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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 knee component qualification tests, as well as full body qualification tests on the head, face, thorax, and upper leg 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.

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

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

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.

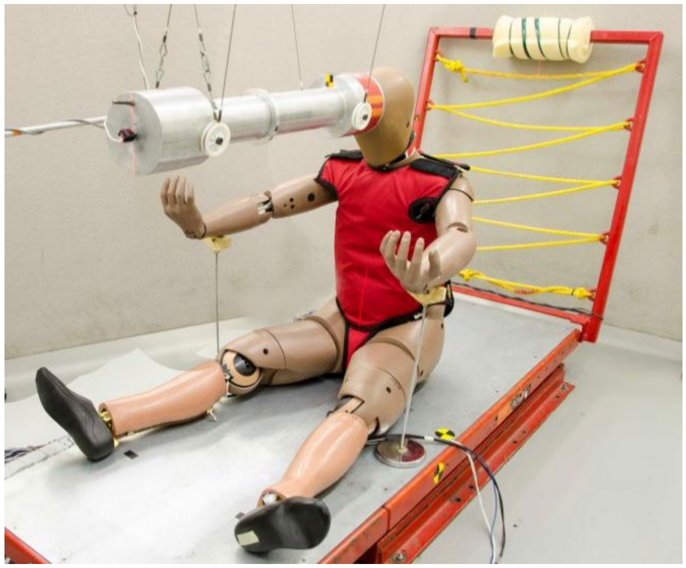

Figure 3-1. Head impact test setup

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

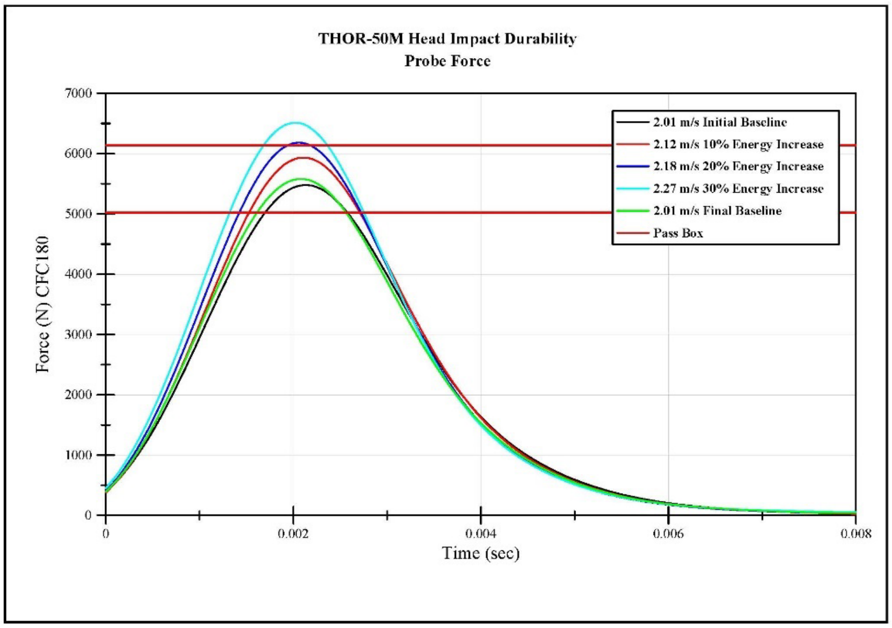

Figure 3-2. Probe force for head durability tests

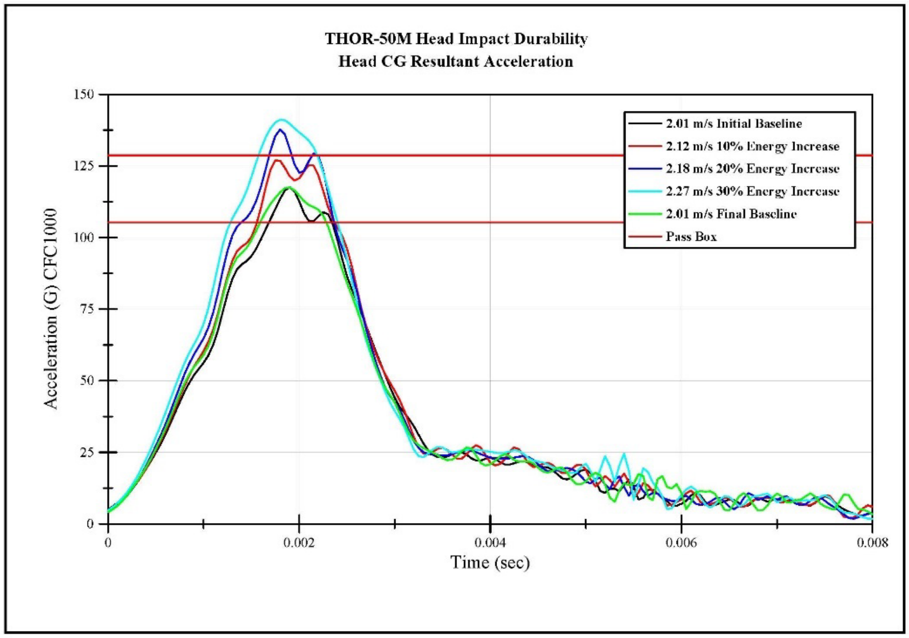

Figure 3-3. Head CG resultant acceleration for head durability tests

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.

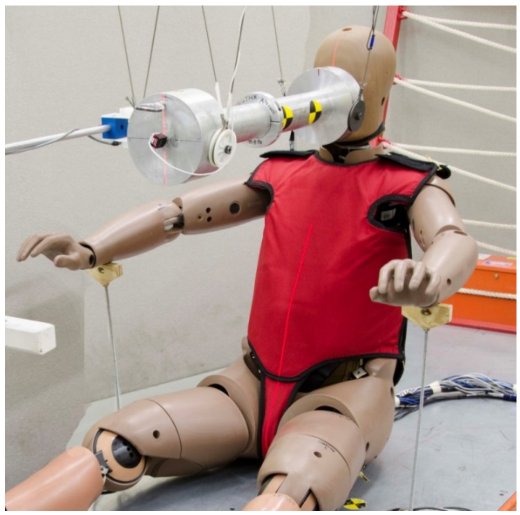

Figure 3-4. Face impact test setup

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

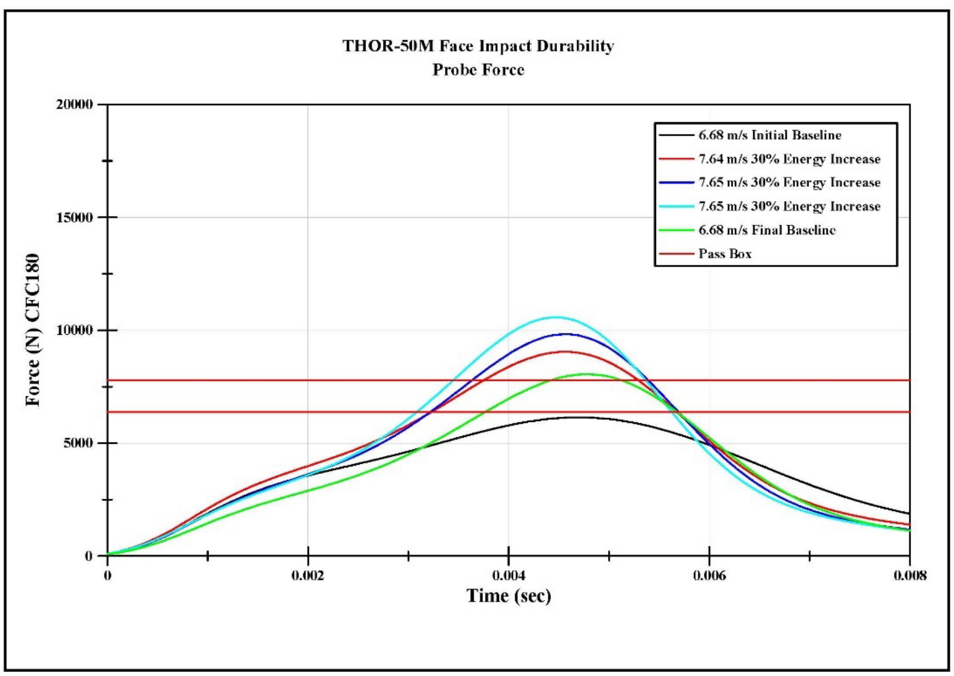

Figure 3-5. Probe force for face impact durability tests

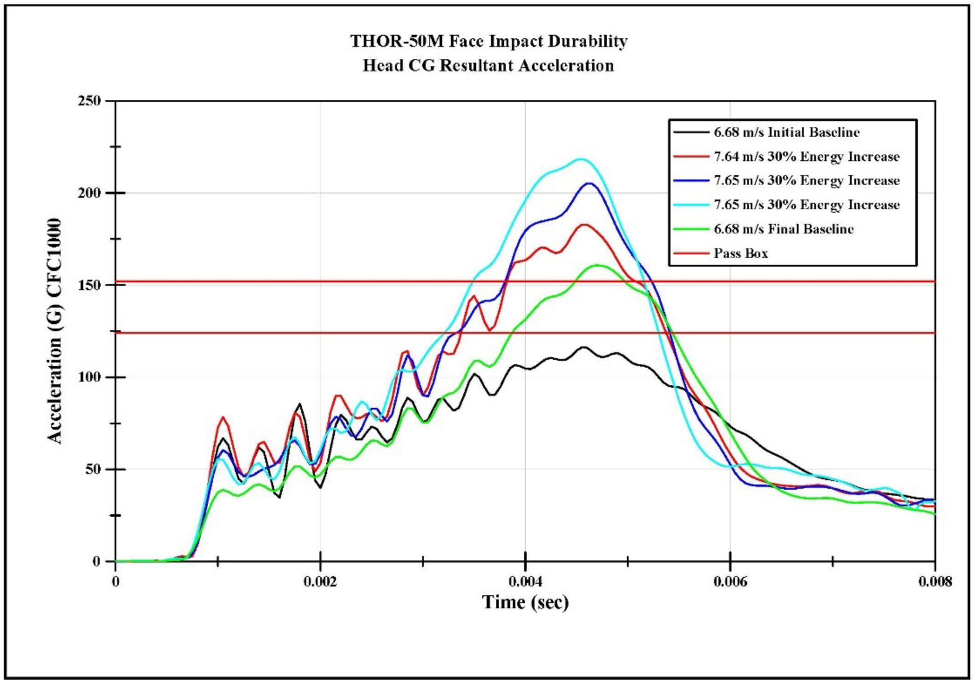

Figure 3-6. Head CG resultant acceleration for face impact durability tests

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.

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[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 ten 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.

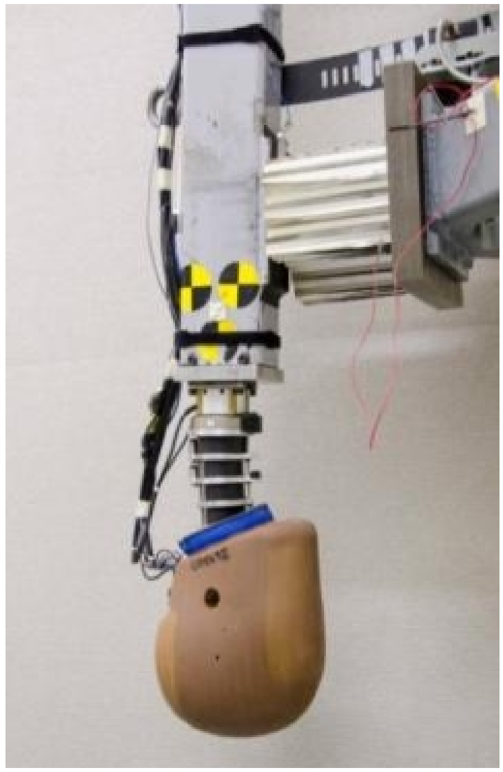

Figure 3-7. Neck flexion test setup

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 Initial Baseline	171023-12 10% Energy Increase	171023-14 20% Energy Increase	171023-16 30% Energy Increase	171024-1 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

