (relative to pendulum) | deg | -68.8 | -70.5 | -72.1 | -73.8 | -68.0 |

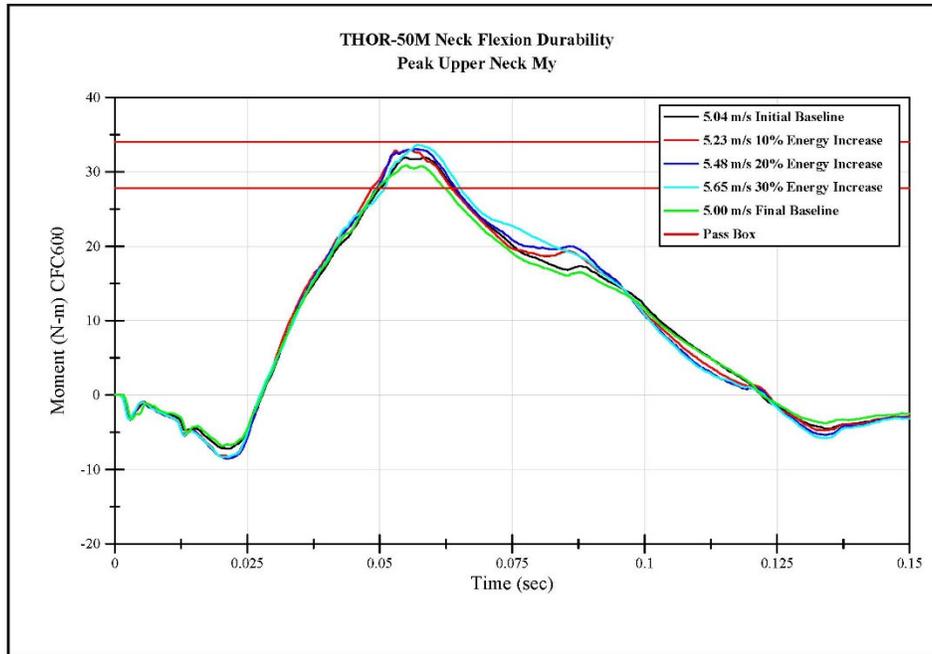


Figure 3-8. Peak upper neck moment about Y axis for neck frontal flexion durability tests

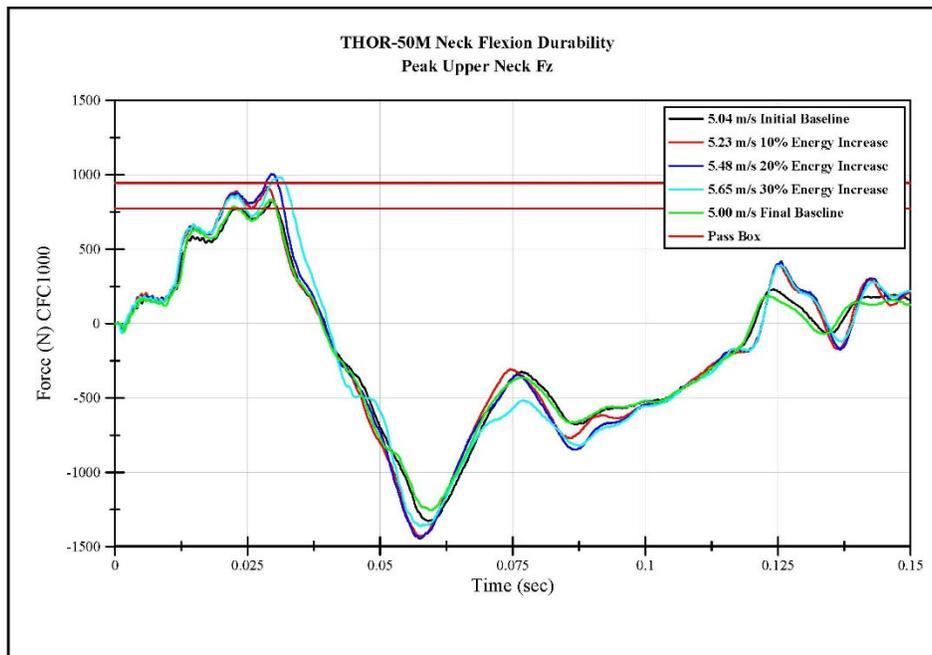


Figure 3-9. Most positive upper neck z axis force value prior to 40 ms for neck frontal flexion durability tests

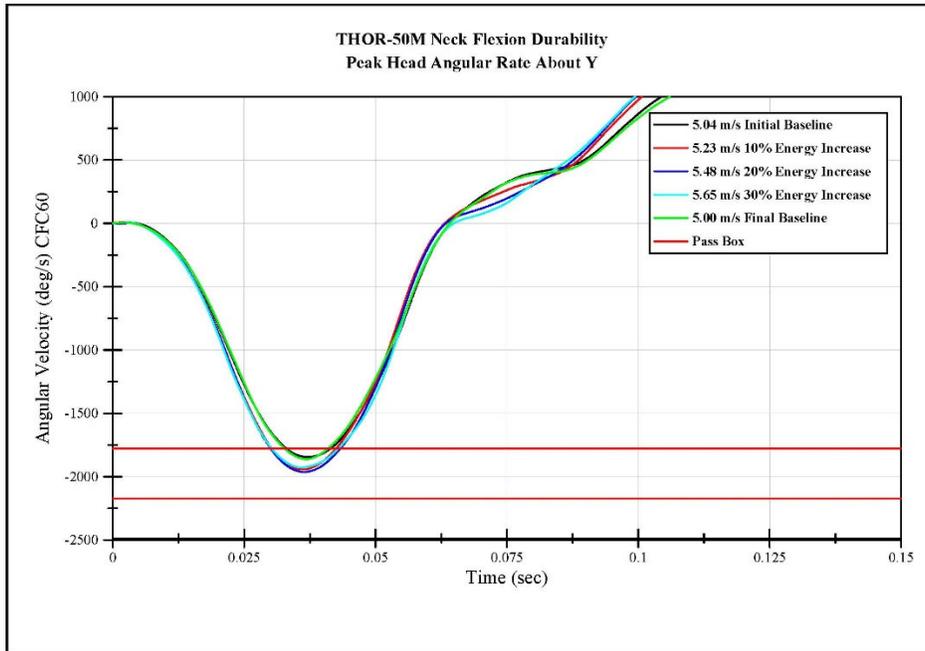


Figure 3-10. Peak head angular rate for neck frontal flexion durability tests

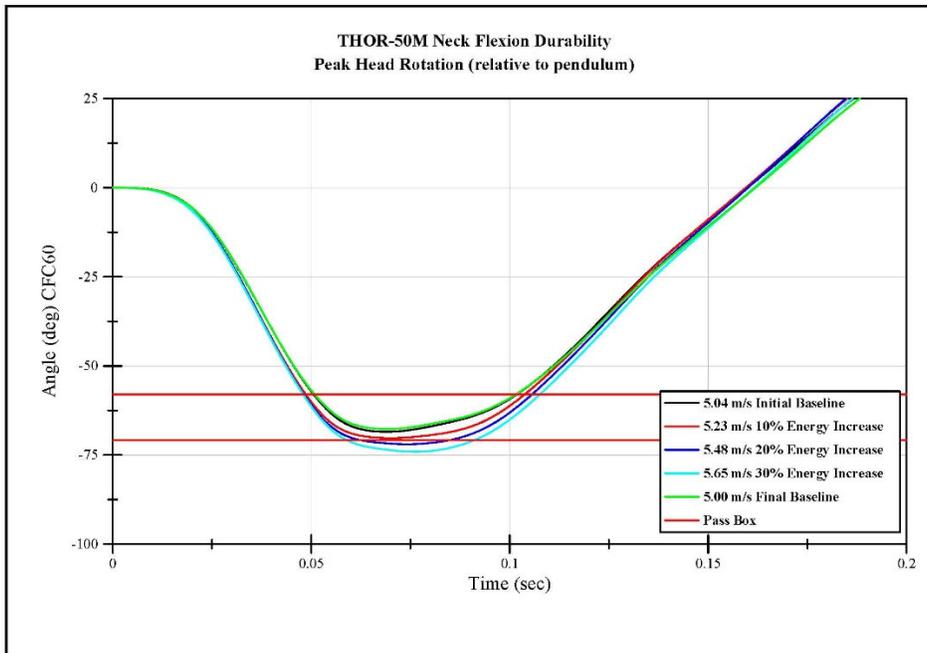


Figure 3-11. Peak head rotation for neck frontal flexion durability tests

3.3.3 Discussion

The final baseline test results showed that the neck returned to specification values for upper neck moment and force (M_y and F_z), head angular rate, and head rotation after the increased energy tests. No visible damage to the neck was observed post-testing. Overall, the results indicate that the neck displays acceptable durability with respect to flexion.

3.4 NECK EXTENSION

3.4.1 Methodology

Durability tests were performed using the neck extension qualification procedures described in the *THOR-50M Qualification Procedures Manual*. The extension tests resemble the Hybrid III head-neck pendulum test defined in CFR Title 49, Part 572, Subpart E with 152.4 mm (6") aluminum honeycomb used to decelerate the pendulum with an impact velocity of 5.00 ± 0.05 m/s (Figure 3-12). For the extension durability tests, the lower neck load cell was attached rigidly to the bottom of the head-neck pendulum, and the pendulum was decelerated from the specified speed during contact with a Hexcel aluminum honeycomb (or equivalent). For durability tests on the neck in extension, the test energy was elevated from the qualification baseline in increments of approximately 10%, to a maximum of approximately 30 percent, by increasing the test velocity (Table 3-10). After the 30 percent energy increase, another baseline test was conducted to make certain that no changes in response were observed due to elevating the test energy level.

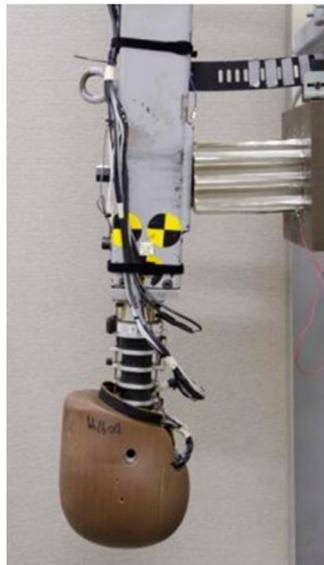


Figure 3-12. Neck extension test setup

Table 3-10. Durability Test Velocities for Neck Extension Tests

| Durability Test | Velocity (m/s) |
|---------------------|----------------|
| Initial Baseline | 4.95 |
| 10% Energy Increase | 5.25 |
| 20% Energy Increase | 5.43 |
| 30% Energy Increase | 5.65 |
| Final Baseline | 5.00 |

3.4.2 Results

For the THOR-50M neck extension baseline qualification tests, the neck extension responses must be within the ranges provided in Table 3-11.

Table 3-12, along with Figure 3-13 through Figure 3-16, illustrates the durability test results.

Table 3-11. Neck Extension Response Requirements

| Parameter | Units | Specification | |
|---|-------|---------------|-------|
| | | Min. | Max. |
| Impact Velocity | m/s | 4.95 | 5.05 |
| Peak Upper Neck M_y | N-m | -25.3 | -20.7 |
| Peak Upper Neck F_z | N | -3210 | -2626 |
| Peak Head Angular Velocity ω_y (relative to earth) | deg/s | 1850 | 2261 |
| Peak Head Rotation (relative to pendulum) | deg | 58.5 | 71.5 |

Table 3-12. Neck Extension Durability Results

| | | 171019-4 | 171019-8 | 171023-1 | 171023-2 | 171023-3 |
|---|-------|------------------|---------------------|---------------------|---------------------|----------------|
| | | Initial Baseline | 10% Energy Increase | 20% Energy Increase | 30% Energy Increase | Final Baseline |
| Date | | 10-19-17 | 10-19-17 | 10-23-17 | 10-23-17 | 10-23-17 |
| Impact Velocity | m/s | 4.95 | 5.25 | 5.43 | 5.65 | 5.00 |
| Peak Upper Neck M_y | N-m | -21.8 | -25.1 | -25.5 | -25.7 | -24.1 |
| Peak Upper Neck F_z | N | -2938 | -2997 | -3118 | -3392 | -3098 |
| Peak Head Angular Velocity ω_y (relative to earth) | deg/s | 1977 | 1957 | 1969 | 2104 | 2088 |
| Peak Head Rotation (relative to pendulum) | deg | 62.6 | 63.4 | 64.0 | 66.2 | 63.8 |

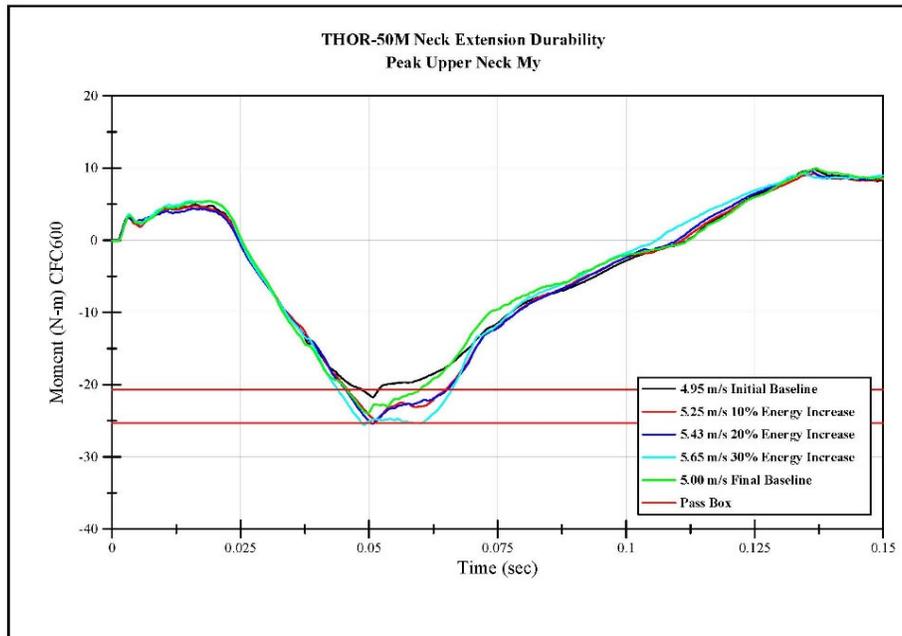


Figure 3-13. Peak upper neck moment about Y axis for neck extension durability tests

