U.S. Department
of Transportation
National Highway
Traffic Safety
Administration

DOT HS 813 258 October 2022

THOR-50M Repeatability And Reproducibility of Qualification Tests

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Suggested APA Format Citation:

Hagedorn, A., Martin, P., Millis, W., Parent, D. (2022, October). *THOR-50M repeatability and reproducibility of qualification tests* (Report No. DOT HS 813 258). National Highway Traffic Safety Administration.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT HS 813 258		

4. Title and Subtitle	5. Report Date
THOR-50M Repeatability and Reproducibility of Qualification Tests	October 2022
	6. Performing Organization Code
7. Authors Alena Hagedorn, Transportation Research Center Inc.; Peter Martin, William Millis, Dan Parent, NHTSA	8. Performing Organization Report No.
9. Performing Organization Name and Address Vehicle Research and Test Center P.O. Box B-67 10820 State Route 347 East Liberty, Ohio	10. Work Unit No. (TRAIS)
	11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Highway Traffic Safety Administration 1200 New Jersey Avenue SE Washington, DC 20590	13. Type of Report and Period Covered 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This report documents NHTSA's evaluation of the repeatability and reproducibility (R&R) of the 50th percentile Test Device for Human Occupant Restraint (THOR-50M) dummy in qualification tests. Repeatability (similarity of test responses from a single dummy when subjected to repeats of a given test condition) and reproducibility (similarity of test responses from several dummies when subjected to repeats of a given test condition) of the THOR-50M were evaluated by calculating the coefficient of variation values for each qualification test using several different dummies and test labs. With few exceptions, the results didn't require a thorough review of the test procedures or necessitate the need for complete dummy inspections. Therefore, the THOR-50M R&R was deemed sufficient for use as a test tool for evaluating the safety of vehicles. Results obtained in a few tests identify areas for potential further investigation or provide opportunities to create future dummy enhancements.

17. Key Words	18. Distribution Statement
THOR-50M, repeatability and reproducibility, R&R, test dummy	This document is available to the public from the DOT, BTS, National Transportation Library, Repository & Open Science Access Portal, rosap.ntl.bts.gov.

19 Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	302	

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1 Background

For several years, 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 the latest advanced 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 repeatability and reproducibility design objective by performing multiple qualification test series on three different THOR-50M dummies, and quantitatively assessing the repeatability and reproducibility of their responses. This assessment of repeatability and reproducibility is based on full body qualification tests on the head, face, thorax, and abdomen, as well as neck and leg component qualification tests, as specified in the *THOR 50th Percentile Male (THOR-50M) Qualification Procedures Manual* (NHTSA, 2018).

2 Objectives

Background. NHTSA has previously established qualification test procedures, described in the *THOR-50M Qualification Procedures Manual*. The rationale behind the procedures themselves (probe masses, velocities, other test conditions, and dummy measurements) and why they are appropriate for the THOR-50M are related to the biofidelity targets for the dummy and the means in which the dummy is used to assess trauma risk (through measurements of forces, accelerations, and displacements) (Parent et al., 2017). The rationale for all qualification test procedures and response requirements are discussed fully in a separate report (NHTSA, in progress).

Thus, the test procedures are highly related to the dummy's instrumentation. While not always feasible, an attempt was made to measure each instrument used in the calculation of injury criteria and to assess the performance at a severity level like that experienced during a vehicle crash test. The set of injury criteria considered to meet this objective are those used in the assessment of the THOR-50M response in the oblique moving deformable barrier test mode (Saunders et al., 2015).

Qualification targets and tolerances. In specifying qualification tests and acceptance criteria, NHTSA's goal is to assure that a "pass" is a true indicator of a dummy that is uniform in its design and performance. This goal is achieved by ensuring that the tests themselves are repeatable (the similarity of responses from a single dummy when subjected to multiple repeats of a given test condition) and reproducible (the similarity of test responses from multiple dummies when subjected to multiple repeats of a given test condition), and by setting limits (or tolerances) on the qualification targets to ensure that all future dummies are uniform. For the THOR-50M, the limits have been set at ±10 percent of a nominal target for each measurement – wide enough to account for normal variations in dummy and laboratory differences, and narrow enough to assure consistent and repeatable measurements in standardized testing with the dummy.