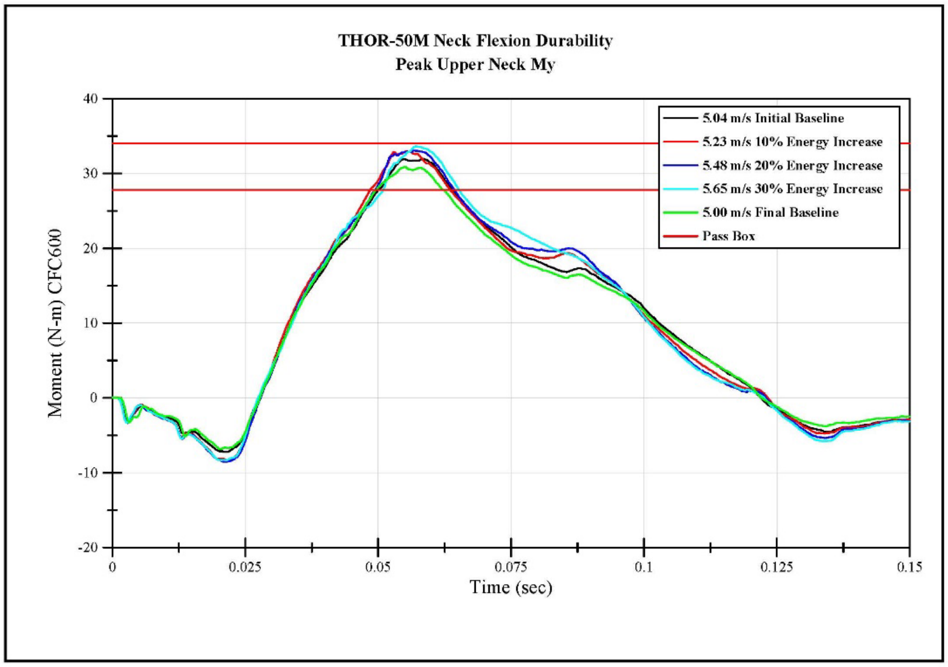

Figure 3-8. Peak upper neck moment about Y axis for neck frontal flexion durability tests

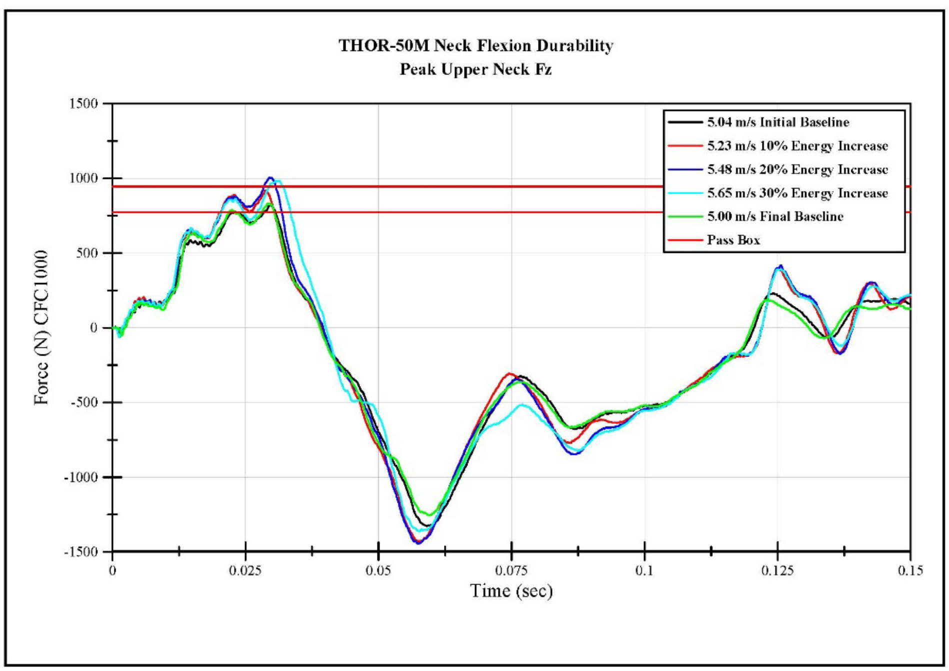

Figure 3-9. Most positive upper neck z axis force value prior to 40 ms for neck frontal flexion durability tests

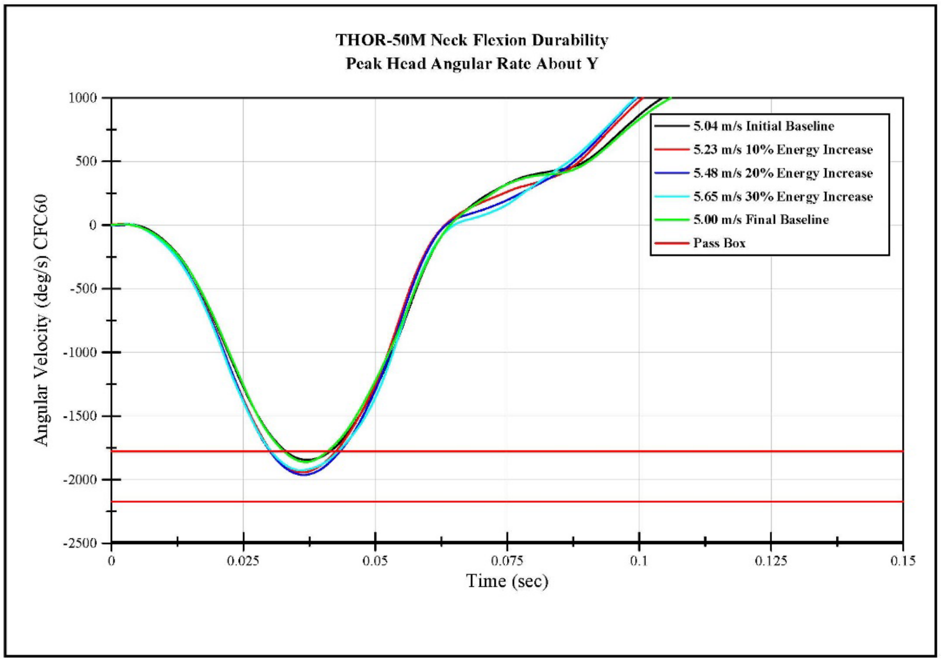

Figure 3-10. Peak head angular rate for neck frontal flexion durability tests

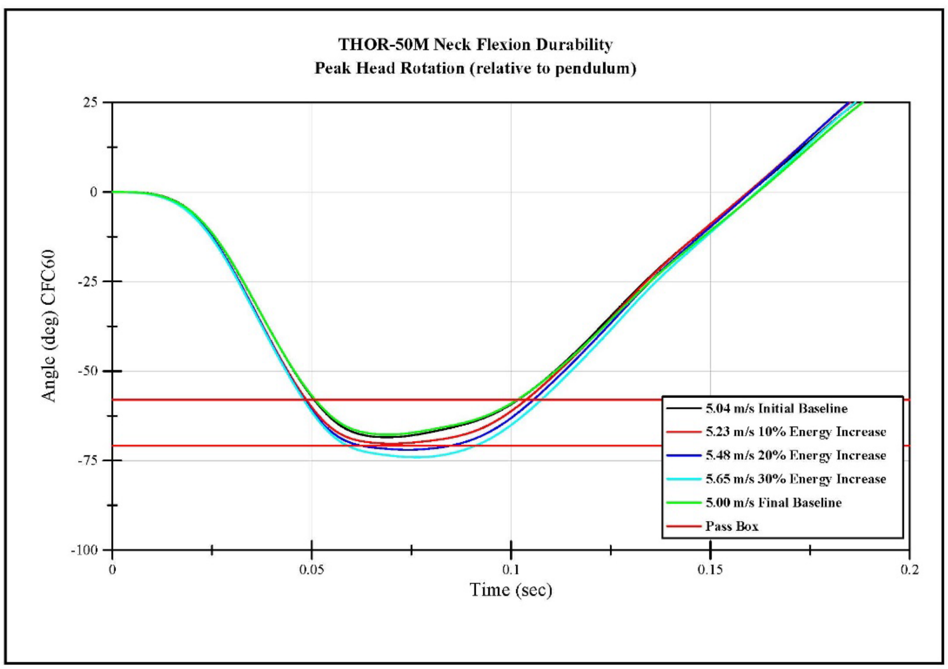

Figure 3-11. Peak head rotation for neck frontal flexion durability tests

3.3.3 Discussion

The final baseline test results showed that the neck returned to specification values for upper neck moment and force (My and Fz), 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.

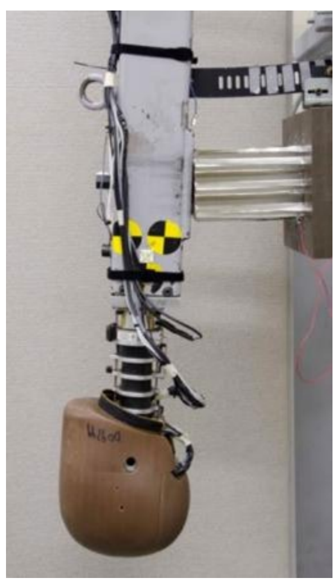

Figure 3-12. Neck extension test setup

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

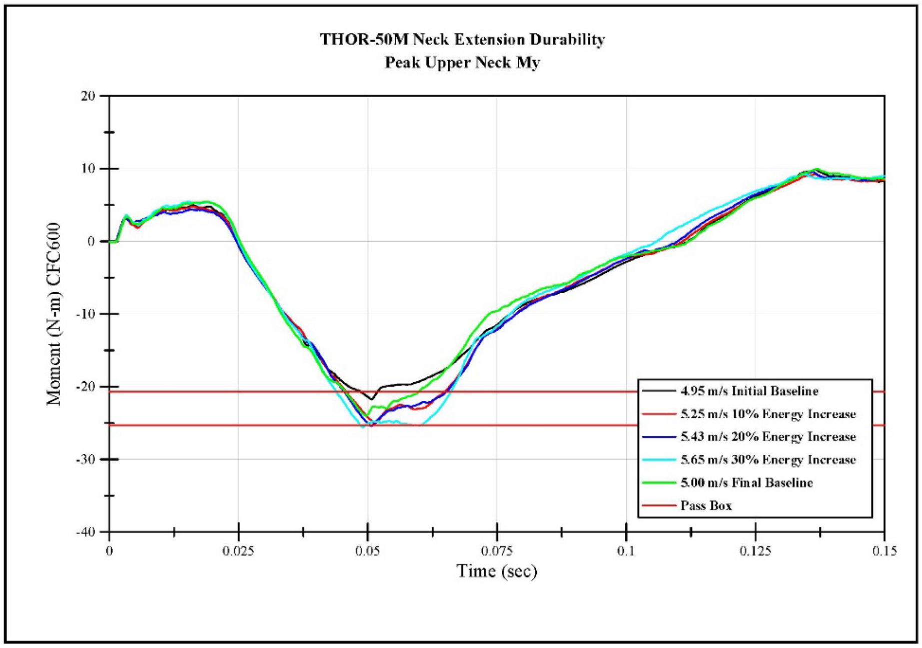

Figure 3-13. Peak upper neck moment about Y axis for neck extension durability tests