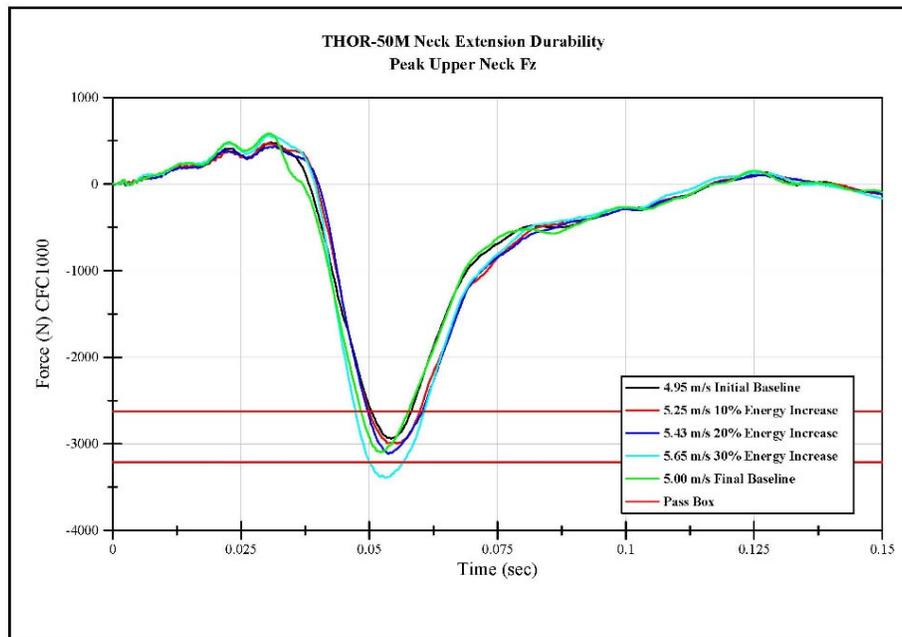


Figure 3-14. Peak upper neck Z axis force for neck extension durability tests

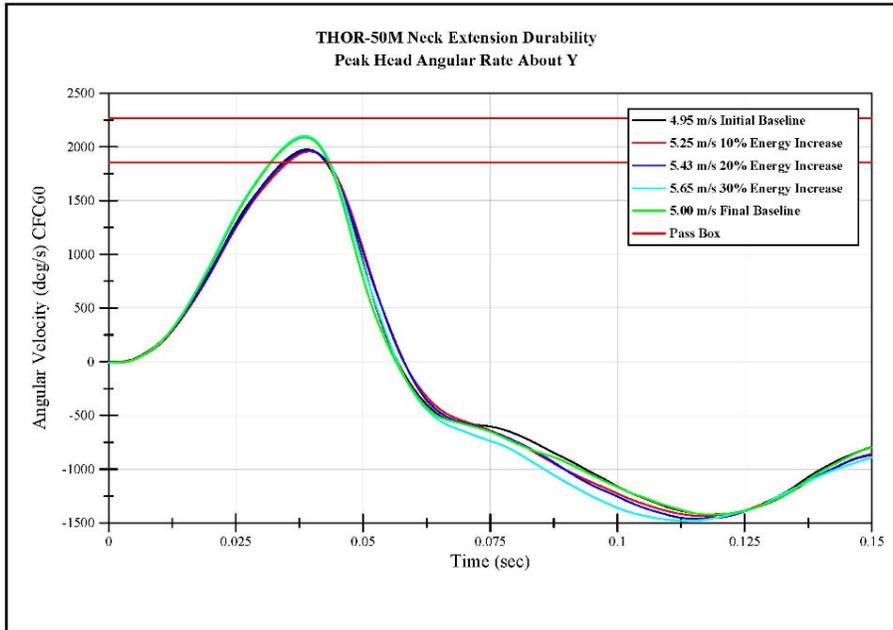


Figure 3-15. Peak head angular rate for neck extension durability tests

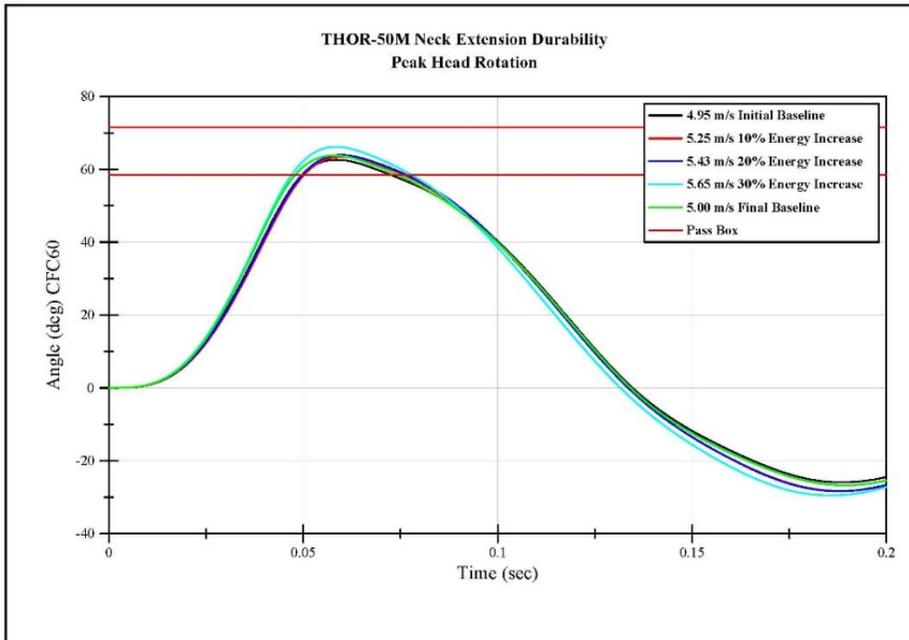


Figure 3-16. Peak head rotation for neck extension durability tests

3.4.3 Discussion

The final baseline test results showed that the neck returned to specification values for the upper neck moment (My), upper neck force (Fz), head angular rate, and head rotation after the increased energy tests. No visible damage to the neck was observed post-testing. Overall results indicate that the neck displays acceptable durability with respect to extension.

3.5 NECK LATERAL FLEXION

3.5.1 Methodology

Durability tests were performed using the neck lateral flexion qualification procedures described in the *THOR-50M Qualification Procedures Manual*. The neck qualification in the lateral mode resembles the ES-2re head-neck lateral pendulum test defined in CFR Title 49, Part 572, Subpart U using 76.2 mm (3") Hexcel aluminum honeycomb (or equivalent) for pendulum deceleration from an impact velocity of 3.40 ± 0.05 m/s (Figure 3-17). For lateral flexion neck tests, the lower neck load cell is attached rigidly to the bottom of the head-neck pendulum, and the pendulum is decelerated from the specified speed during contact with a Hexcel aluminum honeycomb (or equivalent). For durability tests on the neck in lateral mode, the test energy was elevated from the qualification baseline in increments of approximately 10 percent, to a maximum of approximately 30 percent, by increasing the test velocity (Table 3-13). After the 30 percent energy increase, another baseline test was conducted to ensure no changes in response were observed due to elevating the test energy level.

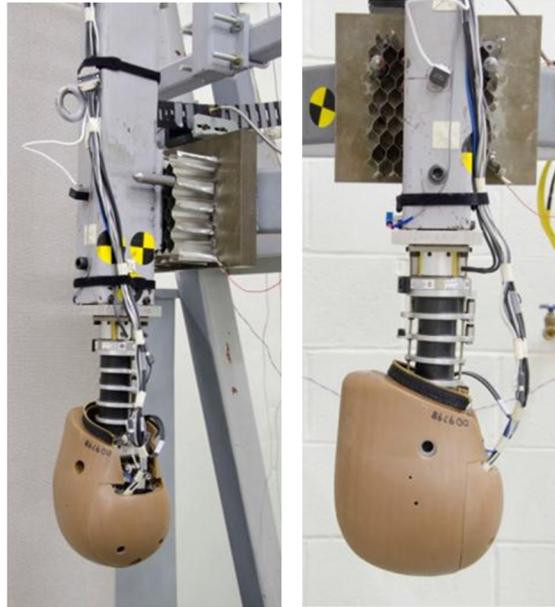


Figure 3-17. Neck lateral flexion test setup

Table 3-13. Durability Test Velocities for Lateral Flexion Neck Tests

| Durability Test | Velocity (m/s) |
|------------------------|-----------------------|
| Initial Baseline | 3.43 |
| 10% Energy Increase | 3.59 |
| 20% Energy Increase | 3.70 |
| 30% Energy Increase | 3.91 |
| Final Baseline | 3.43 |

3.5.2 Results

For the THOR-50M neck lateral flexion baseline qualification tests, the neck lateral flexion responses must be within the ranges provided in Table 3-14. Table 3-15, along with Figure 3-18 through Figure 3-20, illustrates the neck lateral flexion durability test results.

Table 3-14. Neck Left Lateral Flexion Response Requirements

| Parameter | Units | Specification | |
|---|-------|---------------|-------|
| | | Min. | Max. |
| Impact Velocity | m/s | 3.35 | 3.45 |
| Upper Neck M_x first peak after 40.0 ms | N-m | 44.8 | 54.7 |
| First Peak Head Angular Velocity ω_x (relative to earth) | deg/s | -1498 | -1226 |
| Peak Head Rotation (relative to pendulum) | deg | -45.9 | -37.6 |

Table 3-15. Neck Lateral Flexion Durability Results

| | | 171024-2 | 171024-3 | 171024-4 | 171024-5 | 171024-6 |
|---|-------|------------------|---------------------|---------------------|---------------------|----------------|
| | | Initial Baseline | 10% Energy Increase | 20% Energy Increase | 30% Energy Increase | Final Baseline |
| Date | | 10-24-17 | 10-24-17 | 10-24-17 | 10-24-17 | 10-24-17 |
| Impact Velocity | m/s | 3.43 | 3.59 | 3.70 | 3.91 | 3.43 |
| Upper Neck M_x first peak after 40.0 ms | N-m | 51.7 | 54.0 | 55.8 | 57.2 | 50.5 |
| First Peak Head Angular Velocity ω_x (relative to earth) | deg/s | -1346 | -1359 | -1381 | -1421 | -1309 |
| Peak Head Rotation (relative to pendulum) | deg | -42.0 | -43.7 | -45.6 | -48.4 | -42.3 |

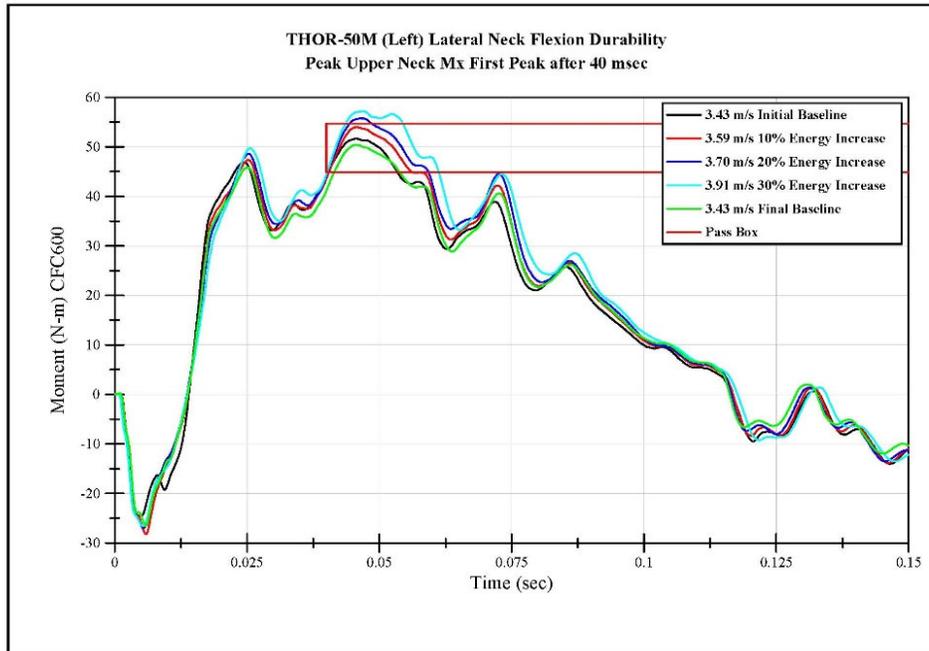


Figure 3-18. Peak upper neck moment about X axis for neck lateral flexion durability tests

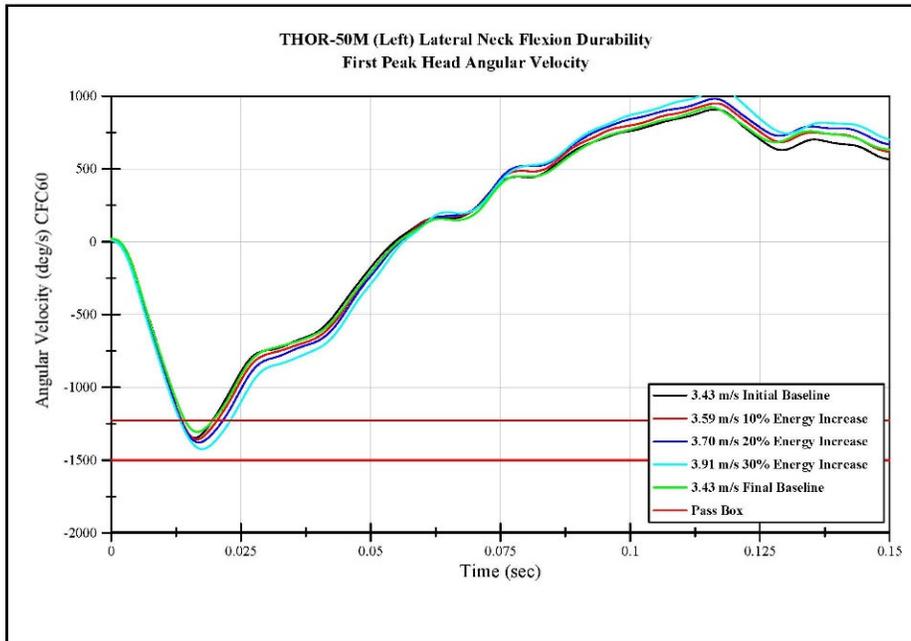


Figure 3-19. Peak head angular rate about X axis for neck lateral flexion durability tests

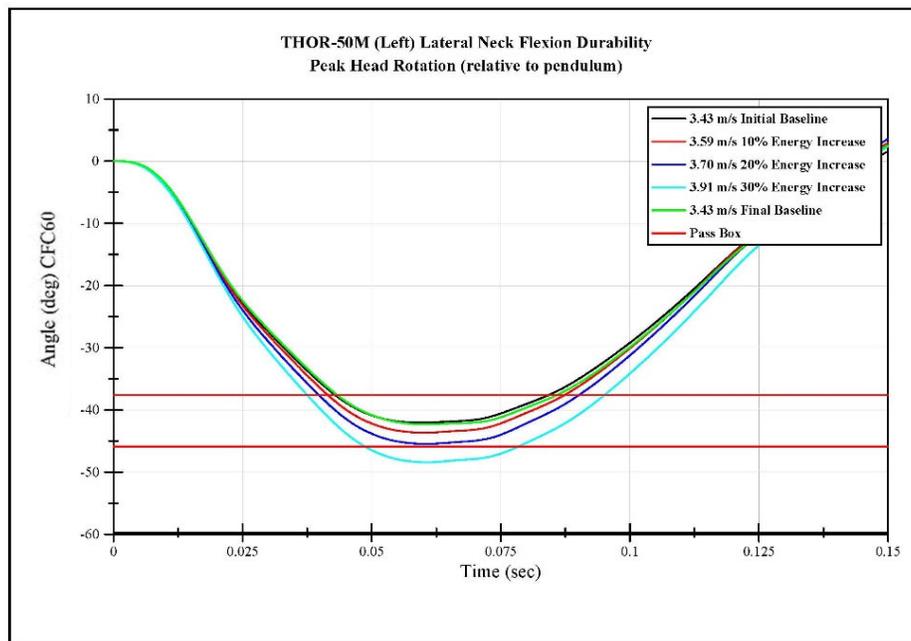


Figure 3-20. Peak head rotation for neck lateral flexion durability tests

3.5.3 Discussion

The final baseline test results showed that the neck returned to specification values for the upper neck moment (M_x), head angular rate, and head rotation after the increased energy tests. No visible damage to the neck was observed post-testing. Overall results indicate that the neck displays acceptable durability with respect to durability in lateral flexion.

3.6 NECK TORSION

3.6.1 Methodology

Durability tests were performed using the neck torsion qualification procedures described in the *THOR-50M Qualification Procedures Manual*. The neck torsion tests assess the response of the neck about the Z axis. The pendulum is also used for neck torsion tests, but instead of the lower neck load cell being attached to the pendulum, a neck torsion fixture (drawing DL472-1000) is used (Figure 3-21). The neck qualification in the torsion mode uses 152.4 mm (6") Hexcel aluminum honeycomb (or equivalent) for pendulum deceleration from an impact velocity of 5.00 ± 0.05 m/s. For durability tests on the neck torsion, the test energy was elevated from the qualification baseline in increments of approximately 10 percent, to a maximum of approximately 30 percent, by increasing the test velocity (Table 3-16). After the 30 percent energy increase, another baseline test was conducted to make certain that no changes in response were observed due to elevating the test energy level.

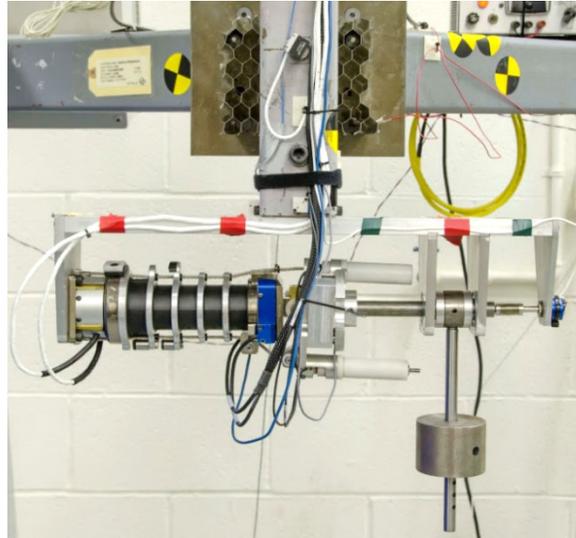


Figure 3-21. Neck torsion test setup

Table 3-16. Durability Test Velocities for Neck Torsion Tests

| Durability Test | Velocity (m/s) |
|---------------------|----------------|
| Initial Baseline | 5.04 |
| 10% Energy Increase | 5.28 |
| 20% Energy Increase | 5.48 |
| 30% Energy Increase | 5.71 |
| Final Baseline | 5.04 |

3.6.2 Results

For the THOR-50M neck torsion baseline qualification tests, the neck torsion responses must be within the ranges provided in Table 3-17. Table 3-18, along with Figure 3-22 through Figure 3-24, illustrates the durability test results.

Table 3-17. Neck Left Torsion Response Requirements

| Parameter | Units | Specification | |
|---|-------|---------------|-------|
| | | Min. | Max. |
| Impact Velocity | m/s | 4.95 | 5.05 |
| Peak Upper Neck M_z | N-m | 37.3 | 45.6 |
| Peak Neck Fixture Rotation | deg | -52.7 | -43.1 |
| First Peak Upper Neck Angular Velocity ω_z | deg/s | -1529 | -1251 |

Table 3-18. Neck Torsion Durability Results

| | | 171024-7 | 171024-8 | 171024-9 | 171025-1 | 171025-2 |
|---|--------------|------------------|---------------------|---------------------|---------------------|----------------|
| | | Initial Baseline | 10% Energy Increase | 20% Energy Increase | 30% Energy Increase | Final Baseline |
| Date | | 10-24-17 | 10-24-17 | 10-24-17 | 10-25-17 | 10-25-17 |
| Impact Velocity | m/s | 5.04 | 5.28 | 5.48 | 5.71 | 5.04 |
| Peak Upper Neck M_z | N-m | 41.6 | 42.9 | 44.5 | 45.7 | 41.0 |
| Peak Neck Fixture Rotation | deg | -46.8 | -49.8 | -51.9 | -53.1 | -47.7 |
| First Peak Upper Neck Angular Velocity ω_z | deg/s | -1344 | -1423 | -1448 | -1484 | -1398 |

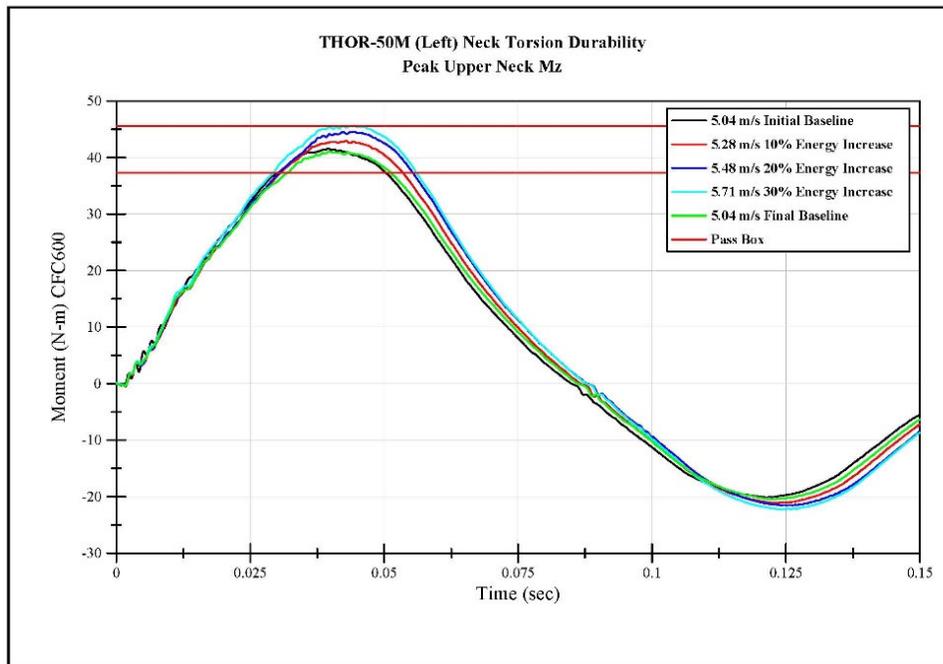


Figure 3-22. Peak upper neck moment about Z axis for neck torsion durability tests

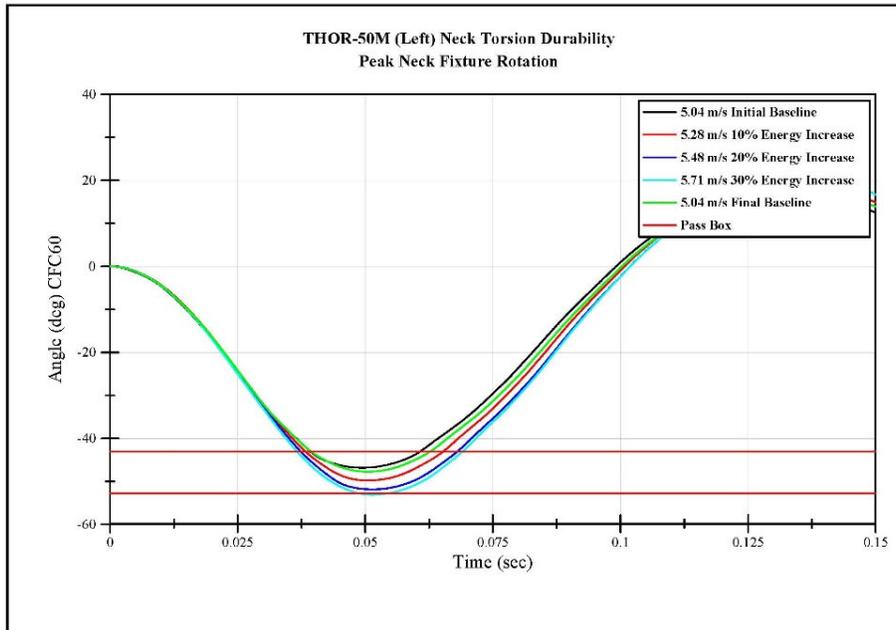


Figure 3-23. Peak neck fixture rotation for neck torsion durability tests

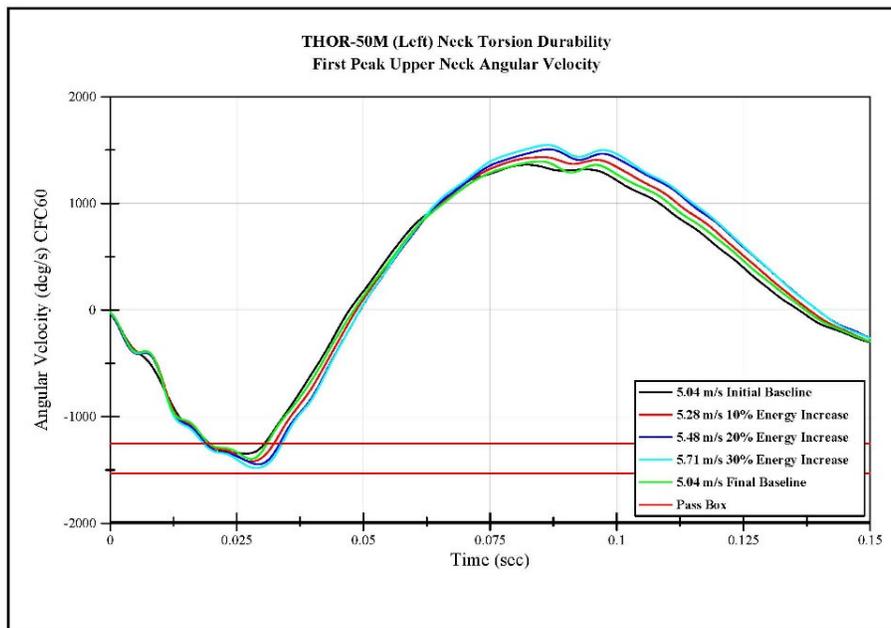


Figure 3-24. Peak head angular rate about Z axis for neck torsion durability tests

3.6.3 Discussion

The final baseline test results showed that the neck returned to specification values for the upper neck moment (M_z), neck angular rate, and neck fixture rotation after the increased energy tests. No visible damage to the neck was observed post-testing. Overall results indicate that the neck displays acceptable durability with respect to durability in torsion.

3.7 UPPER THORAX

3.7.1 Methodology

Upper thorax durability tests followed the qualification procedures described in the *THOR-50M Qualification Procedures Manual*. This test requires a blunt thoracic impact to the sternum, similar to the Hybrid III 50th percentile male certification test, but at a lower speed of $4.3 \text{ m/s} \pm 0.05 \text{ m/s}$ (Figure 3-25). The upper thorax test uses the same impactor as the Hybrid III 50th percentile male ATD. In this test, an impactor with a rigid disk face that has a diameter of 152.40 mm and a mass of 23.36 kg contacts the ATD at mid-sternum level. For durability tests on the upper thorax, the test energy was elevated from the qualification baseline in increments of approximately 10 percent, to a maximum of approximately 30 percent, by increasing the test velocity (Table 3-19). After the 30 percent energy increase, another baseline test was conducted to make certain that no changes in response were observed due to elevating the test energy level. THOR-50M serial number DO9798 was used for these tests.

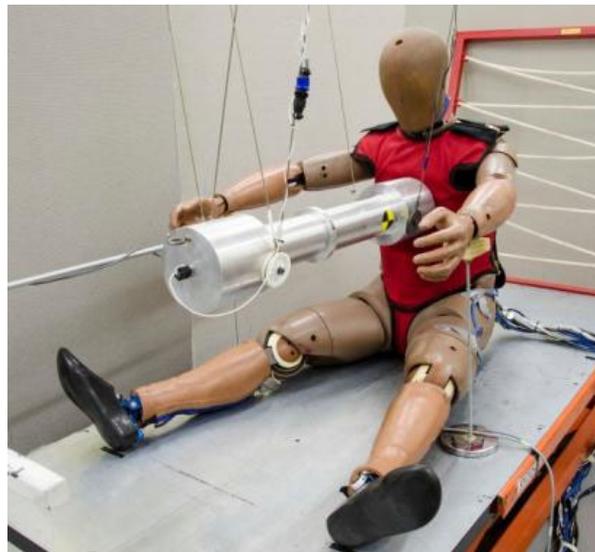


Figure 3-25. Upper thorax impact test setup

Table 3-19. Durability Velocities for Upper Thorax Impact Tests

| Durability Test | Velocity (m/s) |
|---------------------|----------------|
| Initial Baseline | 4.31 |
| 10% Energy Increase | 4.50 |
| 20% Energy Increase | 4.75 |
| 30% Energy Increase | 4.88 |
| Final Baseline | 4.31 |

3.7.2 Results

For the baseline THOR-50M upper thorax qualification tests, the upper thorax responses must be within the ranges provided in Table 3-20. Table 3-21, along with Figure 3-26 through Figure 3-28, illustrates the durability test results.

The primary response specifications for the upper thorax qualification test are the resultant deflections of the left and right upper ribs as calculated *in the local spine coordinate system*, as measured by the 3-D InfraRed Telescoping Rod for Assessment of Chest Compression (IR-TRACC) assemblies, and the reaction force, as calculated using the pendulum acceleration and probe mass. The resultant deflections of the left and right 3-D IR-TRACC assemblies are assessed individually to ensure proper functionality.

Table 3-20. Upper Thorax Qualification Response Requirements

| Parameter | Units | Specification | |
|--|-------|---------------|-------|
| | | Min. | Max. |
| Impact Velocity | m/s | 4.25 | 4.35 |
| Peak Probe Force | N | | 3039 |
| Peak Upper Left Resultant Deflection | mm | 48.3 | 59.0 |
| Peak Upper Right Resultant Deflection | mm | | |
| Difference Between Peak Left & Right Resultant Deflections | mm | | < 5.0 |
| Force at Left & Right Peak Resultant Deflection | N | 2409 | 2944 |

Table 3-21. Upper Thorax Durability Results (THOR-50M DO9798)

| Date | Test Number | Durability Description | Impact Velocity (m/s) | Peak Probe Force (N) | Peak Upper Left Resultant Deflection (mm) | Peak Upper Right Resultant Deflection (mm) | Absolute Diff Between Left & Right Resultant Deflection (mm) | Force at Left Peak Resultant Deflection (N) | Force at Right Peak Resultant Deflection (N) |
|------------------------------------|-------------|------------------------|-----------------------|----------------------|---|--|--|---|--|
| Left Side (THOR-50M DO9798) | | | | | | | | | |
| 5-17-18 | 180517-9 | Initial Baseline | 4.31 | 2726 | 55.6 | 55.7 | 0.1 | 2712 | 2719 |
| 5-21-18 | 180521-1 | 10% Energy Increase | 4.50 | 2741 | 58.5 | 57.0 | 1.5 | 2733 | 2693 |
| 5-21-18 | 180521-4 | 20% Energy Increase | 4.75 | 2996 | 59.0 | 60.7 | 1.7 | 3003 | 2912 |
| 5-21-18 | 180521-5 | 30% Energy Increase | 4.88 | 3337 | 62.6 | 62.5 | 0.1 | 3320 | 3344 |
| 5-21-18 | 180521-6 | Final Baseline | 4.31 | 2636 | 54.9 | 55.8 | 0.9 | 2639 | 2638 |