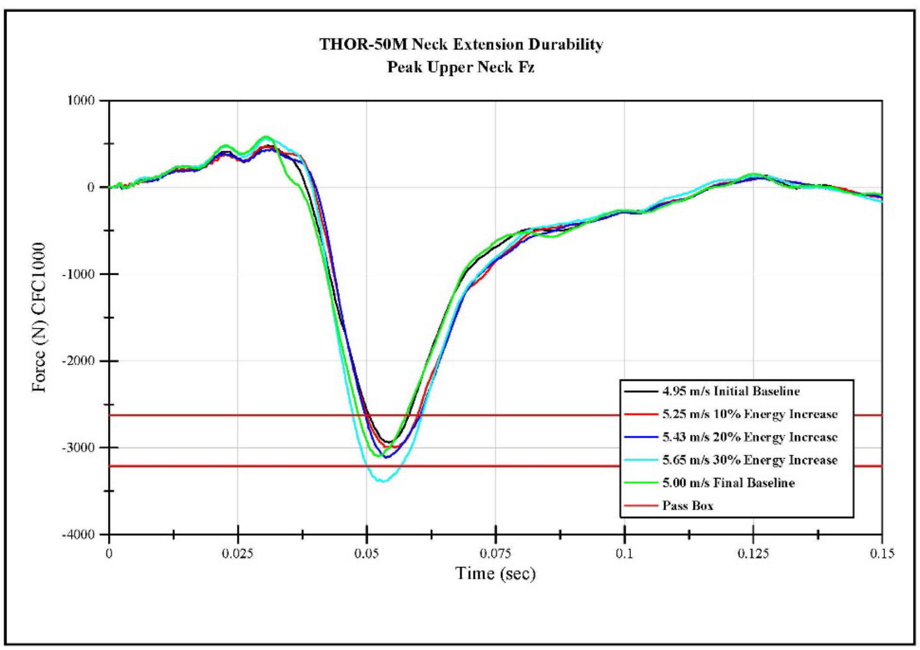

Figure 3-14. Peak upper neck Z axis force for neck extension durability tests

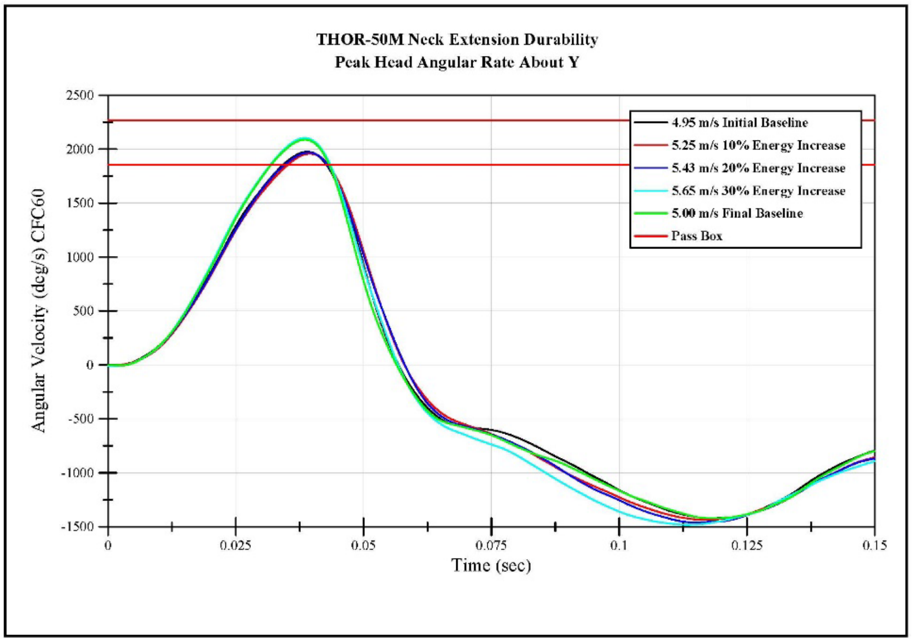

Figure 3-15. Peak head angular rate for neck extension durability tests

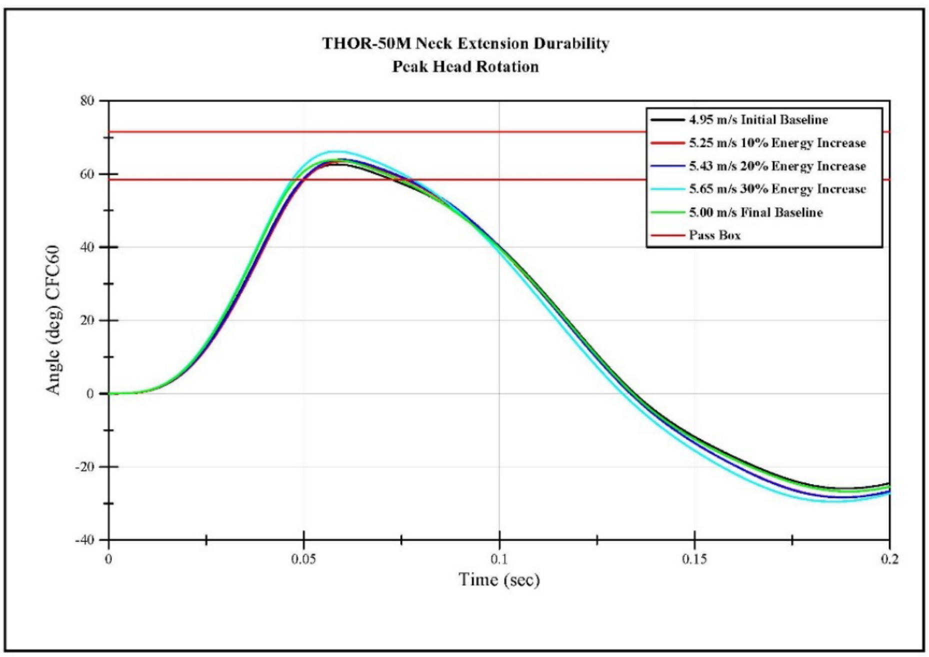

Figure 3-16. Peak head rotation for neck extension durability tests

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.

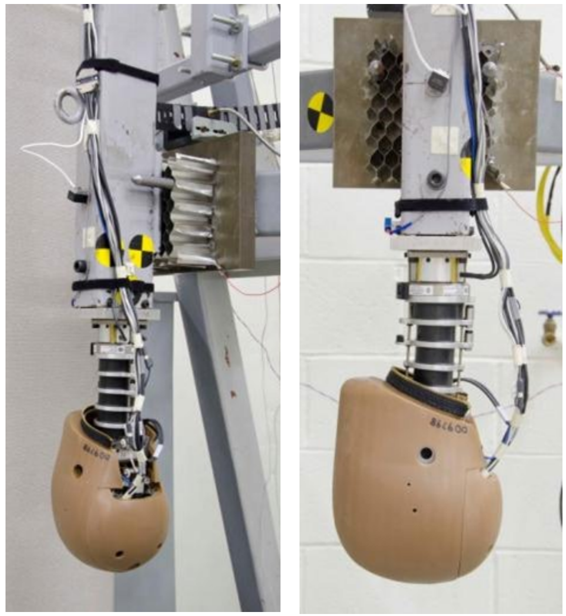

Figure 3-17. Neck lateral flexion test setup

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 Initial Baseline	171024-3 10% Energy Increase	171024-4 20% Energy Increase	171024-5 30% Energy Increase	171024-6 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

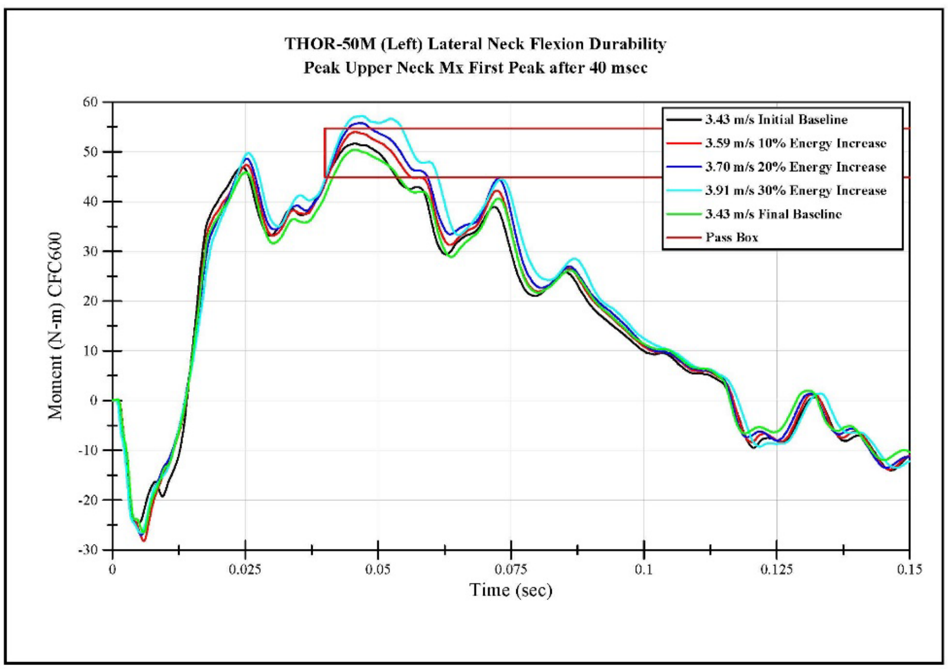

Figure 3-18. Peak upper neck moment about X axis for neck lateral flexion durability tests

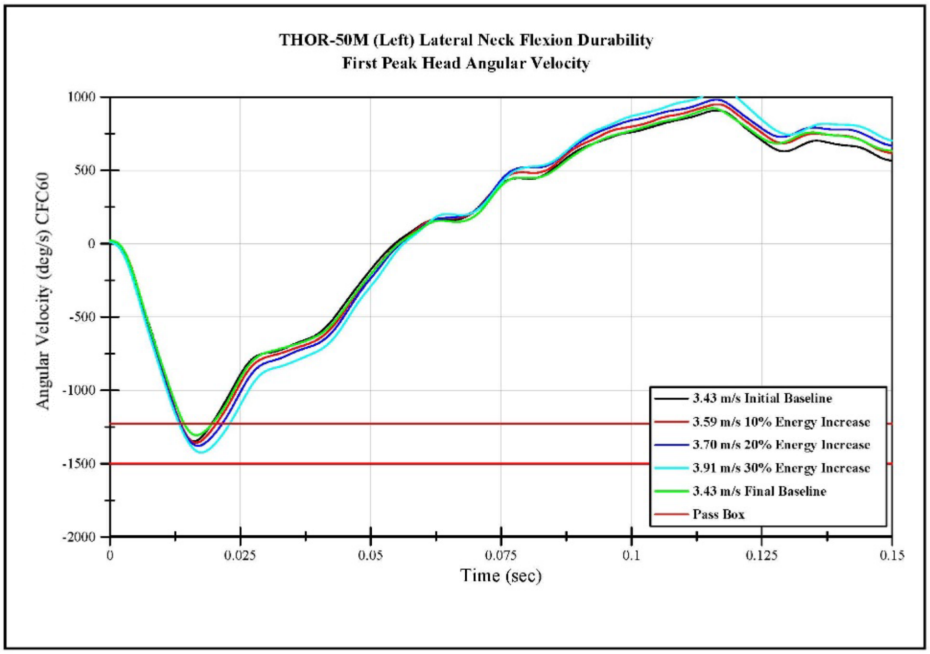

Figure 3-19. Peak head angular rate about X axis for neck lateral flexion durability tests

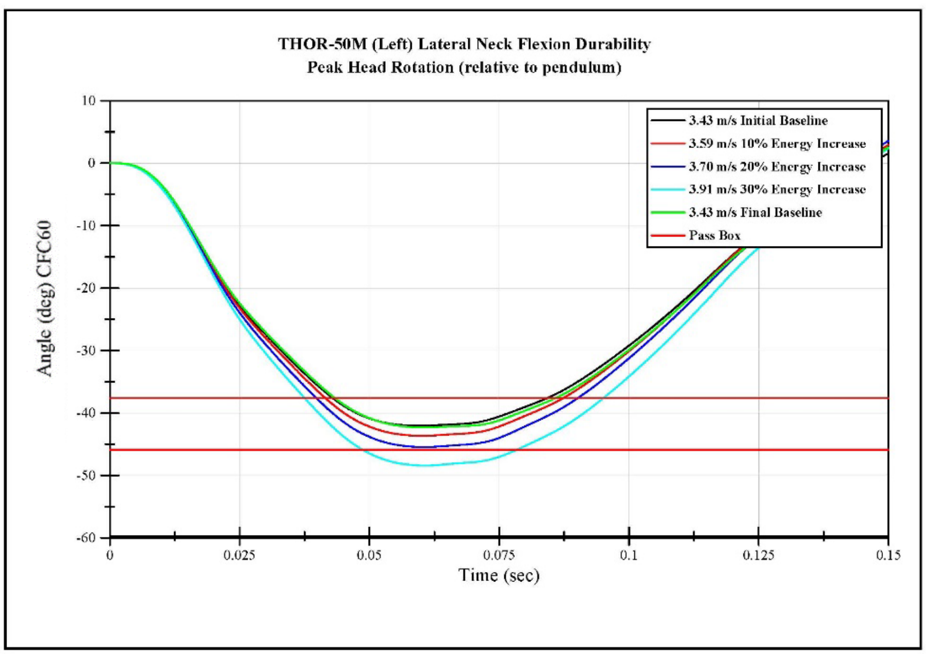

Figure 3-20. Peak head rotation for neck lateral flexion durability tests

3.5.3 Discussion

The final baseline test results showed that the neck returned to specification values for the upper neck moment (Mx), 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 in the torsion 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 3-16). 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.