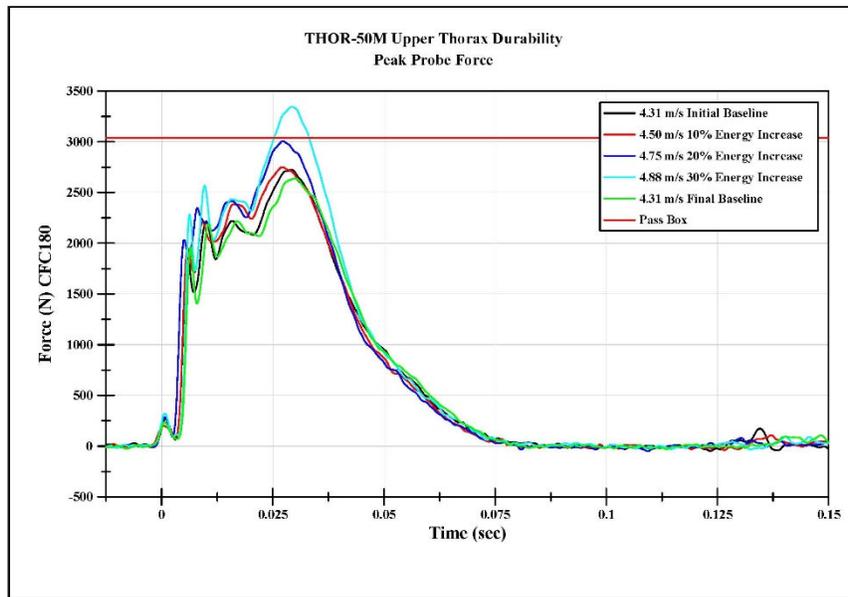


Figure 3-26. Peak probe force for upper thorax durability tests

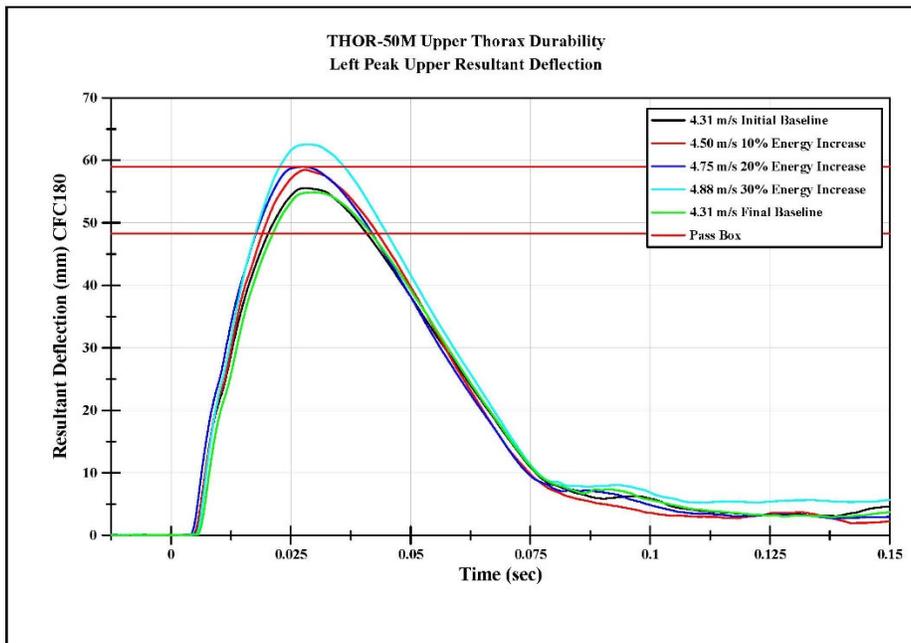


Figure 3-27. Left peak upper resultant deflections for upper thorax durability tests

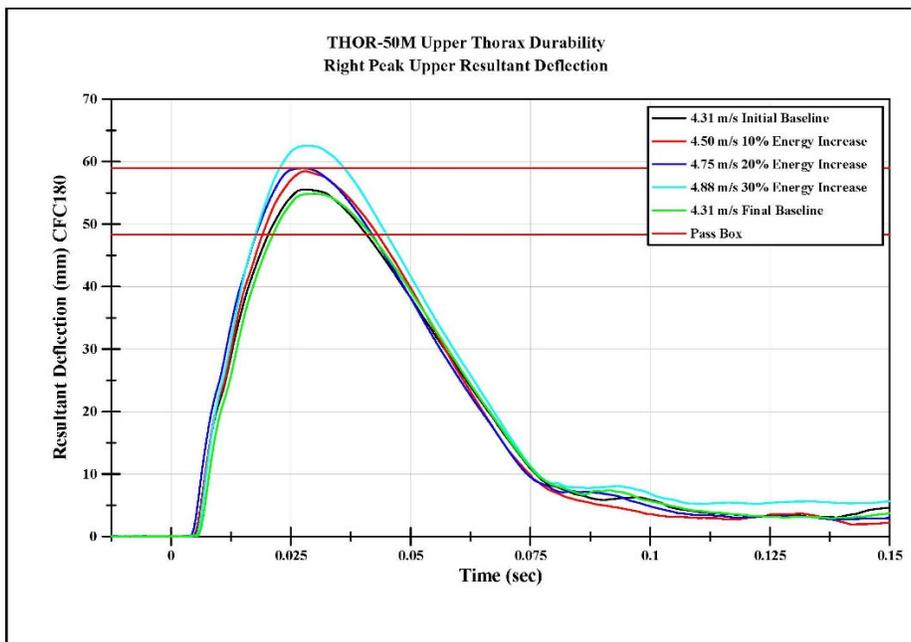


Figure 3-28. Right peak upper resultant deflection for upper thorax durability tests

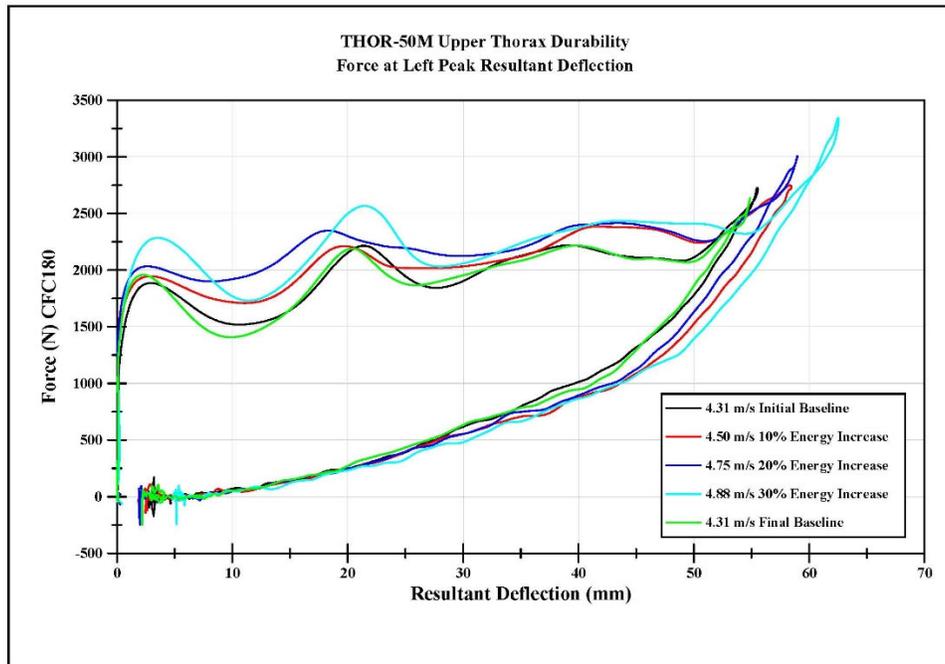


Figure 3-29. Force at left peak resultant deflection for upper thorax durability tests

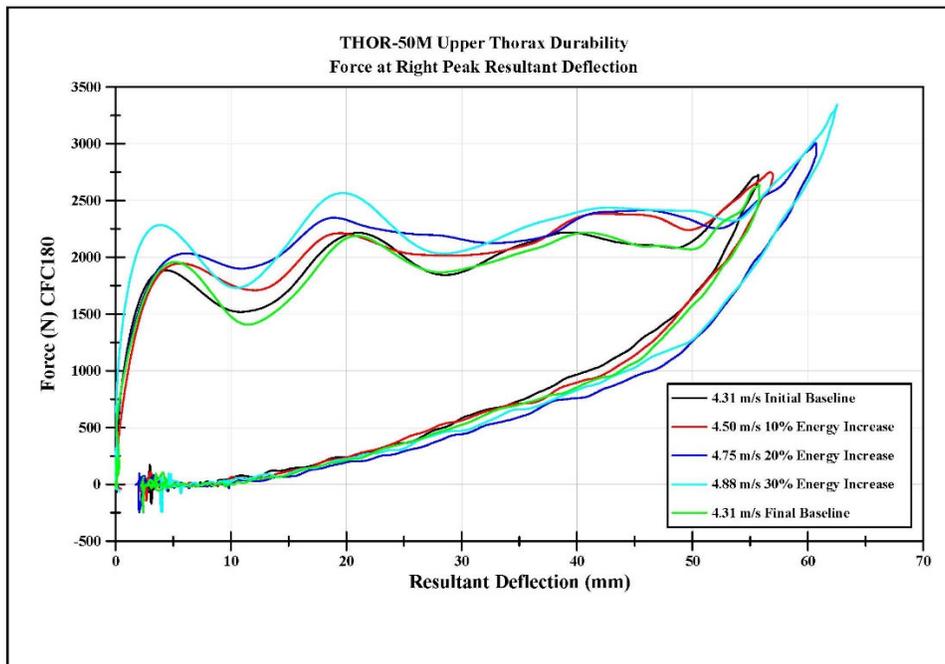


Figure 3-30. Force at right peak resultant deflection for upper thorax durability tests

3.7.3 Discussion

The final baseline test results showed that the upper thorax returned to specification values for probe force, resultant upper deflections, and force at peak deflection after the increased energy tests. No visible damage to the thorax or ribs was observed post-testing. Results indicate that the upper thorax displays acceptable durability.

3.8 LOWER THORAX

3.8.1 Methodology

Lower thorax durability tests followed the qualification procedures described in the *THOR-50M Qualification Procedures Manual*. This test mode impacts the lower ribcage on either the right or left side of the thorax (Figure 3-31). The lower thorax test uses the same impactor as the upper thorax test. This impactor has a mass of 23.36 kg and a 152.40 mm diameter rigid disk impact surface which contacts the THOR-50M at 4.30 ± 0.05 m/s. In these tests, the impactor is centered over the lower left or right thorax IR-TRACC's attachment to the bib with the line of impact horizontal and parallel to the dummy's sagittal plane. For durability tests on the lower thorax, the test energy was elevated from the qualification baseline in increments of approximately 10 percent, to a maximum of approximately 30 percent, by increasing the test velocity (Table 3-22). After the 30 percent energy increase, another baseline test was conducted to ensure no changes in response were observed due to elevating the test energy level.

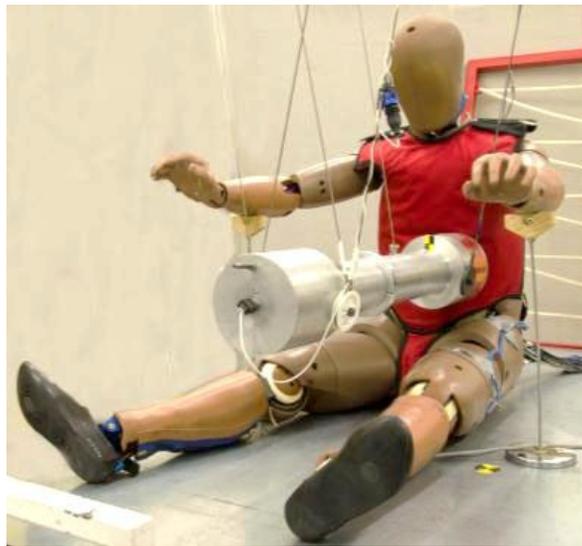


Figure 3-31. Lower thorax impact test setup

Table 3-22. Durability Test Velocities for Lower Thorax Impact Tests

| Durability Test | Velocity (Left) (m/s) | Velocity (Right) (m/s) |
|---------------------|-----------------------|------------------------|
| Initial Baseline | 4.30 | 4.30 |
| 10% Energy Increase | 4.50 | 4.50 |
| 20% Energy Increase | 4.66 | 4.66 |
| 30% Energy Increase | 4.88 | 4.93 |
| Final Baseline | 4.31 | 4.31 |

3.8.2 Results

For the baseline THOR-50M lower thorax qualification tests, the lower thorax responses must be within the ranges provided in Table 3-23. Table 3-24, along with Figure 3-32 and Figure 3-33, illustrates the durability test results. The resultant deflection of the lower thorax IR-TRACC (on the impacted side) is calculated *in the local spine coordinate system* to examine the force-deflection response of the lower ribcage.

Table 3-23. Lower Thorax Qualification Response Requirements

| Parameter | Units | Specification | |
|--|-------|---------------|------|
| | | Min. | Max. |
| Impact Velocity | m/s | 4.25 | 4.35 |
| Peak Probe Force | N | 3136 | 3832 |
| Left or Right Resultant Deflection at Peak Force | mm | 45.8 | 56.0 |

Table 3-24. Lower Thorax Durability Results

| Date | Test Number | Durability Description | Impact Velocity (m/s) | Peak Probe Force (N) | Resultant Deflection at Peak Force (mm) |
|-------------------|-------------|------------------------|-----------------------|----------------------|---|
| Left Side | | | | | |
| 10-26-16 | 161026-10 | Initial Baseline | 4.31 | 3450 | 51.7 |
| 10-26-16 | 161026-12 | 10% Energy Increase | 4.50 | 3807 | 54.2 |
| 10-26-16 | 161026-13 | 20% Energy Increase | 4.66 | 4074 | 58.0 |
| 10-26-16 | 161026-14 | 30% Energy Increase | 4.88 | 4448 | 59.3 |
| 10-27-16 | 161027-1 | Final Baseline | 4.31 | 3427 | 51.7 |
| Right Side | | | | | |
| 10-27-16 | 161027-5 | Initial Baseline | 4.31 | 3409 | 51.7 |
| 10-27-16 | 161027-6 | 10% Energy Increase | 4.50 | 3832 | 50.5 |
| 10-27-16 | 161027-9 | 20% Energy Increase | 4.66 | 4217 | 50.5 |
| 10-27-16 | 161027-10 | 30% Energy Increase | 4.93 | 4558 | 53.9 |
| 10-27-16 | 161027-15 | Final Baseline | 4.31 | 3453 | 50.6 |

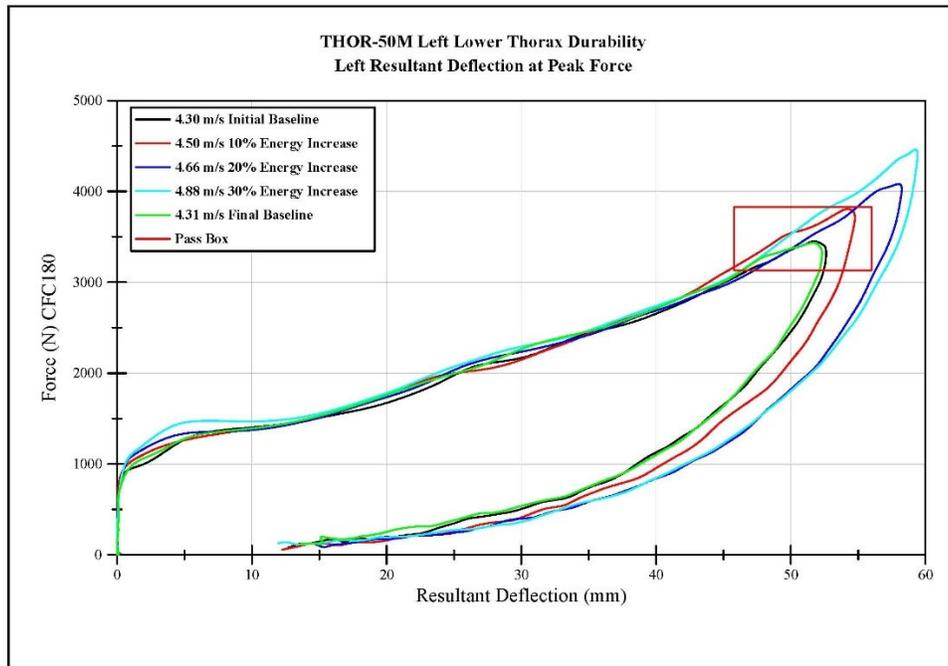


Figure 3-32. Force-deflection for left lower thorax durability tests

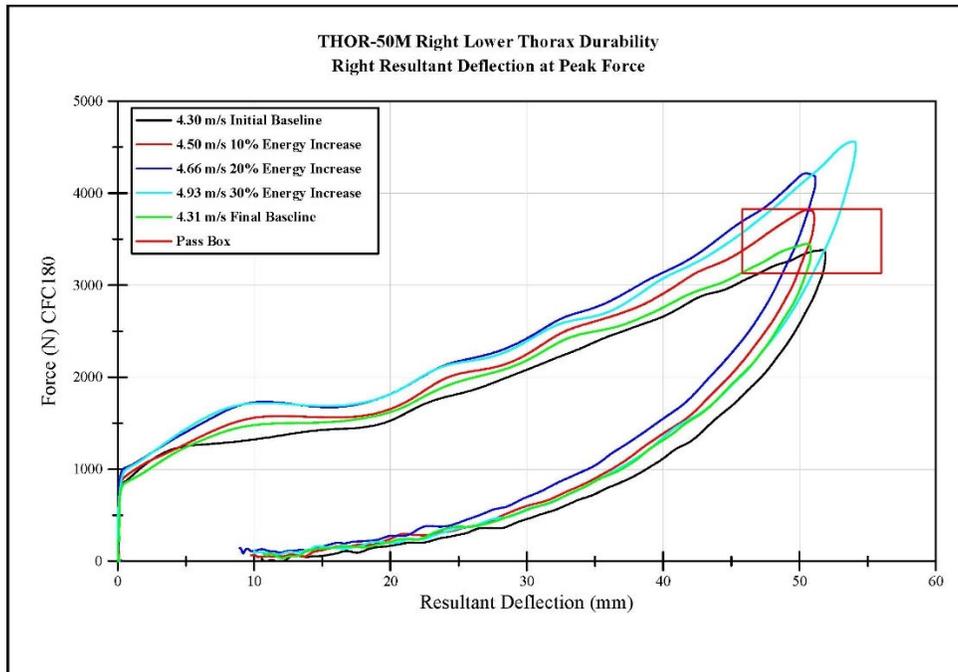


Figure 3-33. Force-deflection for right lower thorax durability tests

3.8.3 Discussion

For the lower thorax durability test series, both the initial baseline test and the final baseline test demonstrated resultant deflection and probe force within the specification. No visible damage to the thorax or ribs was noted post-testing. Results from this testing indicate that the lower thorax displays acceptable durability in deflection and probe force at the time of peak deflection.