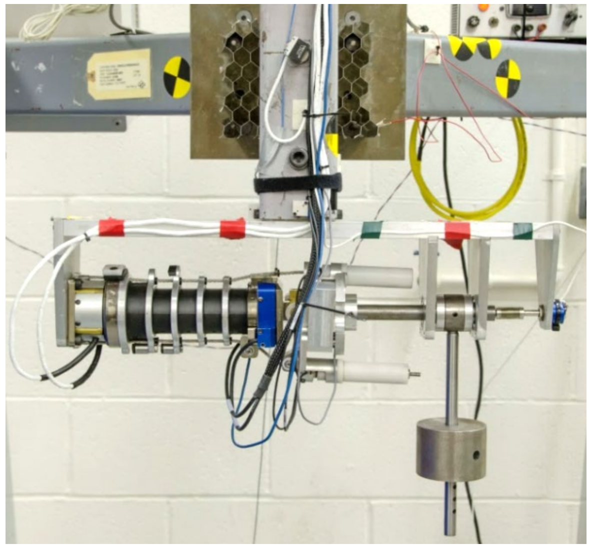

Figure 3-21. Neck torsion test setup

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 Initial Baseline	171024-8 10% Energy Increase	171024-9 20% Energy Increase	171025-1 30% Energy Increase	171025-2 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

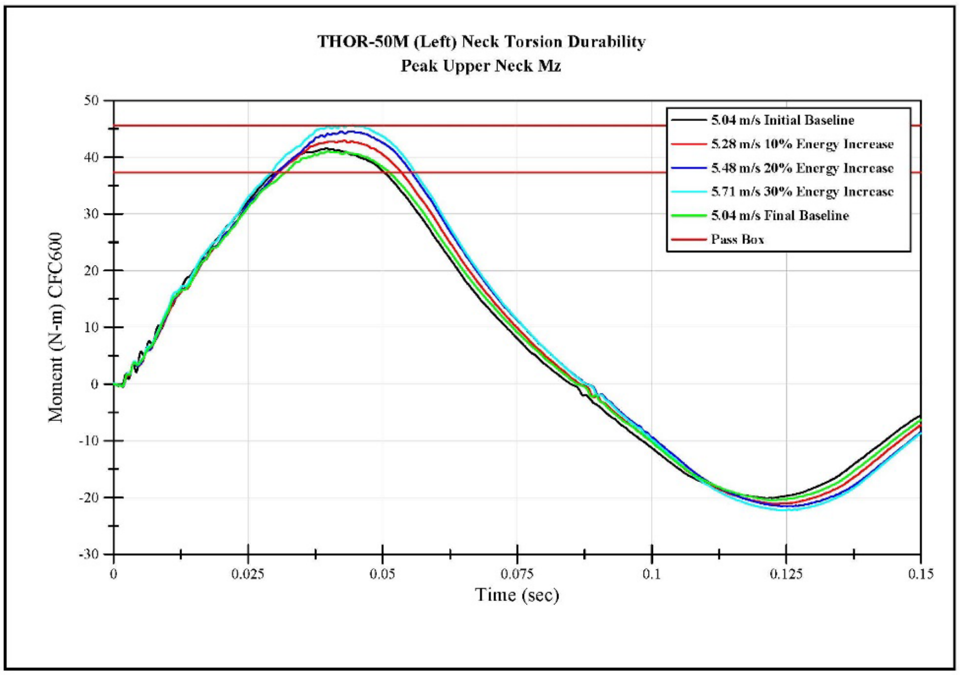

Figure 3-22. Peak upper neck moment about Z axis for neck torsion durability tests

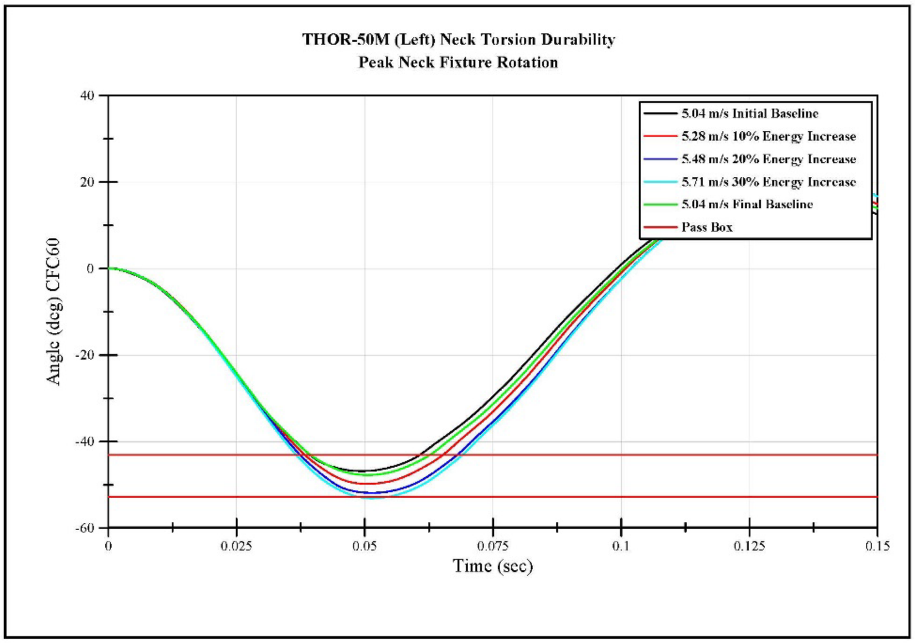

Figure 3-23. Peak neck fixture rotation for neck torsion durability tests

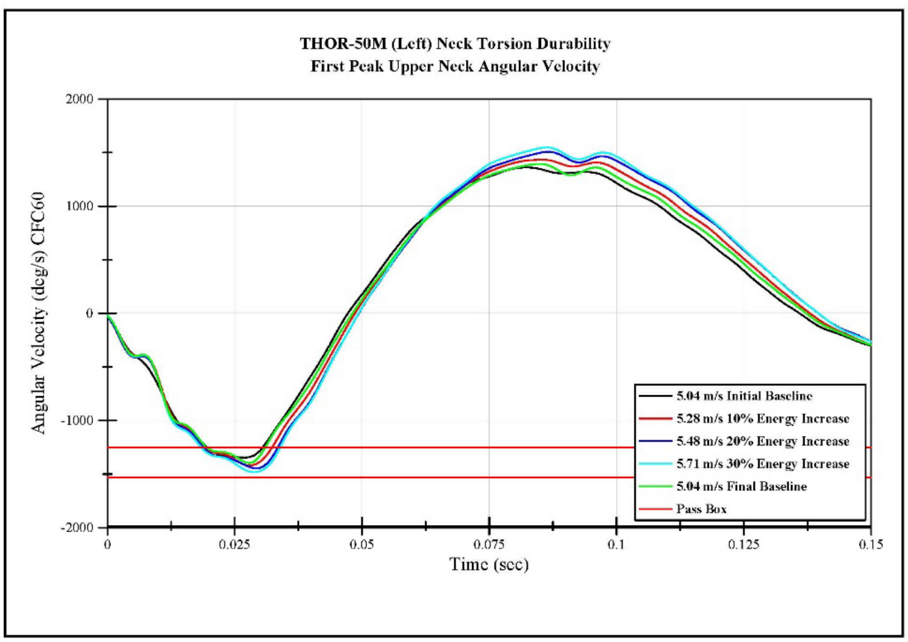

Figure 3-24. Peak head angular rate about Z axis for neck torsion durability tests

3.6.3 Discussion

The final baseline test results showed that the neck returned to specification values for the upper neck moment (Mz), 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 m/s ± 0.05 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.

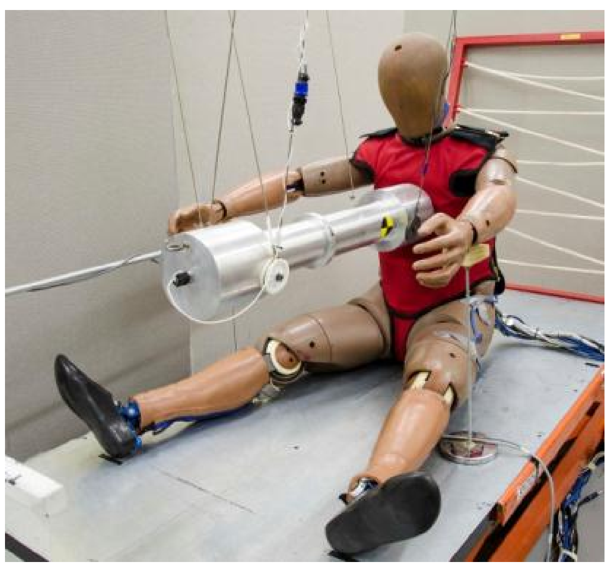

Figure 3-25. Upper thorax impact test setup

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 3-30, 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)
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

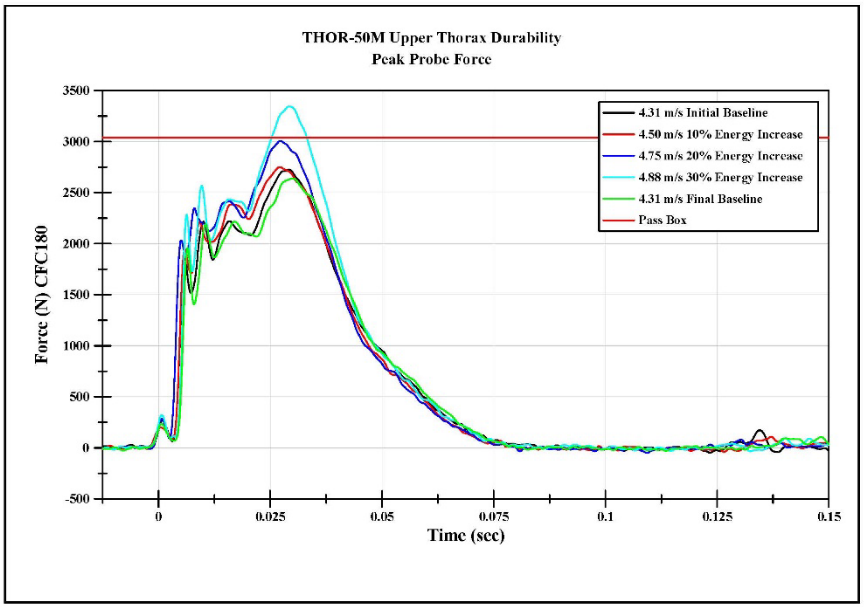

Figure 3-26. Peak probe force for upper thorax durability tests

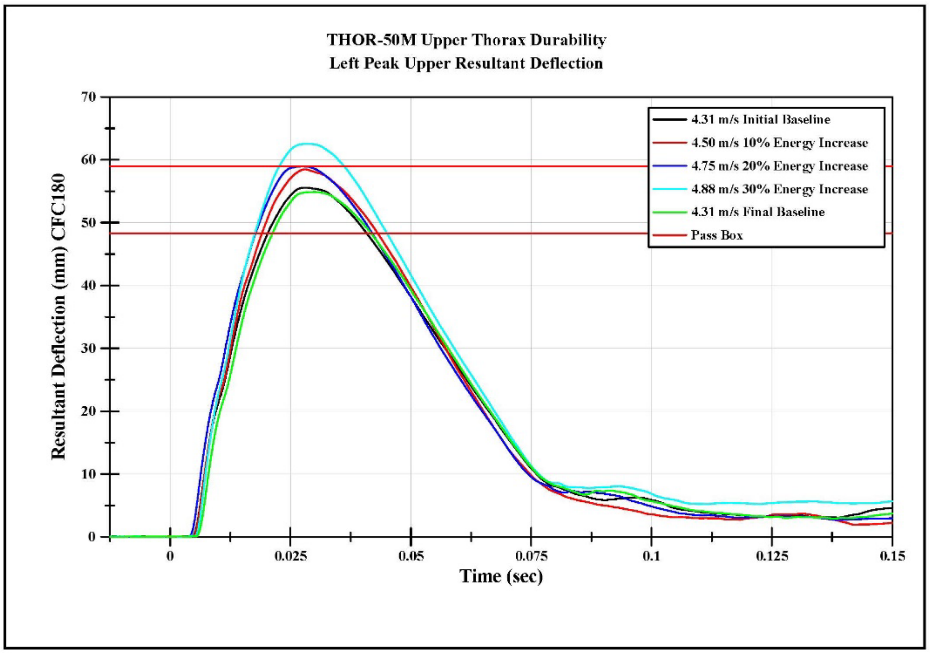

Figure 3-27. Left peak upper resultant deflections for upper thorax durability tests

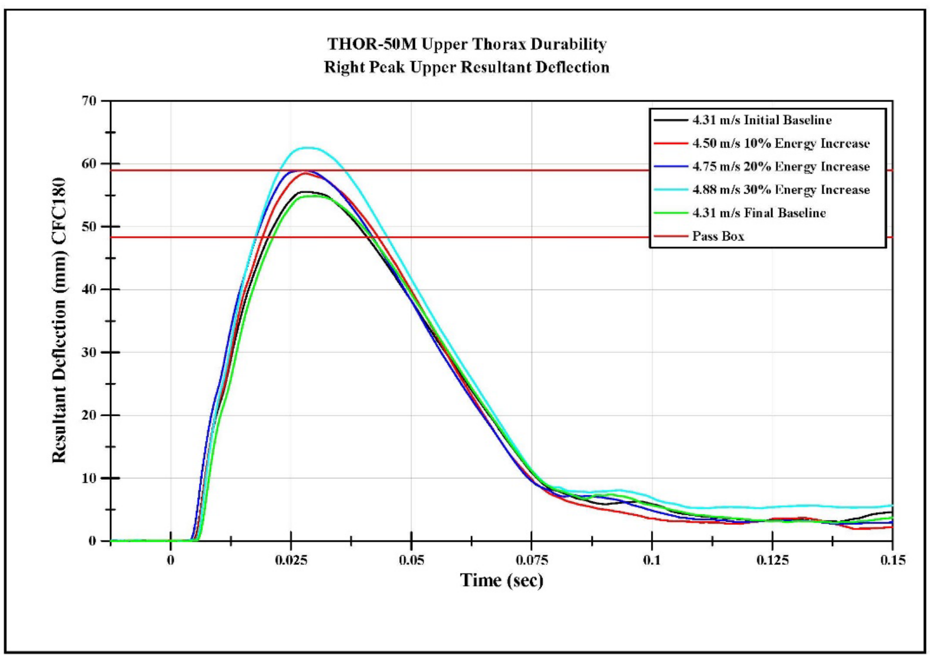

Figure 3-28. Right peak upper resultant deflection for upper thorax durability tests