3.9 LOWER ABDOMEN

As specified in the *THOR-50M Qualification Procedures Manual*, the peak X axis deflection for the lower abdomen qualification test must be within 74.7 to 91.3 mm (Table 3-25). In developing the current qualification procedures, the goal was to maintain a range near the biofidelity tests⁹ without bottoming out the abdomen or damaging instrumentation. During the THOR-50M repeatability and reproducibility testing at VRTC¹⁰, peak X axis deflections ranged from 77.8 to 90.9 mm. The maximum deflection seen during vehicle crash tests is 73.7 mm (Saunders et al)¹¹. Increased energy tests were not conducted on the lower abdomen because the qualification test already demonstrates a higher energy condition than a vehicle crash test, as evidenced by a deflection specification for the lower abdomen qualification test that is higher than the maximum deflection measured in vehicle crash tests. Impacts at a higher energy level could cause damage due to exhausting the stroke of the abdomen instrumentation; this finding would not be meaningful as it would represent a loading condition not representative of the vehicle crash test environment. Since the lower abdomen demonstrated good to excellent repeatability and reproducibility at an energy level exceeding that seen in vehicle crash testing without damage to the lower abdomen components, durability of the lower abdomen is considered to be good.

⁹ Parent, D., Craig, M., & Moorhouse, K. (2017). Biofidelity evaluation of the THOR and Hybrid III 50th percentile male frontal impact anthropomorphic test devices. *Stapp Car Crash Journal*, 61, 227-2761-50

¹⁰ Ibid

¹¹ Saunders, J., Parent, D., Ames, E., “*NHTSA Oblique Crash Test Results: Vehicle Performance and Occupant Injury Risk Assessment in Vehicles with Small Overlap Countermeasures*,” International Technical Conference for the Enhanced Safety of Vehicles, Paper Number: 15-0108.

Table 3-25. Abdomen Qualification Response Requirements

| Parameter | Units | Specification | |
|---|-------|---------------|-------|
| | | Min. | Max. |
| Impact Velocity | m/s | 3.25 | 3.35 |
| Peak Probe Force | N | 2626 | 3210 |
| Lower Left Abdomen X-axis Deflection at Time of Peak Force | mm | -91.3 | -74.7 |
| Lower Right Abdomen X-axis Deflection at Time of Peak Force | | | |
| Difference Between Peak Left & Right X-axis Deflections | mm | | < 8.0 |

3.10 KNEE

3.10.1 Methodology

Knee durability tests followed the qualification procedures described in the *THOR-50M Qualification Procedures Manual*. This test examines the response of the anterior-posterior translation of the tibia with respect to the femur at the knee joint. A 12.00 kg impactor with a 76.2 mm diameter rigid disk impact surface impacts a load distribution bracket attached at the knee slider at 2.20 ± 0.05 m/s (Figure 3-34). For durability tests on the knee, the test energy was elevated from the qualification baseline in increments of approximately 10 percent, to a maximum of approximately 30 percent, by increasing the test velocity (Table 3-26). After the 30 percent energy increase, another baseline test was conducted to be sure that there were no changes in response due to elevating the test energy level. For these tests, knees from THOR-50M DO9798 were used.

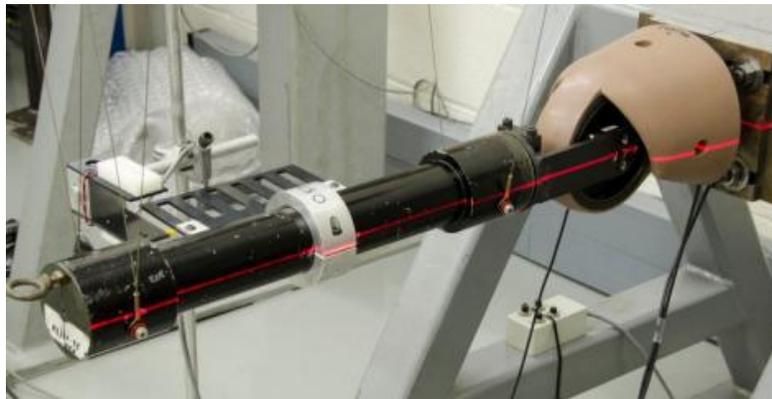


Figure 3-34. Knee slider impact test setup

Table 3-26. Durability Test Velocities for Knee Slider Impact Tests

| Durability Test | Velocity (m/s) |
|---------------------|----------------|
| Initial Baseline | 2.21 |
| 10% Energy Increase | 2.32 |
| 20% Energy Increase | 2.42 |
| 30% Energy Increase | 2.51 |
| Final Baseline | 2.22 |

3.10.2 Results

For the baseline THOR-50M knee qualification tests, the knee slider responses must be within the ranges provided in Table 3-27. Table 3-28 along with Figure 3-35, illustrates the durability test results.

Table 3-27. Knee Qualification Response Requirements

| Parameter | Units | Specification | |
|-------------------------------------|-------|---------------|-------|
| | | Min. | Max. |
| Impact Velocity | m/s | 2.15 | 2.25 |
| Peak Femur Z-axis Force | N | -7156 | -5855 |
| Knee Deflection at Peak Femur Force | mm | -22.2 | -18.2 |

Table 3-28. Knee Slider Durability Results

| Date | Test Number | Durability Description | Impact Velocity (m/s) | Peak Femur Z axis Force (N) | Knee Deflection at Peak Femur Force (mm) |
|---------|-------------|------------------------|-----------------------|-----------------------------|--|
| 9-29-15 | 092915_01 | Initial Baseline | 2.21 | -6510 | -19.9 |
| 9-29-15 | 092915_02 | 10% Energy Increase | 2.32 | -7712 | -20.3 |
| 9-29-15 | 092915_03 | 20% Energy Increase | 2.42 | -8465 | -20.5 |
| 9-29-15 | 092915_04 | 30% Energy Increase | 2.51 | -9315 | -20.7 |
| 9-29-15 | 092915_05 | Final Baseline | 2.22 | -6824 | -20.2 |

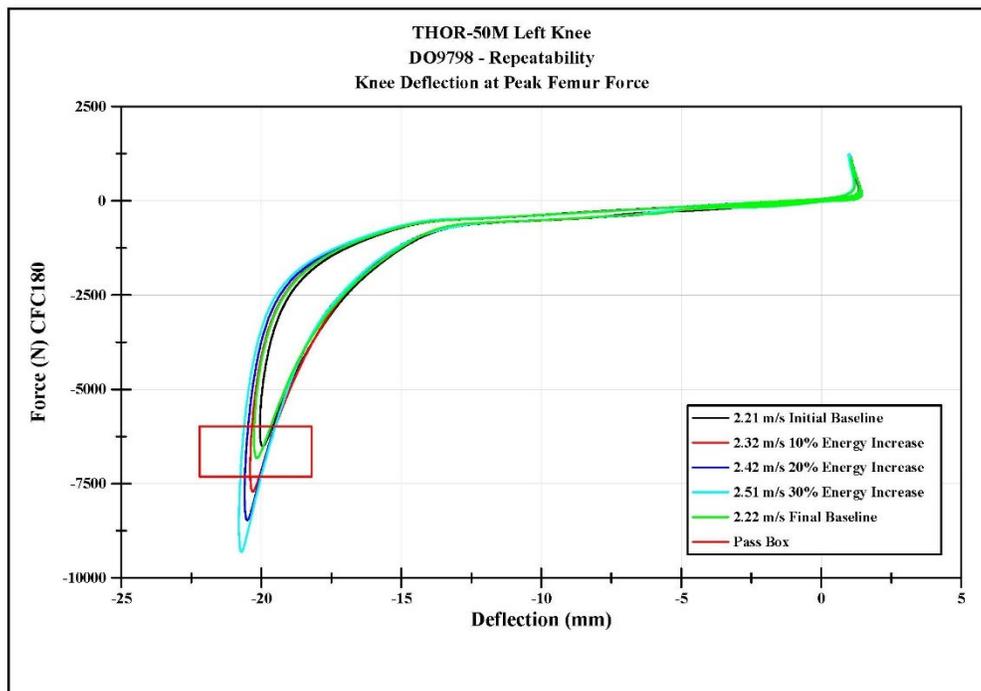


Figure 3-35. Force-deflection for knee slider durability tests

3.10.3 Discussion

The final baseline test results showed that the knee slider returned to specification values for knee deflection and femur force (F_z) after the increased energy tests. No visible damage to the knee slider was observed post-testing. Results indicate that the knee displays acceptable durability.

3.11 UPPER LEG

3.11.1 Methodology

Upper leg durability tests followed the qualification procedures described in the *THOR-50M Qualification Procedures Manual*. This test examines the response of the femur to axial impacts at the knee using a 5.00 kg impactor with a 76.2 mm diameter rigid disk impact surface at 2.6 ± 0.05 m/s (Figure 3-36). For durability tests on the upper leg, the test energy was elevated from the qualification baseline in increments of approximately 10 percent, to a maximum of approximately 30 percent, by increasing the test velocity. After the 30 percent energy increase, another baseline test was conducted to ensure that no changes in response were observed due to elevating the test energy level. For upper leg tests, a block to brace the dummy was added behind the pelvis *during the elevated energy tests* because the dummy would slide out

of the way during those tests; however, the baseline tests were performed *without* a block behind the pelvis. For these tests, femurs from THOR-50M DO9798 were used.



Figure 3-36. Upper leg impact test for knee skin and compliant bushing

However, after conducting the initial test series, it was found that the peak resultant acetabulum force did not meet the initial requirements of durability assessment, that the value should represent a 50 percent risk of injury based on previously published injury risk functions or have a magnitude greater than the mean plus one standard deviation of the NHTSA oblique vehicle tests. Therefore, additional tests were conducted at higher energy levels until the measured peak resultant acetabulum load was above 3,619 N, the mean plus standard deviation from the NHTSA oblique vehicle tests described in Saunders et al.¹² (Table 3-29).

¹² Ibid.

Table 3-29. Durability Test Velocities for Upper Leg Impact Tests

| Durability Test | Velocity (m/s) |
|------------------------|----------------|
| Initial Baseline | 2.57 |
| Energy Increase (150%) | 4.10 |
| Energy Increase (300%) | 5.13 |
| Energy Increase (450%) | 6.05 |
| Final Baseline | 2.57 |

3.11.2 Results

For the baseline THOR-50M upper leg qualification tests, the upper leg responses must be within the ranges provided in Table 3-30. Table 3-31, along with Figure 3-37 through Figure 3-39, illustrates the durability test results.

Table 3-30. Upper Leg Qualification Response Requirements

| Parameter | Units | Specification | |
|---------------------------------|-------|---------------|-------|
| | | Min. | Max. |
| Impact Velocity | m/s | 2.55 | 2.65 |
| Peak Probe Force | N | 4221 | 5158 |
| Peak Femur Force, F_z | N | -3314 | -2712 |
| Peak Resultant Acetabulum Force | N | 1478 | 1806 |

Table 3-31. Upper Leg Durability Results

| Date | Test Number | Durability Description | Impact Velocity (m/s) | Peak Probe Force (N) | Peak Femur Force F_z (N) | Peak Resultant Acetabulum (N) |
|---------|-------------|------------------------|-----------------------|----------------------|----------------------------|-------------------------------|
| 9-24-15 | 092415_04 | Initial Baseline | * | 4841 | -3170 | 1528 |
| 9-28-15 | 092815_13 | 150% Energy Increase | 4.10 | 9435 | -5318 | 2453 |
| 9-28-15 | 092815_14 | 300% Energy Increase | 5.13 | 13375 | -7135 | 3014 |
| 9-28-15 | 092815_11 | 450% Energy Increase | 6.05 | 16977 | -8923 | 3642 |
| 9-28-15 | 092815_15 | Final Baseline | 2.57 | 4734 | -3047 | 1584 |

*Velocity was not successfully recorded, but it was assumed that a target velocity of 2.57 m/s was achieved.