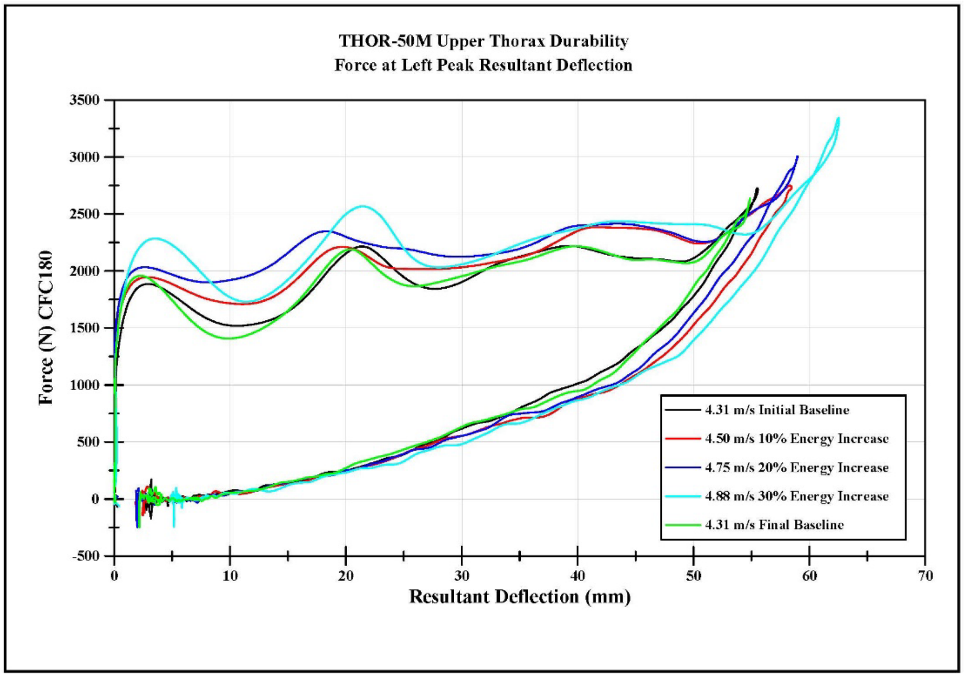

Figure 3-29. Force at left peak resultant deflection for upper thorax durability tests

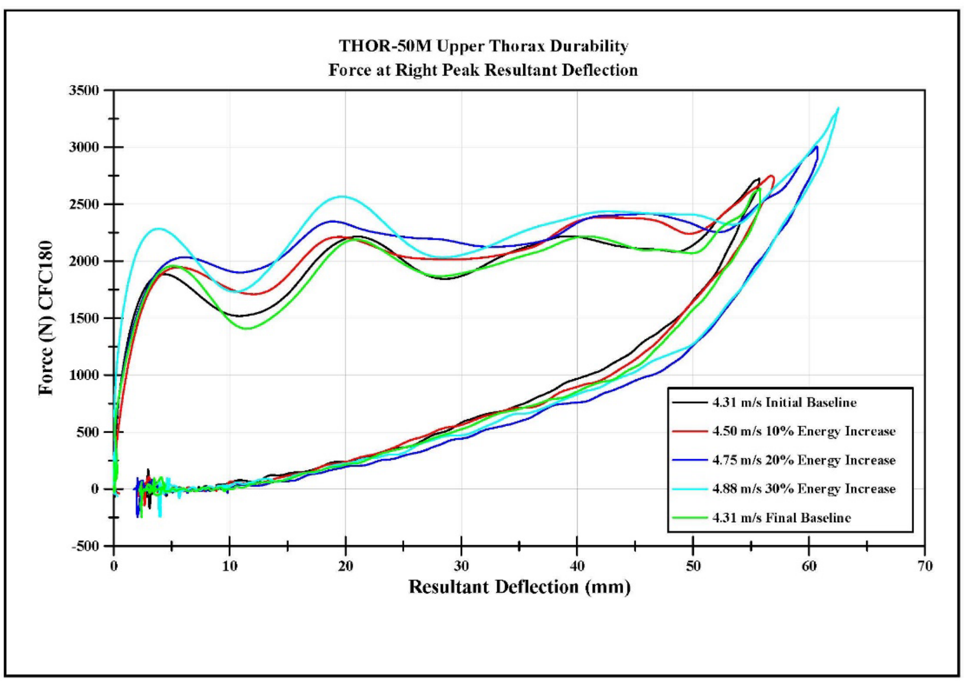

Figure 3-30. Force at right peak resultant deflection for upper thorax durability tests

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.

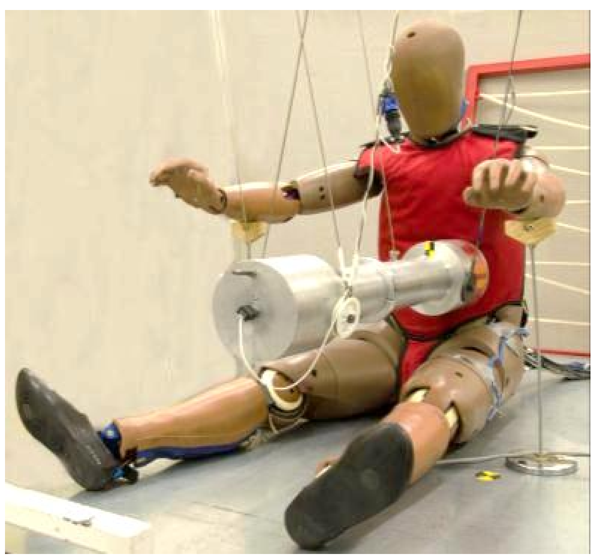

Figure 3-31. Lower thorax impact test setup

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

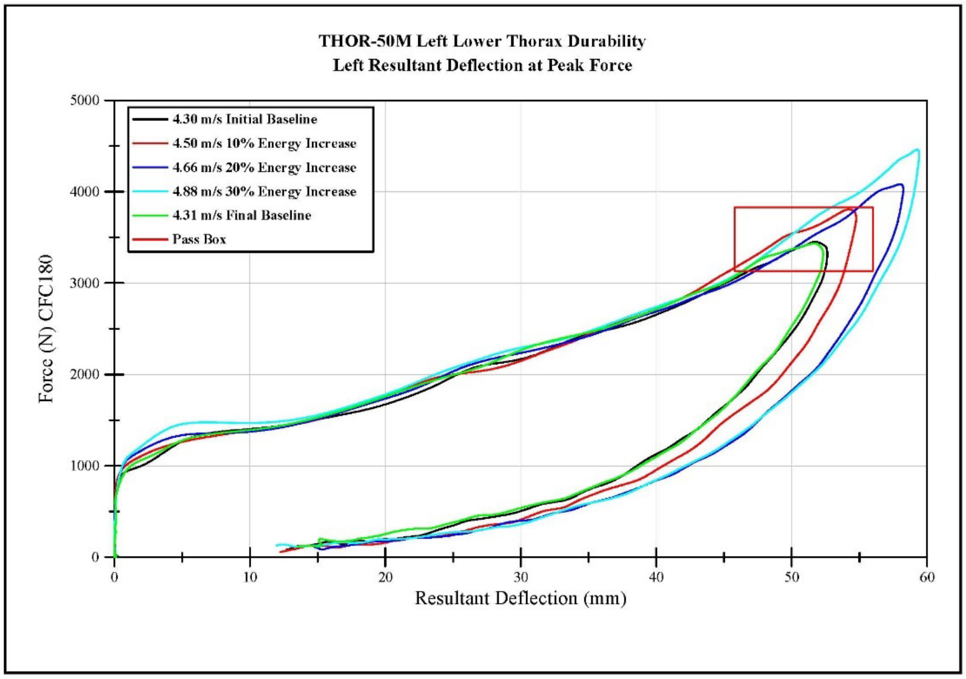

Figure 3-32. Force-deflection for left lower thorax durability tests

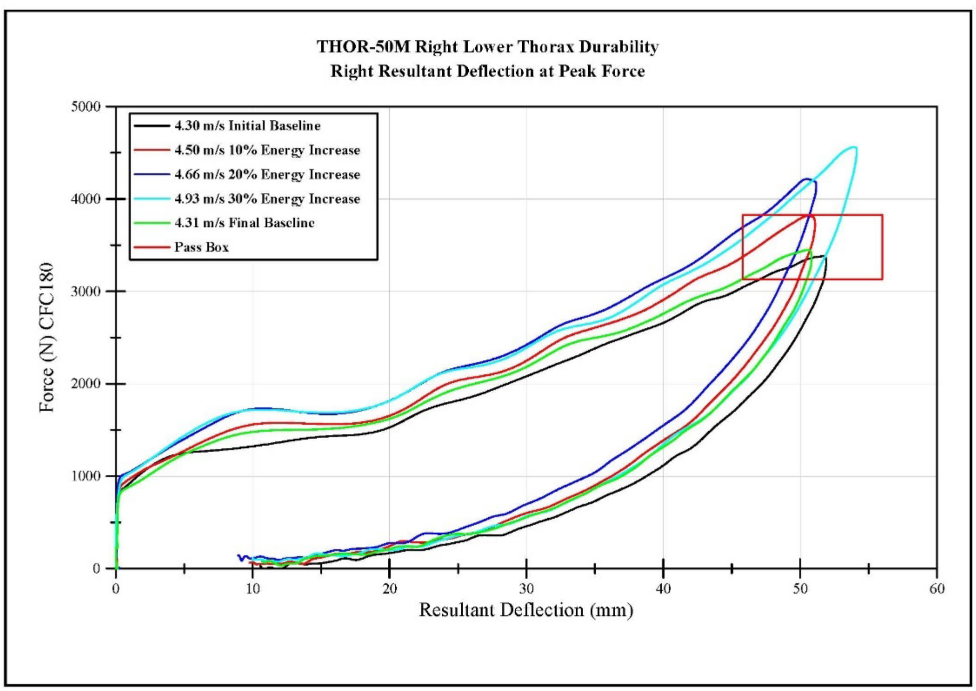

Figure 3-33. Force-deflection for right lower thorax durability tests

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 tests[9] without bottoming out the abdomen or damaging instrumentation. During the THOR-50M repeatability and reproducibility testing at VRTC[10], 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.

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[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	mm	-91.3	-74.7
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.

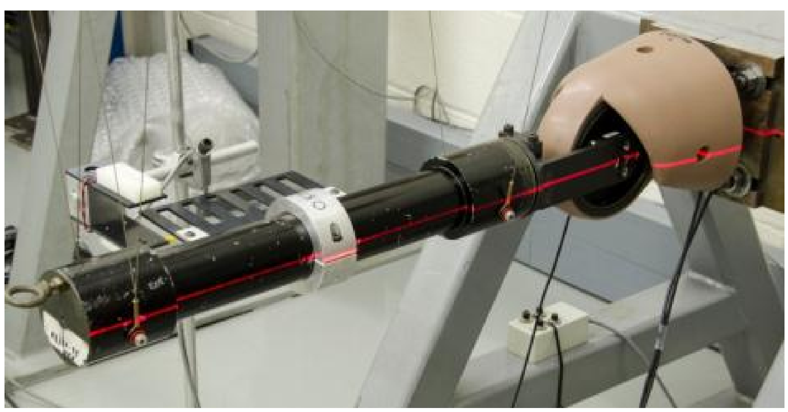

Figure 3-34. Knee slider impact test setup

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

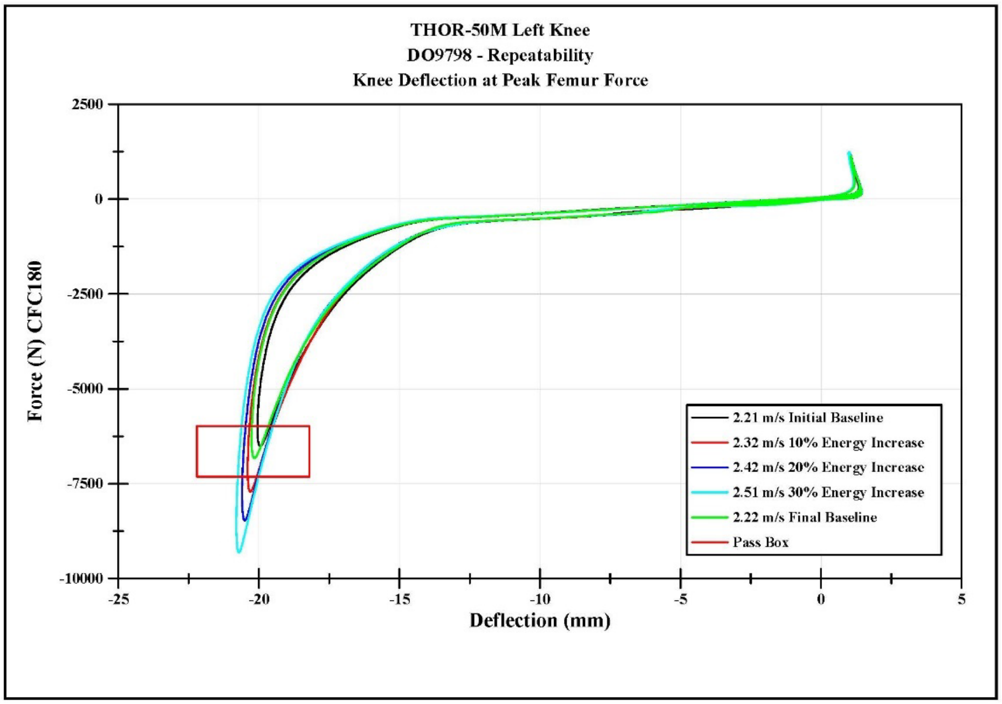

Figure 3-35. Force-deflection for knee slider durability tests

3.10.3 Discussion

The final baseline test results showed that the knee slider returned to specification values for knee deflection and femur force (Fz) 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.

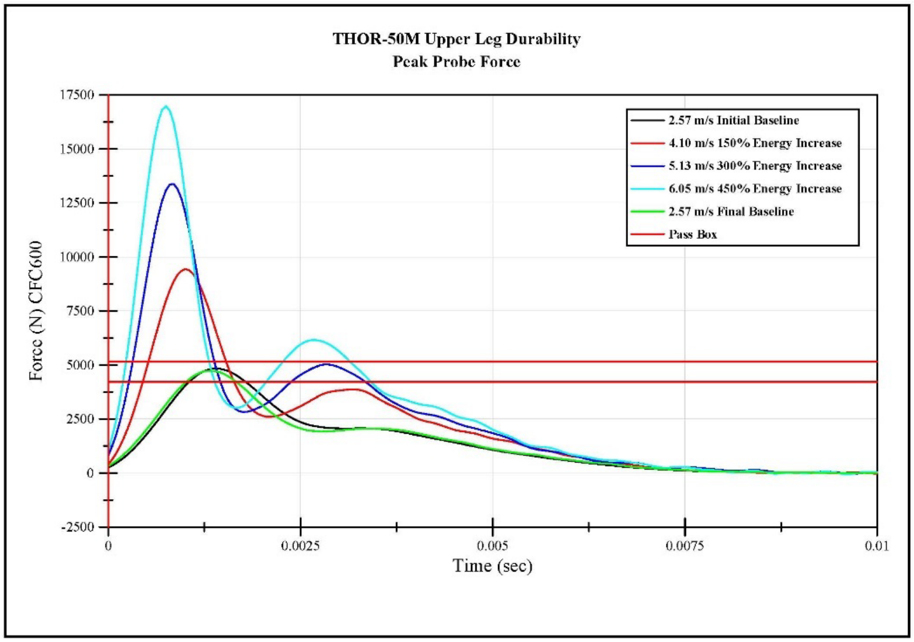

Figure 3-37. Peak probe force for upper leg durability tests

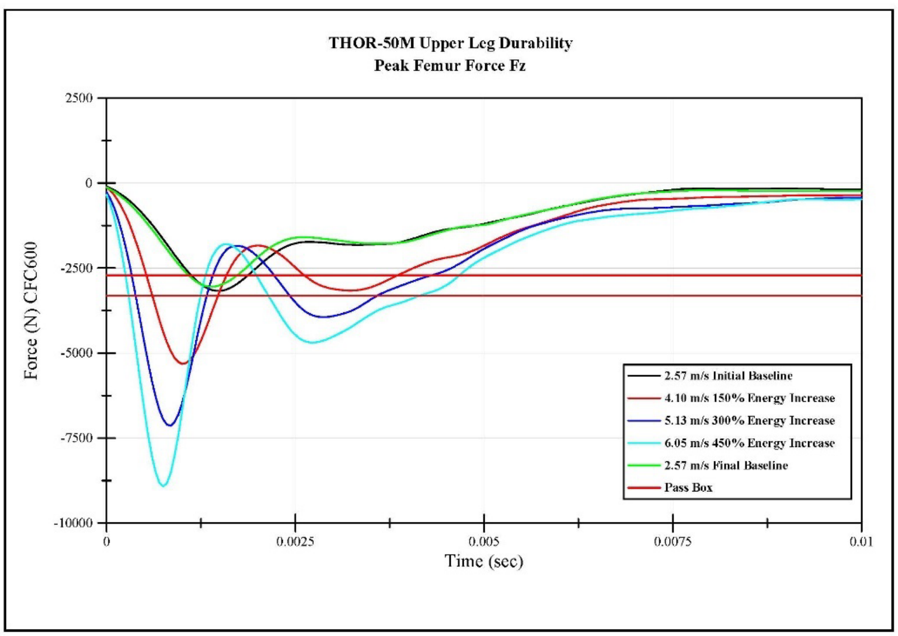

Figure 3-38. Peak Z femur force for left upper leg durability tests

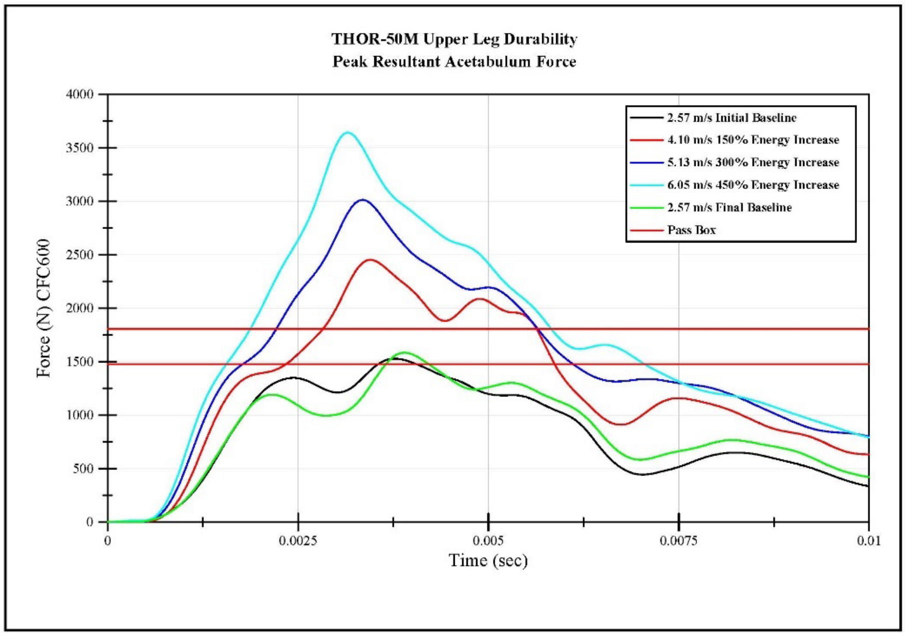

Figure 3-39. Peak resultant acetabulum force for upper leg durability tests

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 attached in place of the molded shoe (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] The pendulum arm is mounted to a rigid shaft which is pivoted on low friction ball bearings. The

[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.

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.

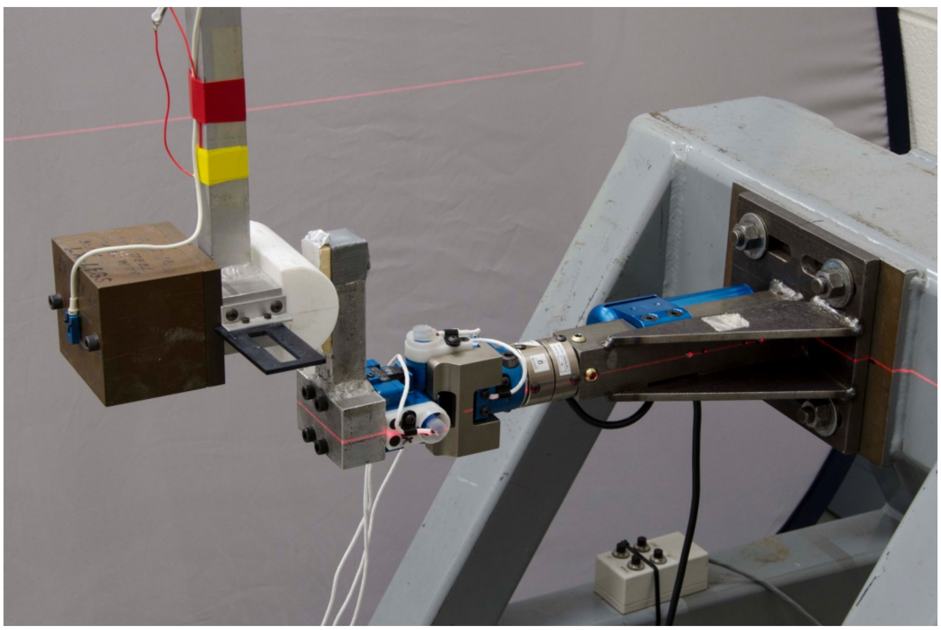

Figure 3-40. Ankle Inversion Test

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 Fz (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