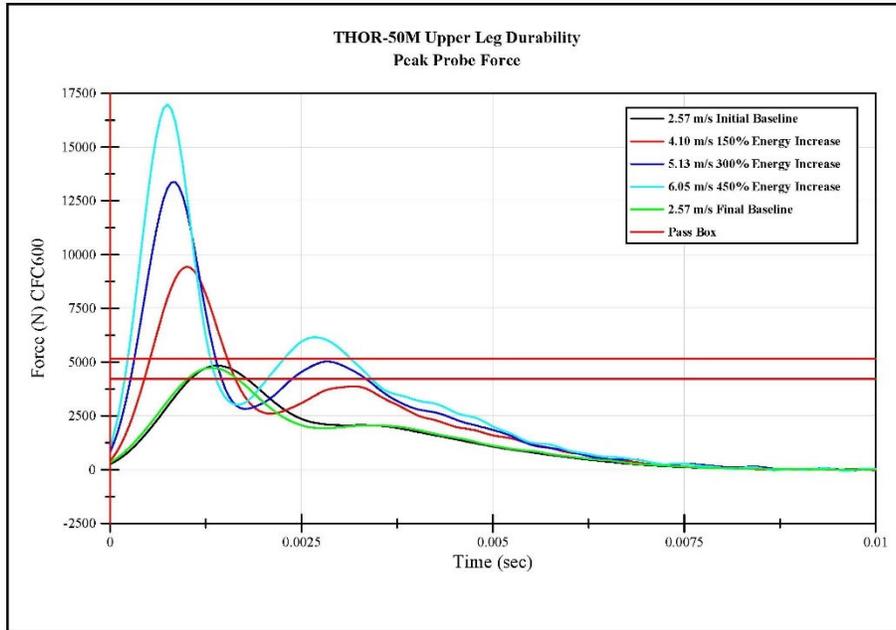


Figure 3-37. Peak probe force for upper leg durability tests

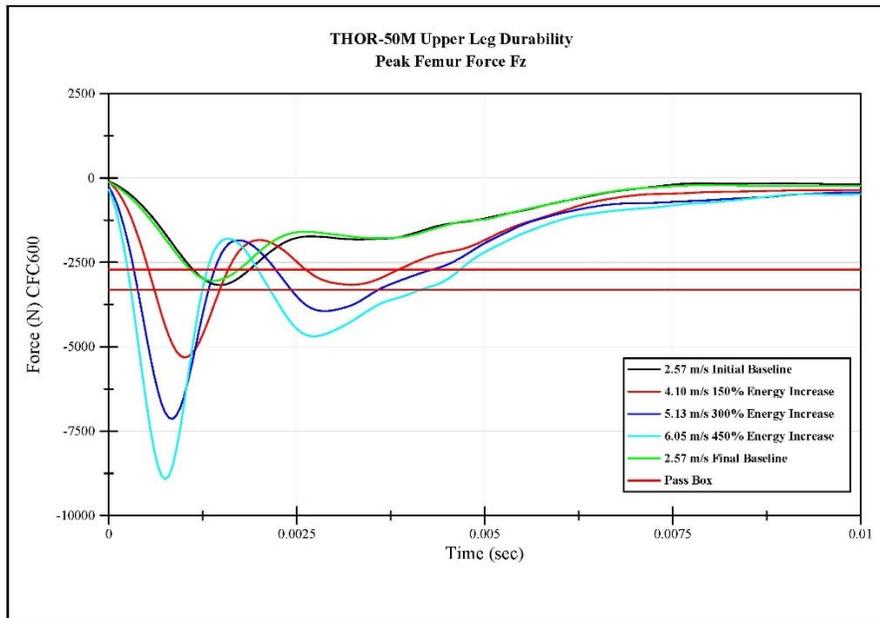


Figure 3-38. Peak Z femur force for left upper leg durability tests

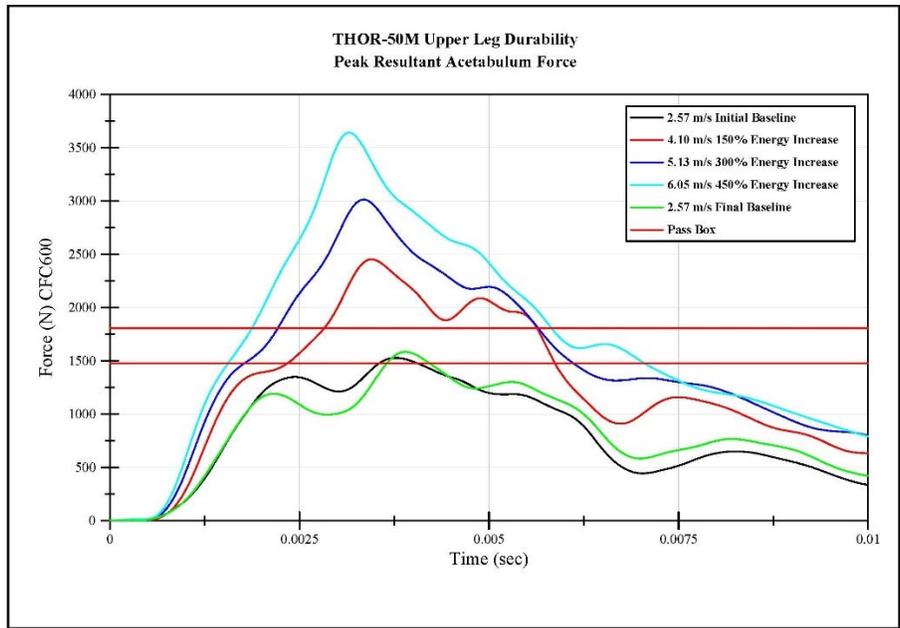


Figure 3-39. Peak resultant acetabulum force for upper leg durability tests

3.11.3 Discussion

The final baseline test results showed that the upper leg returned to specification values for probe force, femur force (Fz), and resultant acetabulum force after the increased energy tests. No visible damage to the knee insert or compliant bushing was observed post-testing. Results indicate that the upper leg displays acceptable durability.

3.12 ANKLE INVERSION

3.12.1 Methodology

Durability tests were performed using the ankle inversion qualification procedures described in the *THOR-50M Qualification Procedures Manual*. The ankle inversion qualification consists of an impact to a padded bracket which is temporarily secured to the sole plate of the foot (Figure 3-40). The test uses the NHTSA Dynamic Impactor (TLX-9000-013) with an effective mass of 5.00 ± 0.02 kg (11.02 ± 0.04 lb).¹³

¹³ Mass includes the mass of instrumentation, ballast (TLX-9000-001), impactor face (TLX-9000-006), and a portion of the mass of the pendulum arm (TLX-9000-007) including the distal mass welded to the tube and 1/3 of the mass of the tube itself.

The pendulum arm is mounted to a rigid shaft which is pivoted on low friction ball bearings. The impact surface is a rigid semi-cylinder 63.5 ± 2.5 mm in diameter and 88.9 ± 3.5 mm in length, oriented in a horizontal plane perpendicular to the direction of impact. The padded bracket is attached such that the line of impact is offset from the longitudinal axis of the tibia, and the resulting motion of the foot exercises the inversion properties of the ankle assembly. The leg is held rigidly such that the X-Z plane of the foot and lower leg are horizontal. The impact surface of the bracket is covered with Ensolite padding to reduce noise transmission through the bracket into the ankle and load cell. For durability tests, the test energy was elevated from the qualification baseline in increments of approximately 10 percent, to a maximum of approximately 30 percent, by increasing the test velocity (Table 3-32). After the 30 percent energy increase, another baseline test was conducted to ensure that no changes in response were observed due to elevating the test energy level.

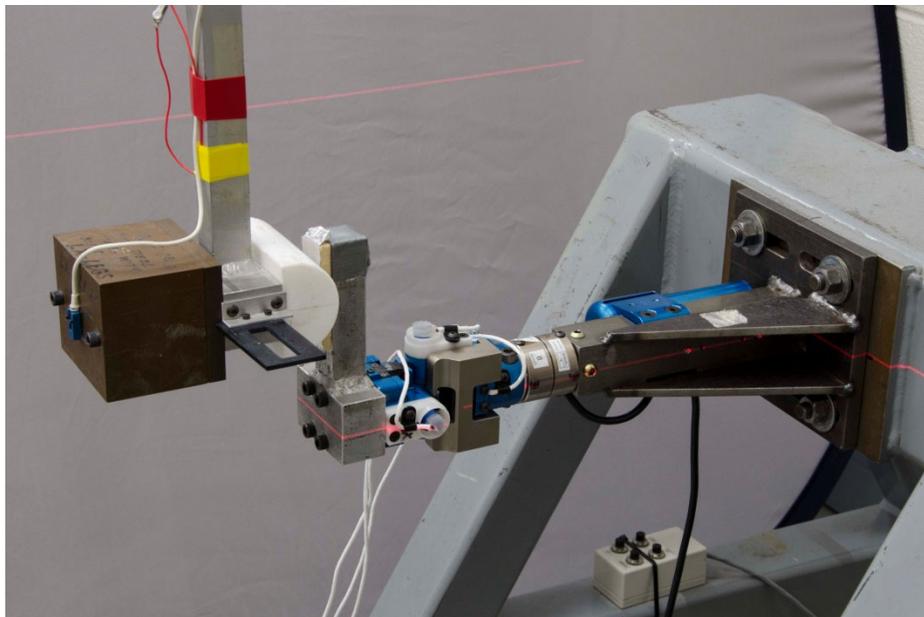


Figure 3-40. Ankle Inversion Test

Table 3-32. Durability Test Velocities for Ankle Inversion Tests

| Durability Test | Velocity (m/s) |
|---------------------|----------------|
| Initial Baseline | 2.01 |
| 10% Energy Increase | 2.09 |
| 20% Energy Increase | 2.19 |
| 30% Energy Increase | 2.30 |
| Final Baseline | 2.03 |

3.12.2 Results

For the baseline THOR-50M ankle inversion qualification tests, the responses must be within the ranges provided in Table 3-33. Table 3-34, along with Figure 3-41 through Figure 3-43, illustrates the durability test results.

Table 3-33. Right Ankle Inversion Qualification Response Requirements

| Parameter | Units | Specification | |
|-----------------------------|-------|---------------|------|
| | | Min. | Max. |
| Impact Velocity | m/s | 1.95 | 2.05 |
| Peak Lower Tibia F_z | N | -555 | -454 |
| Peak Ankle Resistive Moment | Nm | 35.2 | 43.0 |
| Peak Ankle X-axis Rotation | deg | 31.0 | 37.9 |

Table 3-34. Ankle Inversion Durability Results (LX0070)

| Date | Test Number | Durability Description | Impact Velocity (m/s) | Peak Lower Tibia F_z (N) | Peak Ankle Resistive Moment (Nm) | Peak Ankle X axis Rotation (deg) |
|-----------|-------------|------------------------|-----------------------|----------------------------|----------------------------------|----------------------------------|
| 8/17/2016 | 160817-6 | Initial Baseline | 2.02 | -461 | 37.6 | 33.6 |
| 8/17/2016 | 160817-7 | 10% Energy Increase | 2.09 | -496 | 40.7 | 34.1 |
| 8/17/2016 | 160817-8 | 20% Energy Increase | 2.19 | -578 | 48.2 | 35.5 |
| 8/17/2016 | 160817-9 | 30% Energy Increase | 2.30 | -644 | 53.7 | 36.4 |
| 8/18/2016 | 160818-3 | Final Baseline | 2.03 | -460 | 37.7 | 34.3 |

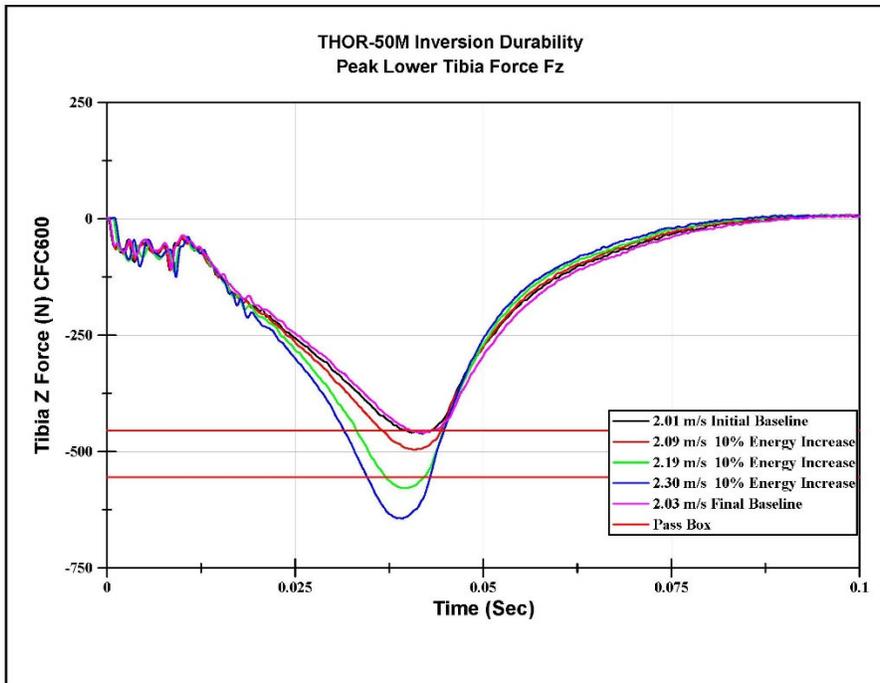


Figure 3-41. Peak lower tibia force Fz for foot inversion durability tests

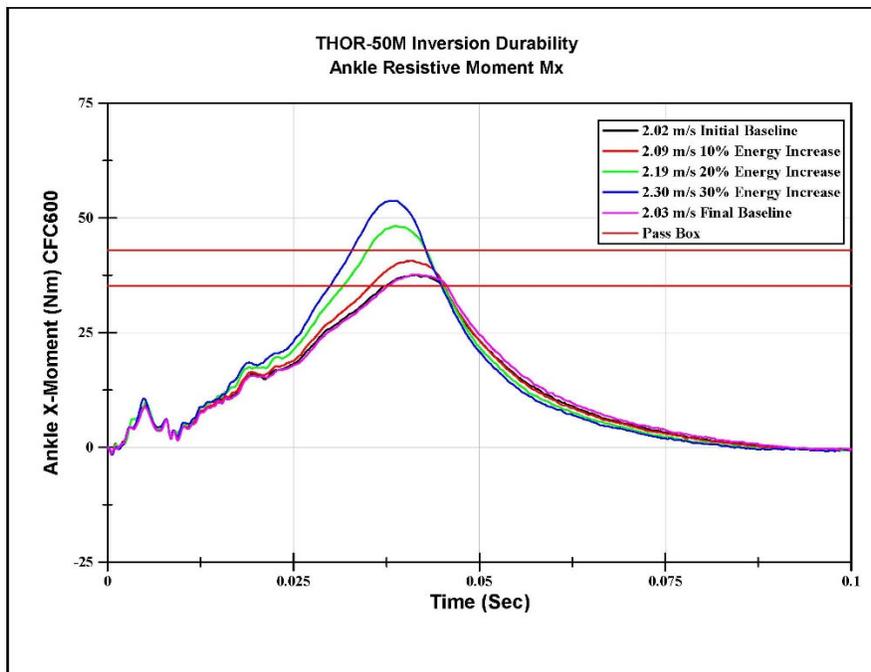


Figure 3-42. Ankle resistive moment Mx for foot inversion durability tests

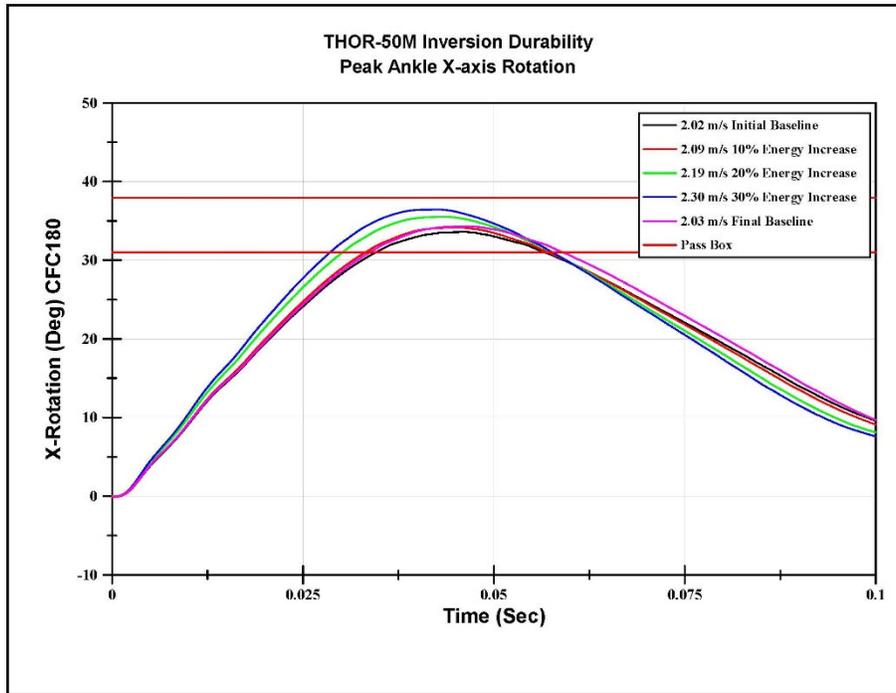


Figure 3-43. Ankle X axis rotation for foot inversion durability tests

3.12.3 Discussion

The final baseline test results showed that the ankle returned to specification values for lower tibia force (Fz), ankle resistive moment, and ankle X axis rotation. No visible damage to the ankle or lower leg was observed post-testing. Results indicate that the ankle displays acceptable durability in inversion.

3.13 ANKLE EVERSION

3.13.1 Methodology

Durability tests were performed using the ankle eversion qualification procedures described in the *THOR-50M Qualification Procedures Manual*. The ankle eversion qualification consists of impact to a padded bracket which is temporarily attached to the sole plate of the foot (Figure 3-44). The test uses the NHTSA

Dynamic Impactor (TLX-9000-013) with an effective mass of 5.00 ± 0.02 kg (11.02 ± 0.04 lb).¹⁴ The pendulum arm is mounted to a rigid shaft which is pivoted on low friction ball bearings. The impact surface is a rigid semi-cylinder 63.5 ± 2.5 mm in diameter and 88.9 ± 3.5 mm in length, oriented in a horizontal plane perpendicular to the direction of impact. The padded bracket is attached such that the line of impact is offset from the longitudinal axis of the tibia, and the resulting motion of the foot exercises the eversion properties of the ankle assembly. The leg is held rigidly such that the X-Z plane of the foot and lower leg are horizontal. The impact surface of the bracket is covered with Ensolite padding to reduce noise transmission through the bracket into the ankle and load cell. For durability tests, the test energy was elevated from the qualification baseline in increments of approximately 10 percent, to a maximum of approximately 30 percent, by increasing the test velocity (Table 3-35). After the 30 percent energy increase, another baseline test was conducted to ensure that no changes in response were observed due to elevating the test energy level.