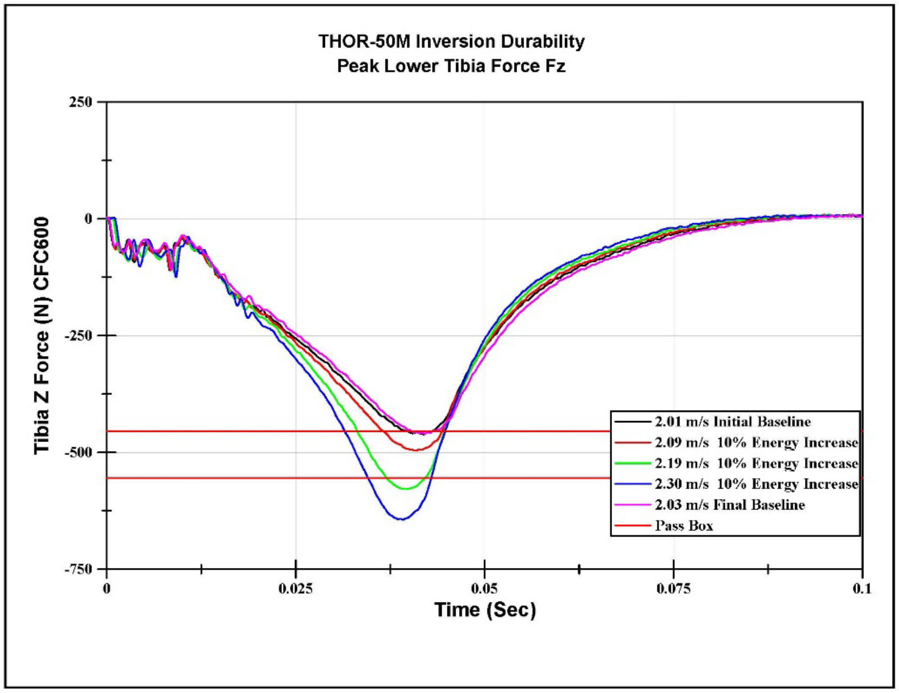

Figure 3-41. Peak lower tibia force Fz for foot inversion durability tests

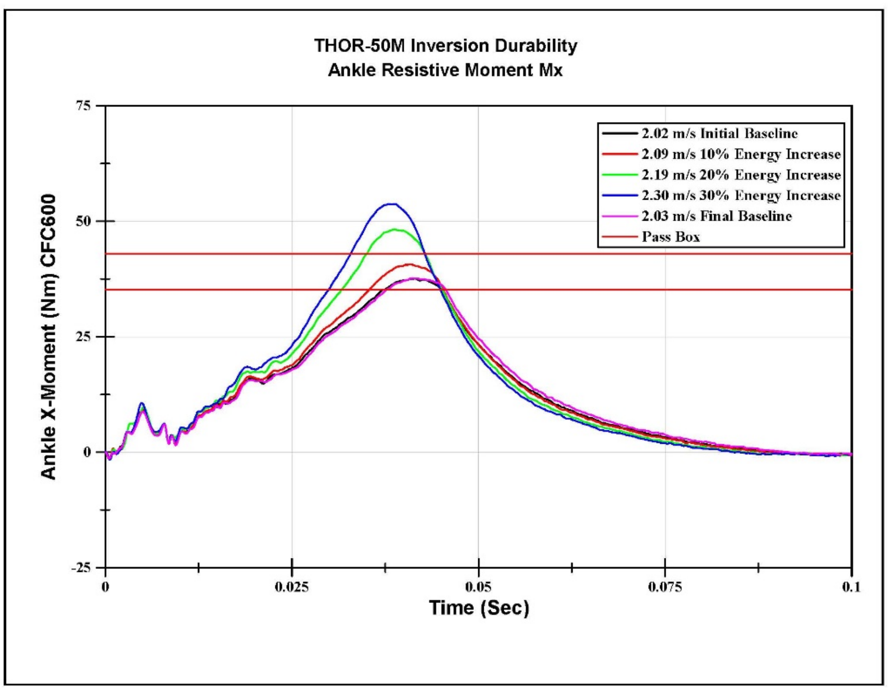

Figure 3-42. Ankle resitive moment Mx for foot inversion durability tests

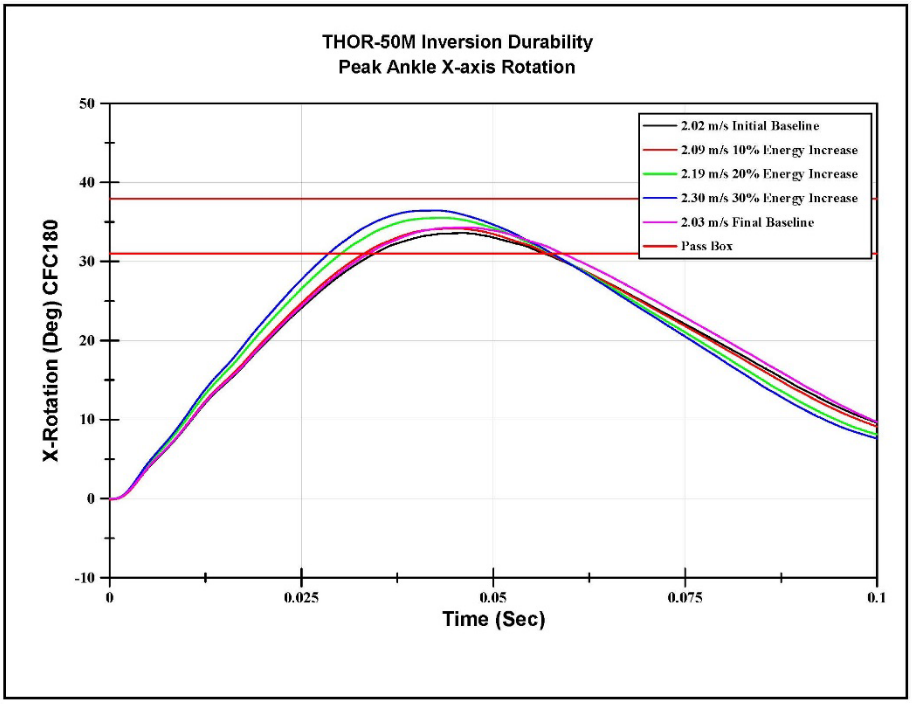

Figure 3-43. Ankle X axis rotation for foot inversion durability tests

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 an impact to a padded bracket which is temporarily attached in place of the molded shoe (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]

[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.

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.

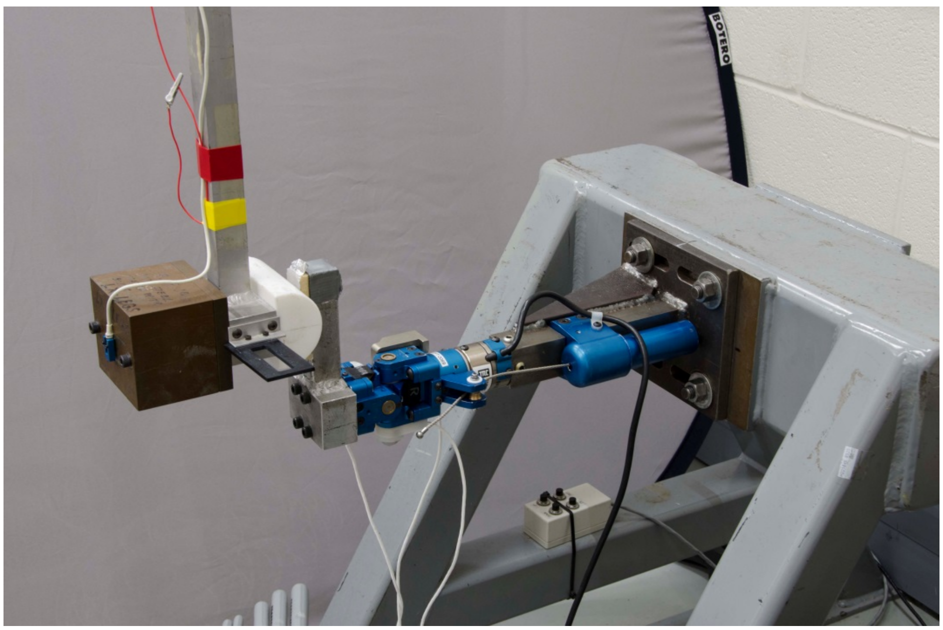

Figure 3-44. Ankle Eversion Test

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 Fz (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

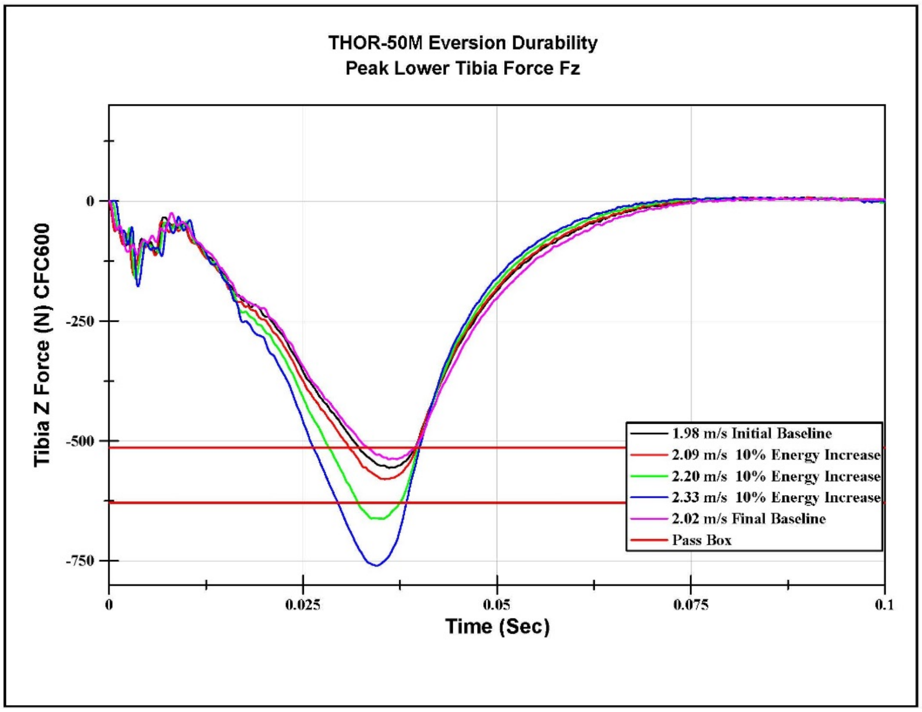

Figure 3-45. Peak lower tibia force Fz for foot eversion durability tests

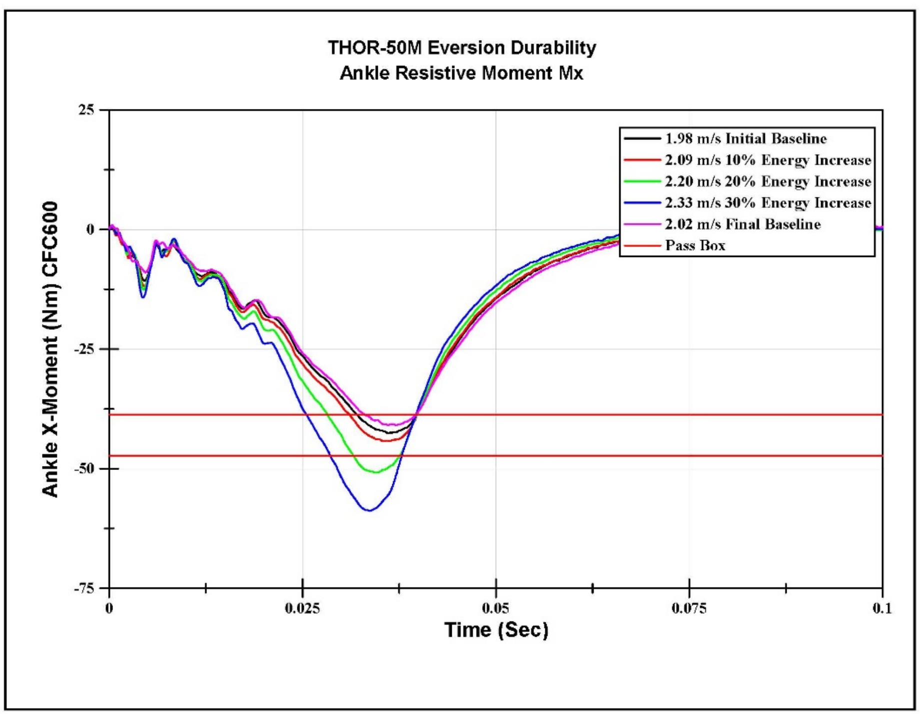

Figure 3-46. Ankle resitive moment Mx for foot eversion durability tests

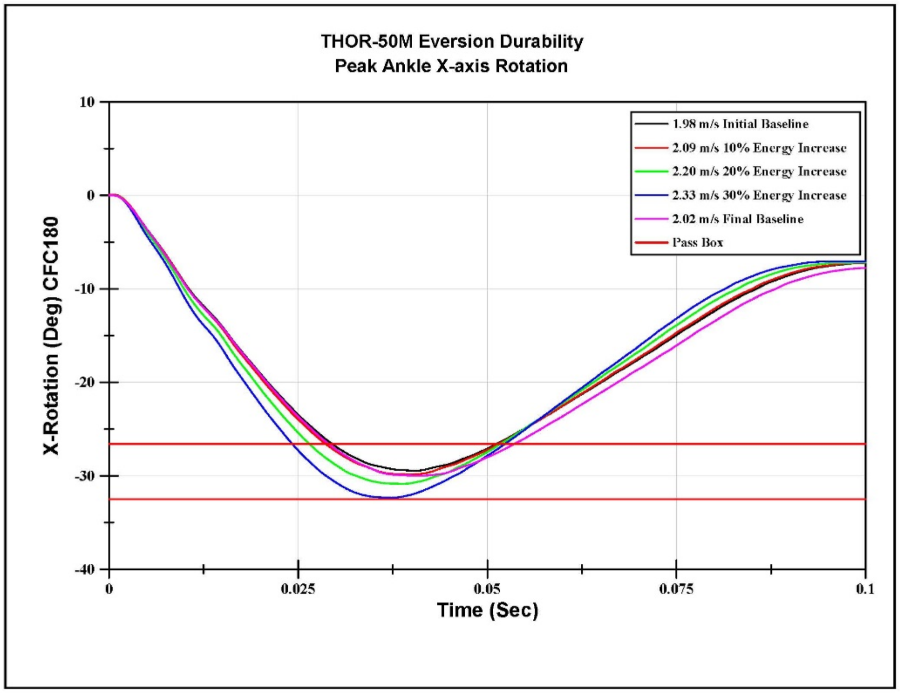

Figure 3-47. Ankle X axis rotation for foot eversion durability tests

3.13.3 Discussion

The final baseline test results showed that the ankle returned to specification values for lower tibia force (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 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

[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.

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.