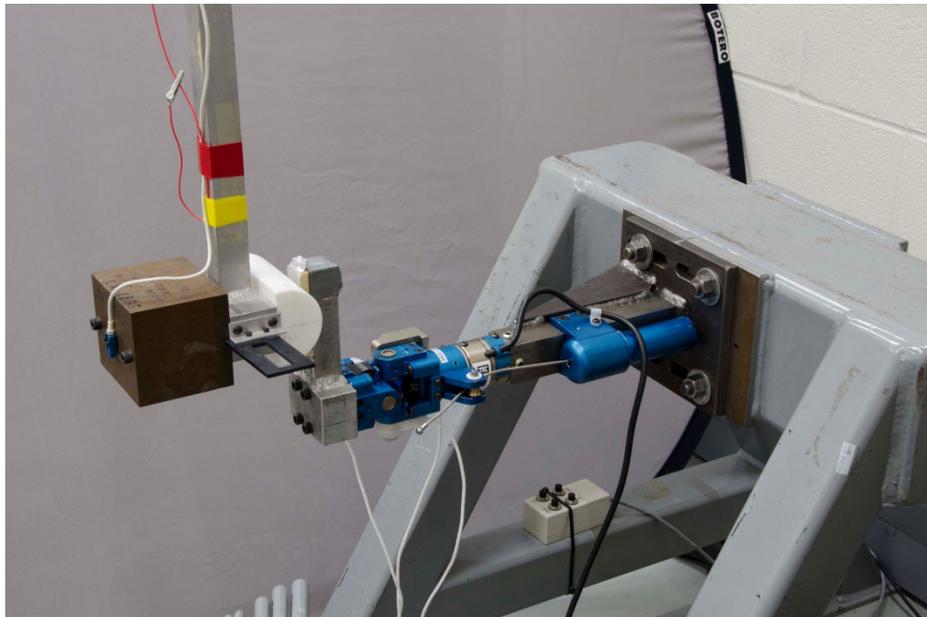


Figure 3-44. Ankle Eversion Test

¹⁴ Mass includes the mass of instrumentation, ballast (TLX-9000-001), impactor face (TLX-9000-006), and a portion of the mass of the pendulum arm (TLX-9000-007) including the distal mass welded to the tube and 1/3 of the mass of the tube itself.

Table 3-35. Durability Test Velocities for Ankle Eversion Tests

| Durability Test | Velocity (m/s) |
|---------------------|----------------|
| Initial Baseline | 1.98 |
| 10% Energy Increase | 2.09 |
| 20% Energy Increase | 2.20 |
| 30% Energy Increase | 2.33 |
| Final Baseline | 2.02 |

3.13.2 Results

For the baseline THOR-50M ankle eversion qualification tests, the responses must be within the ranges provided in Table 3-36.

Table 3-37, along with Figure 3-45 through Figure 3-47, illustrates the durability test results.

Table 3-36. Right Ankle Eversion Qualification Response Requirements

| Parameter | Units | Specification | |
|-----------------------------|-------|---------------|-------|
| | | Min. | Max. |
| Impact Velocity | m/s | 1.95 | 2.05 |
| Peak Lower Tibia F_z | N | -629 | -514 |
| Peak Ankle Resistive Moment | Nm | -47.3 | -38.7 |
| Peak Ankle X-axis Rotation | deg | -32.5 | -26.6 |

Table 3-37. Ankle Eversion Durability Results (LX0070)

| Date | Test Number | Durability Description | Impact Velocity (m/s) | Peak Lower Tibia F_z (N) | Peak Ankle Resistive Moment (Nm) | Peak Ankle X-axis Rotation (deg) |
|-----------|-------------|------------------------|-----------------------|----------------------------|----------------------------------|----------------------------------|
| 8/18/2016 | 160818-4 | Initial Baseline | 1.98 | -556 | -42.5 | -29.5 |
| 8/18/2016 | 160818-5 | 10% Energy Increase | 2.09 | -580 | -44.2 | -29.9 |
| 8/18/2016 | 160818-6 | 20% Energy Increase | 2.20 | -662 | -50.8 | -30.9 |
| 8/18/2016 | 160818-8 | 30% Energy Increase | 2.33 | -760 | -58.8 | -32.3 |
| 8/18/2016 | 160818-9 | Final Baseline | 2.02 | -538 | -40.9 | -30.0 |

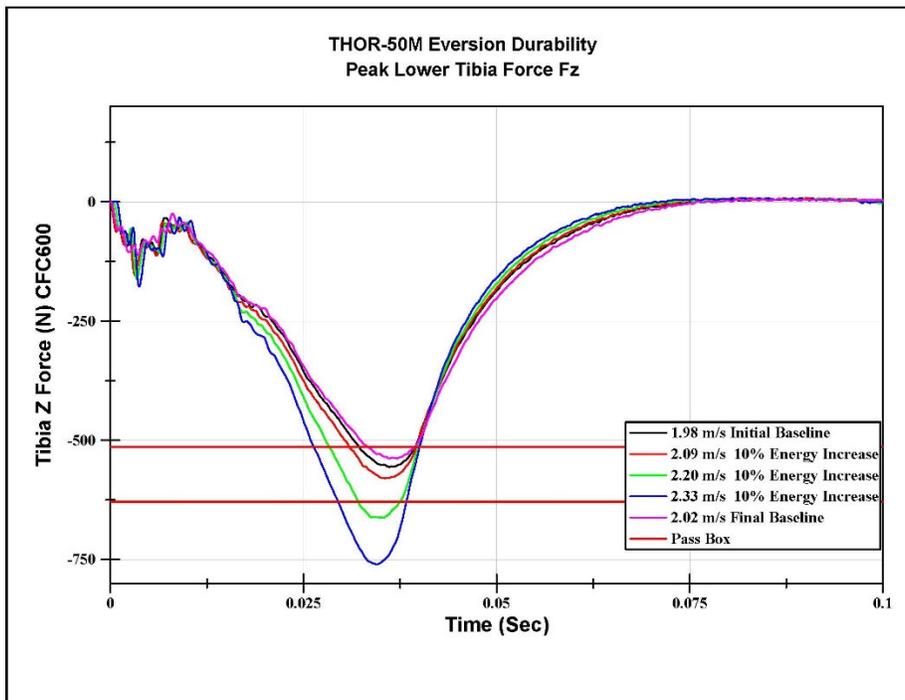


Figure 3-45. Peak lower tibia force Fz for foot eversion durability tests

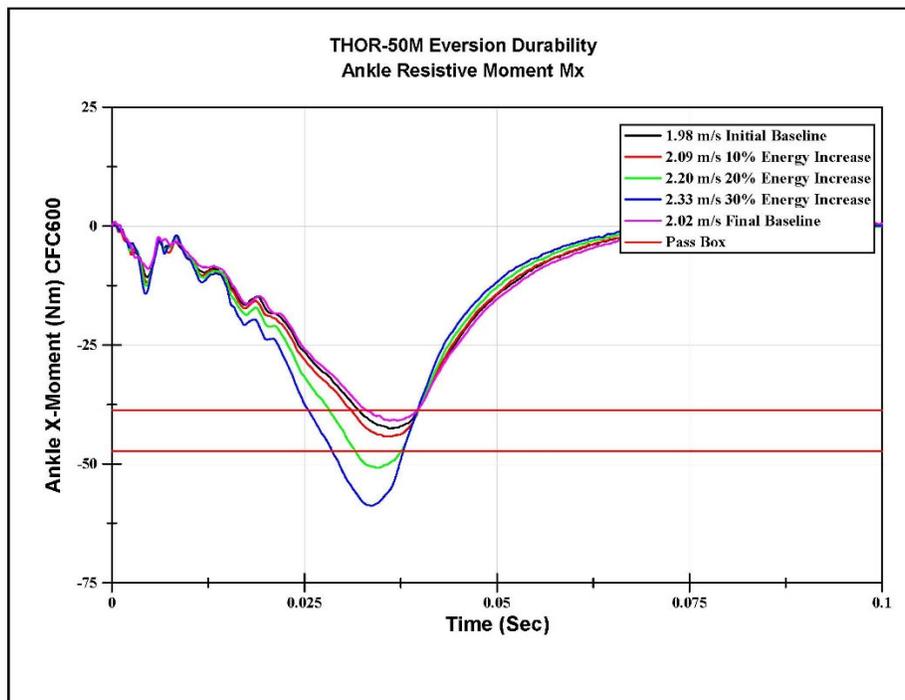


Figure 3-46. Ankle resistive moment Mx for foot eversion durability tests

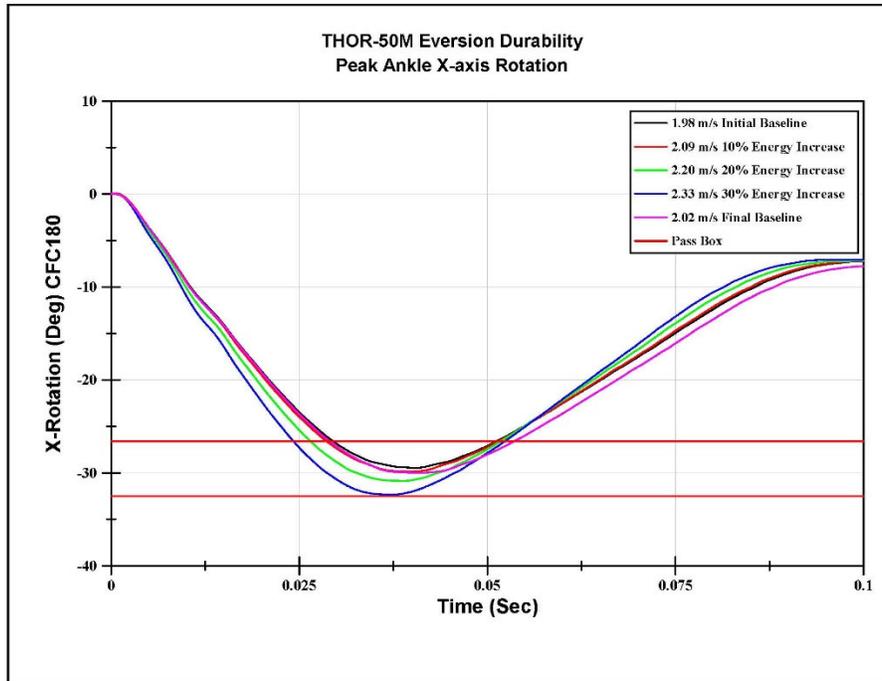


Figure 3-47. Ankle X axis rotation for foot eversion durability tests

3.13.3 Discussion

The final baseline test results showed that the ankle returned to specification values for lower tibia force (F_z), ankle resistive moment, and ankle X axis rotation. No visible damage to the ankle or lower leg was observed post-testing. Results indicate that the ankle displays acceptable durability in eversion.

3.14 BALL OF FOOT

3.14.1 Methodology

Durability tests were performed using the ball of foot impact qualification procedures described in the *THOR-50M Qualification Procedures Manual*. This test examines the dynamic impact response of the ball of the foot. The leg is held rigidly with the tibia horizontal (Figure 3-48). The test uses the NHTSA

Dynamic Impactor (TLX-9000-013) with an effective mass of 5.00 ± 0.02 kg (11.02 ± 0.04 lb).¹⁵ The pendulum arm is mounted to a rigid shaft which is pivoted on low friction ball bearings. The impact surface is a rigid semi-cylinder 63.5 ± 2.5 mm in diameter and 88.9 ± 3.5 mm in length, oriented in a horizontal plane perpendicular to the direction of impact. For durability tests, the test energy was elevated from the qualification baseline in increments of approximately 10 percent, to a maximum of approximately 30 percent, by increasing the test velocity (Table 3-38). After the 30 percent energy increase, another baseline test was conducted to ensure that no changes in response were observed due to elevating the test energy level.

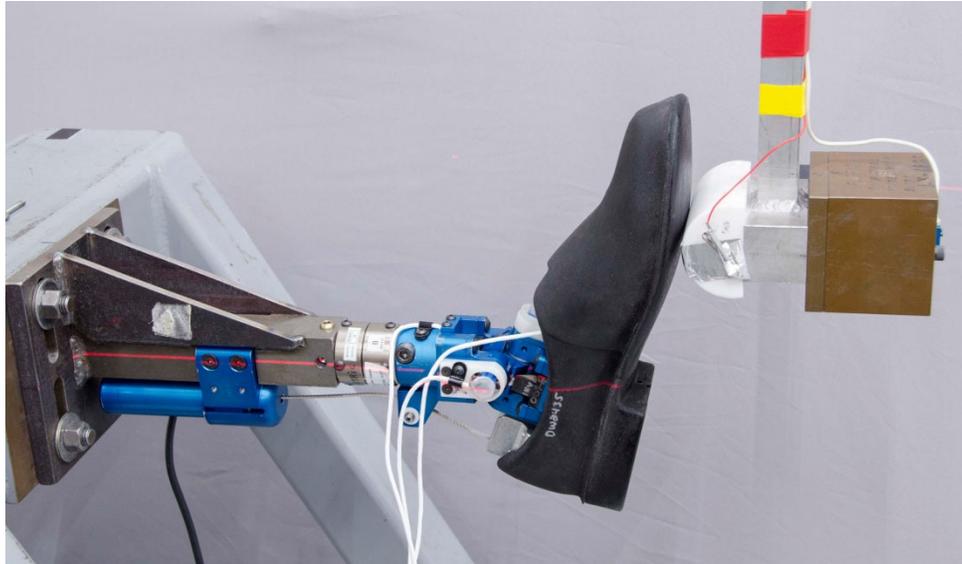


Figure 3-48. Ball of Foot Test

¹⁵ Mass includes the mass of instrumentation, ballast (TLX-9000-001), impactor face (TLX-9000-006), and a portion of the mass of the pendulum arm (TLX-9000-007) including the distal mass welded to the tube and 1/3 of the mass of the tube itself.

Table 3-38. Durability Test Velocities for Ball of Foot Tests

| Durability Test | Velocity (m/s) |
|---------------------|----------------|
| Initial Baseline | 5.00 |
| 10% Energy Increase | 5.27 |
| 20% Energy Increase | 5.52 |
| 30% Energy Increase | 5.68 |
| Final Baseline | 4.97 |

3.14.2 Results

For the baseline THOR-50M ball of foot qualification tests, the responses must be within the ranges provided in Table 3-39. Table 3-40, along with Figure 3-49 through Figure 3-51, illustrates the durability test results.