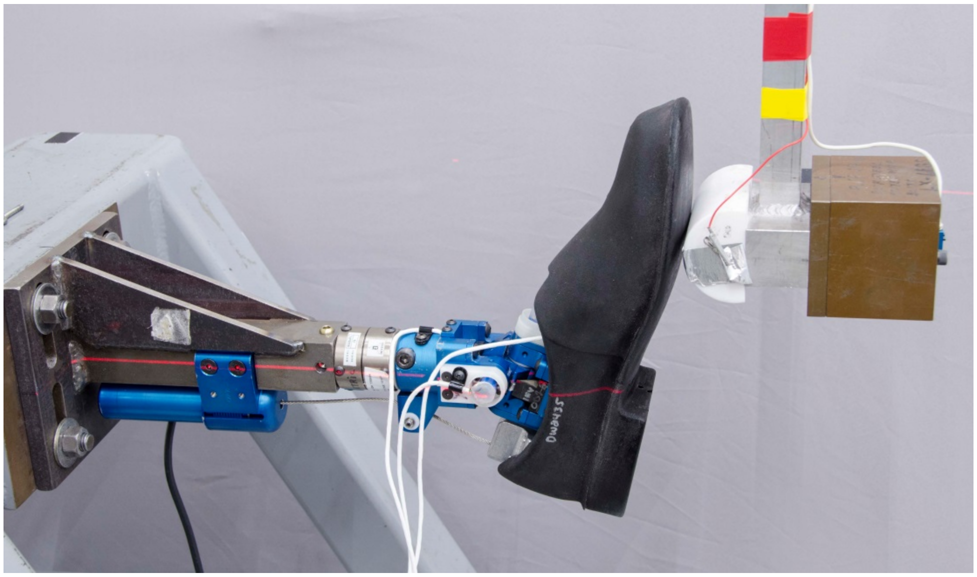

Figure 3-48. Ball of Foot Test

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 Fz (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

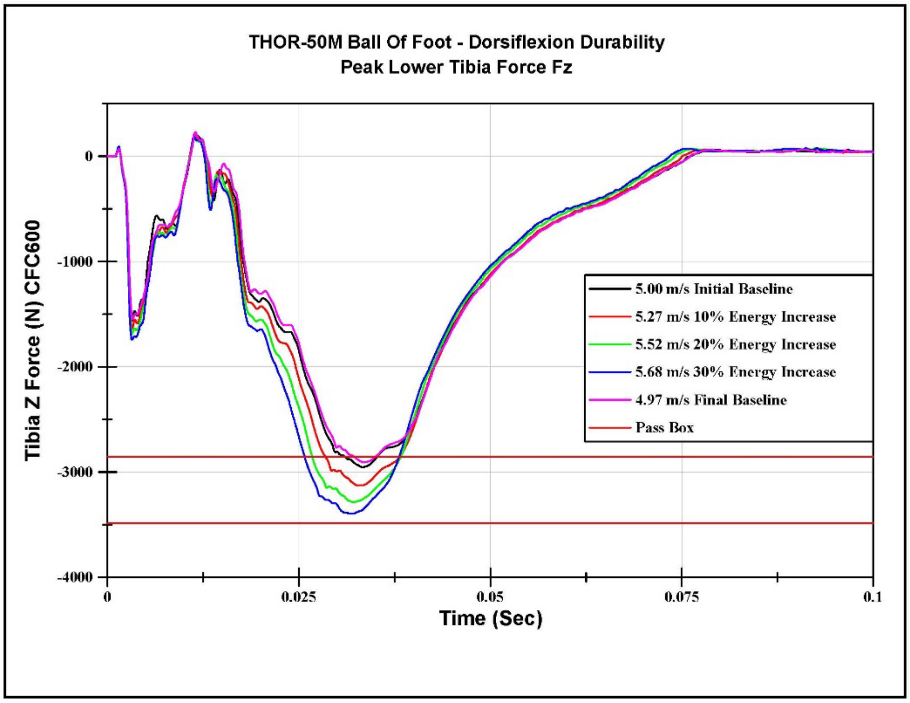

Figure 3-49. Peak lower tibia force Fz for ball of foot durability tests

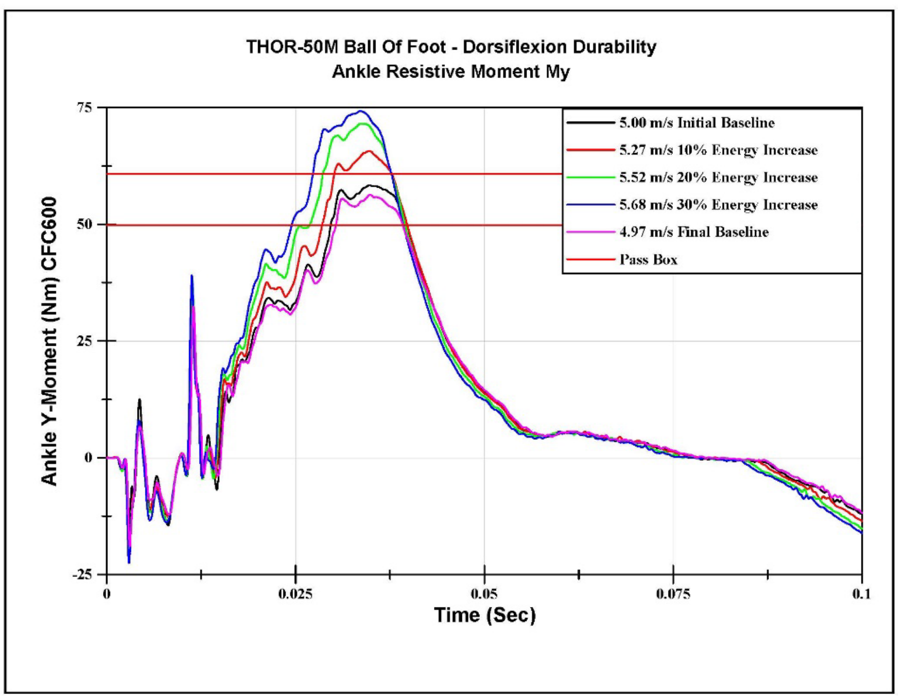

Figure 3-50. Ankle resitive moment My for ball of foot durability tests

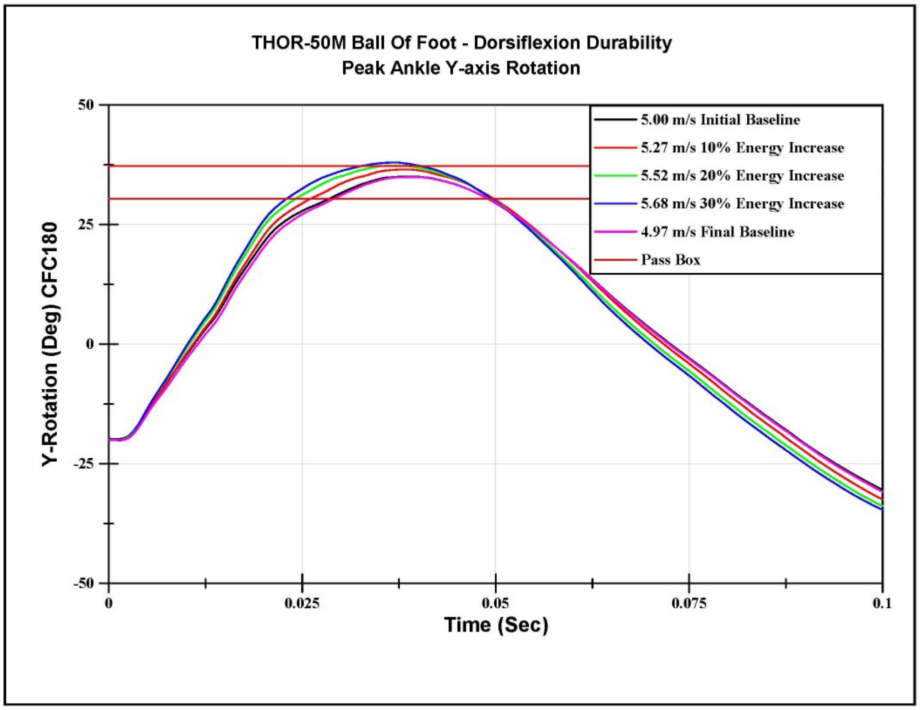

Figure 3-51. Ankle Y axis rotation for ball of foot durability tests

3.14.3 Discussion

The final baseline test results showed that the lower leg returned to specification values for lower tibia force (Fz), peak ankle resistive moment (My), 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, 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

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

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.

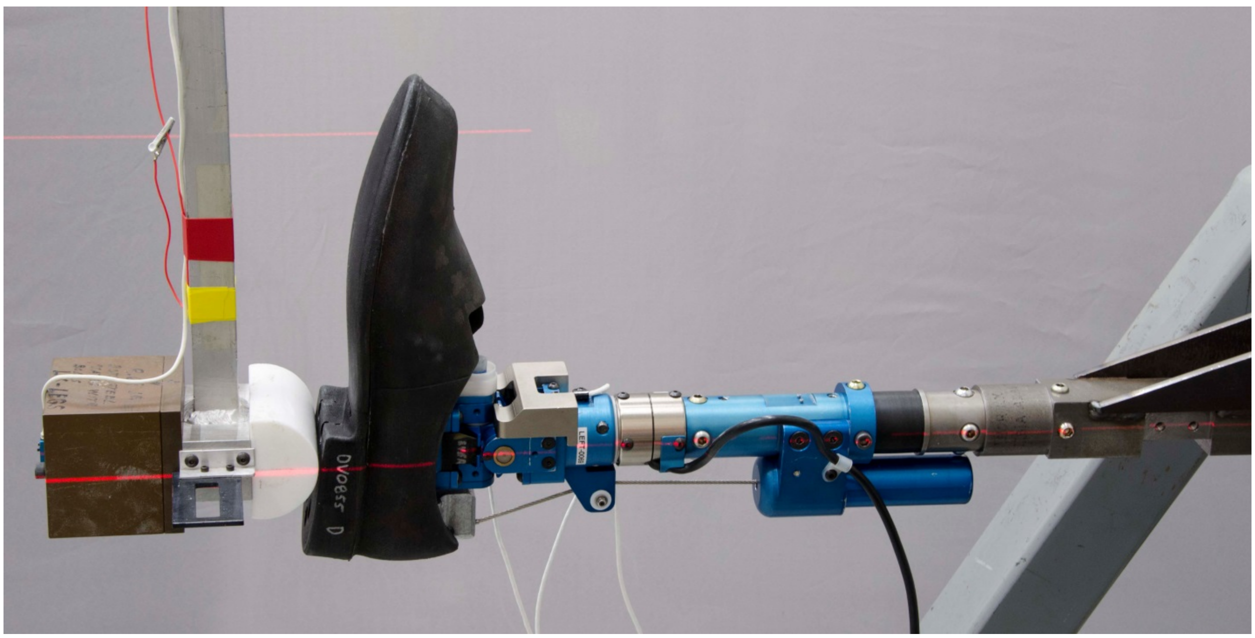

Figure 3-52. Heel Test

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 Fz (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

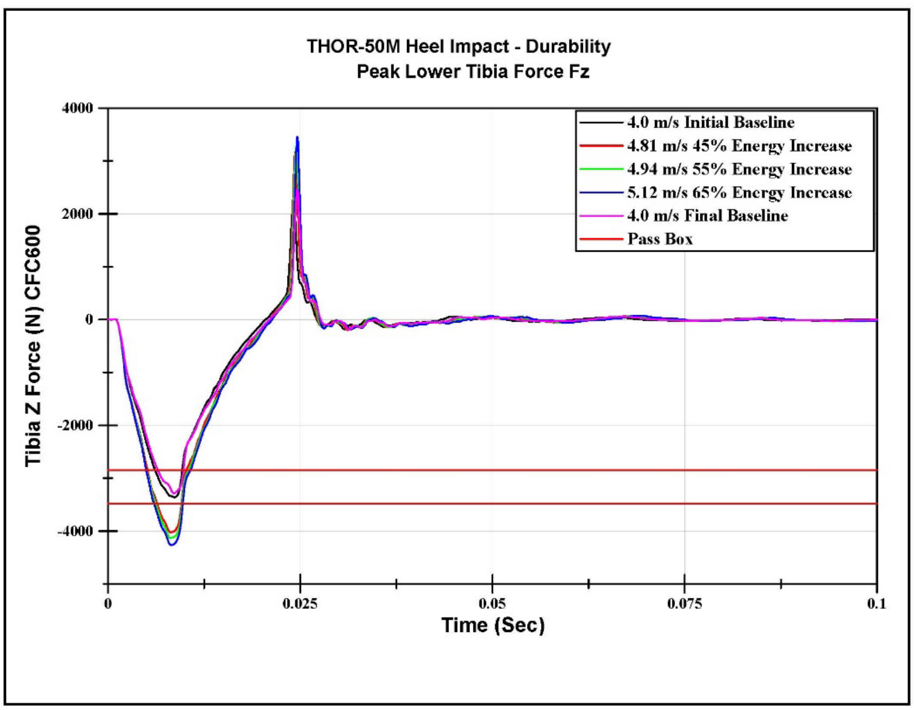

Figure 3-53. Peak lower tibia force Fz for heel durability tests

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

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