Table 3-39. Ball of Foot Qualification Response Requirements

| Parameter | Units | Specification | |
|-----------------------------|-------|---------------|-------|
| | | Min. | Max. |
| Impact Velocity | m/s | 4.95 | 5.05 |
| Peak Lower Tibia F_z | N | -3490 | -2855 |
| Peak Ankle Resistive Moment | Nm | 49.8 | 60.9 |
| Peak Ankle Y-axis Rotation | deg | 30.4 | 37.2 |

Table 3-40. Ball of Foot Durability Results (LX0070)

| Date | Test Number | Durability Description | Impact Velocity (m/s) | Peak Lower Tibia F_z (N) | Peak Ankle Resistive Moment (Nm) | Peak Ankle Y-axis Rotation (deg) |
|----------|-------------|------------------------|-----------------------|----------------------------|----------------------------------|----------------------------------|
| 9/6/2016 | 160906-6 | Initial Baseline | 5.00 | -2952 | 58.3 | 35.1 |
| 9/7/2016 | 160907-2 | 10% Energy Increase | 5.27 | -3126 | 65.7 | 36.5 |
| 9/7/2016 | 160907-3 | 20% Energy Increase | 5.52 | -3287 | 71.6 | 37.3 |
| 9/7/2016 | 160907-4 | 30% Energy Increase | 5.68 | -3393 | 74.3 | 38.0 |
| 9/7/2016 | 160907-8 | Final Baseline | 4.97 | -2907 | 56.3 | 34.9 |

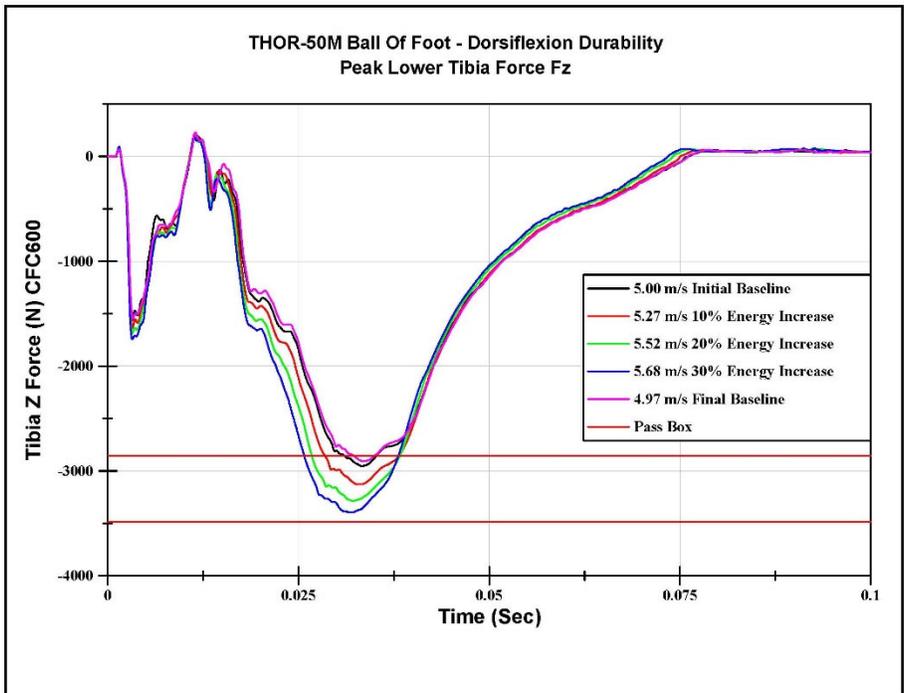


Figure 3-49. Peak lower tibia force Fz for ball of foot durability tests

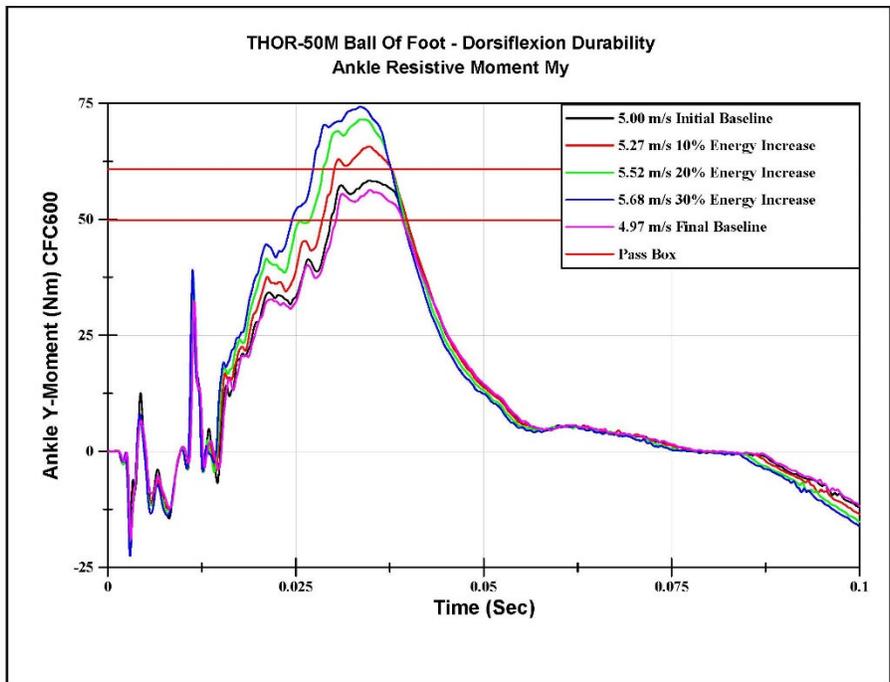


Figure 3-50. Ankle resistive moment My for ball of foot durability tests

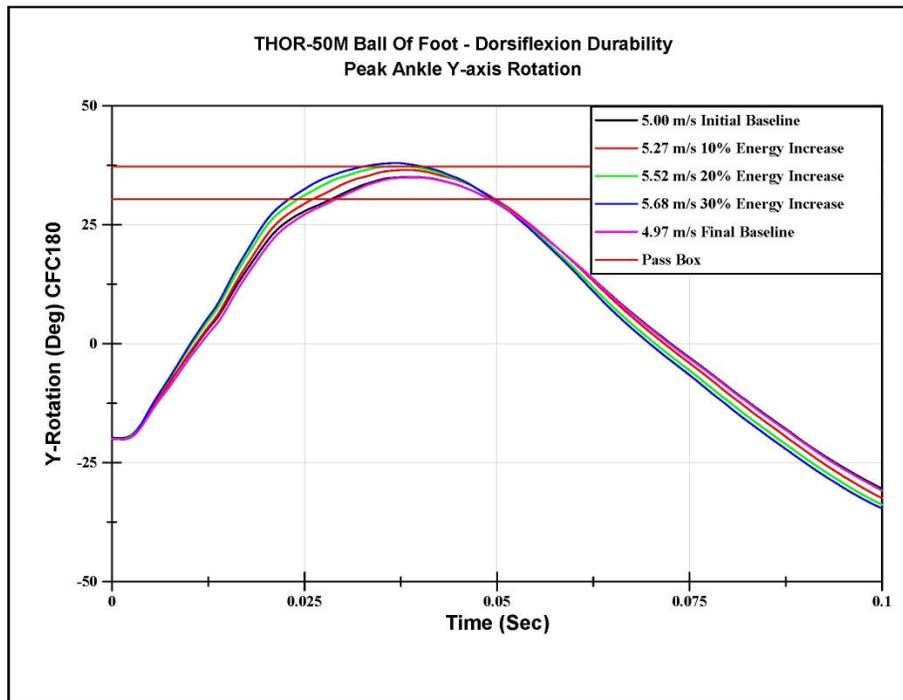


Figure 3-51. Ankle Y axis rotation for ball of foot durability tests

3.14.3 Discussion

The final baseline test results showed that the lower leg returned to specification values for lower tibia force (F_z), peak ankle resistive moment (M_y), and peak ankle Y axis rotation. No visible damage to the molded shoe or lower leg was observed post-testing. Results indicate that the ankle and lower leg display acceptable durability when impacted at the ball of the foot.

3.15 HEEL

3.15.1 Methodology

Durability tests were performed using the heel impact qualification procedures described in the *THOR-50M Qualification Procedures Manual*. This test examines the dynamic impact response of the heel of the

foot and used the newly developed molded shoe, as described in the *THOR-50M Drawing Package*.¹⁶ The leg is held rigidly with the tibia horizontal (Figure 3-52). The test uses the NHTSA Dynamic Impactor (TLX-9000-013) with an effective mass of 5.00 ± 0.02 kg (11.02 ± 0.04 lb) as described for the ball of foot test. The pendulum arm is mounted to a rigid shaft which is pivoted on low friction ball bearings. The impact surface is a rigid semi-cylinder 63.5 ± 2.5 mm in diameter and 88.9 ± 3.5 mm in length, with the length oriented in a horizontal plane perpendicular to the direction of impact. The pendulum impacts the heel at a velocity of 4.0 ± 0.1 m/s.

When the heel impact is run at the qualification speed, the nominal Fz lower tibia force (3162 N) does not yield a Tibia Index high enough to exceed a 50 percent risk of injury based on previously published injury risk functions (6825 N) or the mean plus one standard deviation of the NHTSA oblique vehicle tests (4261 N). Thus, the elevated energy levels were run at even higher speeds.

The test energy was elevated from the qualification baseline in increments of 10 percent, starting at approximately 45 percent, to a maximum of approximately 65 percent, by increasing the test velocity (Table 3-41). After the 65 percent energy increase, another baseline test was conducted to ensure that no changes in response were observed due to elevating the test energy level.

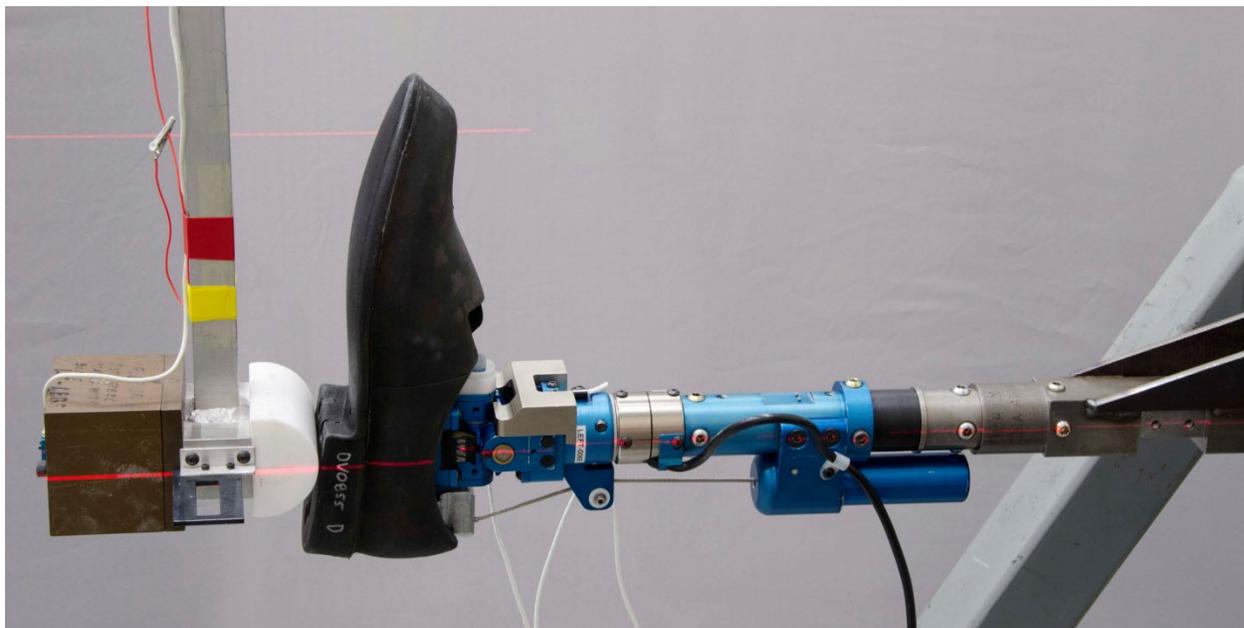


Figure 3-52. Heel Test

¹⁶ National Highway Traffic Safety Administration (2018). *THOR-50M Drawing Package*, August 2018. DOT HS# 812 655, Washington, D.C., National Transportation Library.

Table 3-41. Durability Test Velocities for Heel Tests

| Durability Test | Velocity (m/s) |
|---------------------|----------------|
| Initial Baseline | 4.00 |
| 45% Energy Increase | 4.81 |
| 55% Energy Increase | 4.94 |
| 65% Energy Increase | 5.12 |
| Final Baseline | 4.00 |

3.15.2 Results

For the baseline THOR-50M heel qualification tests, the responses must be within the ranges provided in Table 3-42. Table 3-43, along with Figure 3-53, illustrates the durability test results conducted at approximately 45 percent through 65 percent increased energy levels.

Table 3-42. Heel Qualification Response Requirements

| Parameter | Units | Specification | |
|------------------------|-------|---------------|-------|
| | | Min. | Max. |
| Impact Velocity | m/s | 3.95 | 4.05 |
| Peak Lower Tibia F_z | N | -3478 | -2846 |

Table 3-43. Heel Durability Results (DL5404)

| Date | Test Number | Durability Description | Impact Velocity (m/s) | Peak Lower Tibia F_z (N) |
|------------|-------------|------------------------|-----------------------|----------------------------|
| 10/19/2016 | 161019-1 | Initial Baseline | 4.00 | -3363 |
| 10/19/2016 | 161019-5 | 45% Energy Increase | 4.81 | -4026 |
| 10/19/2016 | 161019-6 | 55% Energy Increase | 4.94 | -4134 |
| 10/19/2016 | 161019-8 | 65% Energy Increase | 5.12 | -4266 |
| 10/20/2016 | 161020-4 | Final Baseline | 4.00 | -3290 |

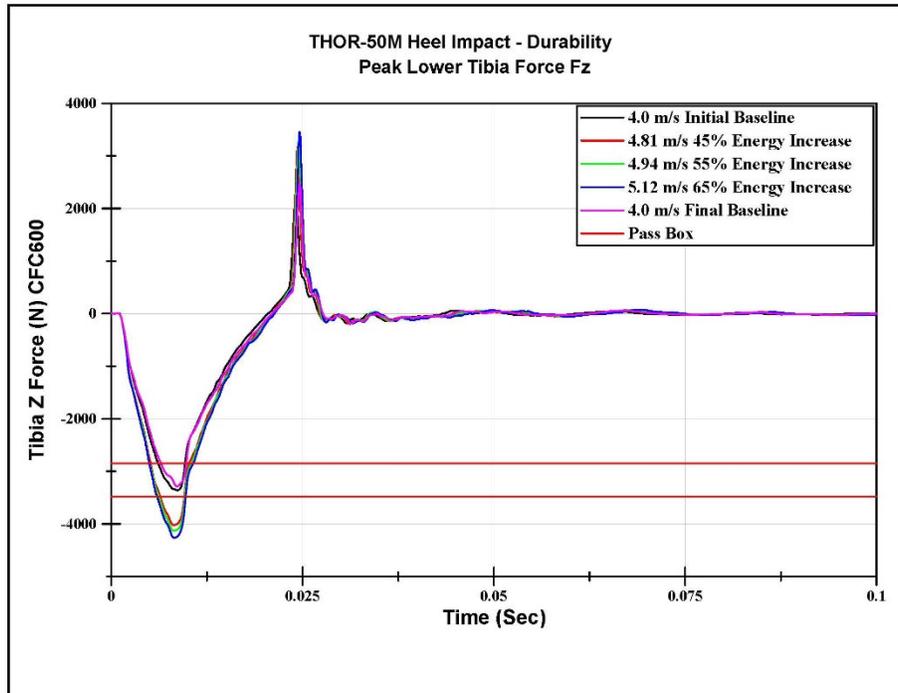


Figure 3-53. Peak lower tibia force Fz for heel durability tests

3.15.3 Discussion

The final baseline test results showed that the lower leg returned to specification values for lower tibia force (Fz). No visible damage to the molded shoe or lower leg was observed post-testing. Results indicate that the ankle and lower leg display acceptable durability when impacted at the heel.

4 SUMMARY

Durability of the THOR-50M was assessed through conducting the test procedures specified in the *THOR-50M Qualification Procedures Manual* at energy levels elevated beyond the typical response from NHTSA Oblique crash test results. The results of a given test condition were considered to show acceptable durability if (a) after elevated energy tests were conducted, a final baseline test demonstrated a response similar to the initial baseline test and within the specification defined in the *THOR-50M Qualification Procedures Manual*, and (b) no damage was found upon visual inspection of the parts involved in the test. Overall, the THOR-50M demonstrated acceptable durability in all qualification test conditions