We also considered limits calculated from the mean response ± two standard deviations. If this practice was applied to the data collected here, it would have narrowed the window of acceptability for almost all responses. However, most of the THOR-50M components were new at the time of testing, and the allowance of ±10 percent thus accounts for slight variations that may arise from different dummy manufactures or lot-to-lot differences in the fabrication of parts from the same manufacturer. It also accounts for slight changes to individual THOR-50M units over time, either due to aging of polymeric components or wear and tear under normal use.

The limits of ±10 percent for the THOR-50M are in line with those for the other Part 572 ATDs. For instance, the Hybrid III 10-year-old child dummy (HIII-10C, Subpart T) limits are spaced ±9.9 percent from the nominal midpoint on average. The low is 8.4 percent (neck rotation in the neck extension test) and the high is 10.8 percent (seen in two qualifications: neck moment in the extension test and chest deflection in the thorax impact test). Limits of ±11 percent represent the average for all Part 572 dummies.

Purpose of this data collection exercise. This exercise sets out to perform tests at multiple labs using multiple THOR-50M units for the following purposes.

- Set the qualification target for each response.
- Assess the ability of a particular dummy or lab to attain the targets (within +/- 10 percent).
- Identify possible errors, discrepancies, and ambiguities in the qualification procedures.
- Reveal and resolve functional limitations of the dummy.

Sources of variability. In assessing the ability to attain the target responses, this study evaluates the sources of variability that could affect the outcome of the tests. By running multiple tests for each type of qualification test on three dummies at one lab and one of those three dummies at two different labs, we were able to identify and quantify factors contributing to the overall variability. Four basic components were examined: *Test Repeatability*, *Dummy Repeatability*, *Test Reproducibility*, and *Dummy Reproducibility*.

Test Repeatability. Test repeatability is a measure of the similarity of responses from the same test article (i.e., a single dummy with a high degree of dummy repeatability as defined below) at a single laboratory when subjected to multiple repeats of a given test condition. Good test repeatability indicates a high degree of uniformity in the way a given lab carries out their tests. Poor test repeatability usually indicates a problem exists with a test lab's internal test protocol or test equipment.

Dummy Repeatability. Dummy repeatability is a measure of how much the response of a given dummy changes during the course of testing. A dummy with a high degree of dummy repeatability exhibits little change. A change in response could be caused by a hardening or softening of polymeric components over time or the propagation of cracks and other defects that occur after repeated impacts. If this is detected, protocols for assessing damage should be followed. Repeatability could also be affected by users who do not adhere to the Procedures for Assembly and Disassembly, and Inspection (i.e., the PADI, which is incorporated by reference in Part 572). Dummies are routinely disassembled and re-assembled, and misaligned components or improper settings (such as the joint torques) could result in poor repeatability.

Test Reproducibility. Test reproducibility is a measure of how well a given test procedure can be duplicated at other labs. It is typically assessed using the same dummy to guard against variability among test articles that could confound the assessment. Good test reproducibility indicates test procedures are well defined. Poor reproducibility usually indicates lab-to-lab differences in the way a test is set up, in the equipment or instrumentation used, or in some other factor associated with the accuracy of measurements. Poor test reproducibility also indicates further specificity may be needed in written qualification test procedures.

Dummy Reproducibility. Dummy reproducibility is a measure of variability within the dummies themselves (three different dummies from the same manufacturer were tested). Dummy reproducibility is typically assessed using dummy units that have been shown to produce repeatable responses and using test procedures known to be repeatable and reproducible. If variability is identified from one dummy to another, they are examined more closely to discern any differences among them. Poor dummy reproducibility is usually caused by variability in the way dummy components are manufactured, including the selection of raw materials and the manufacturing processes.

Interpreting Repeatability and Reproducibility Assessments. At each test lab the primary objective was to conduct a series of trials in a highly repeatable manner. Once an initial test was run, the succeeding trials were carried out the same way without changing input parameters. In other words, even if the initial trial may have appeared to be too high or too low relative to a target response, no adjustment to the input parameters was made to succeeding trials. Thus, the repeatability assessments took priority because of the difficulties with assessing reproducibility without high repeatability.

Furthermore, the targets had not been set at the time the trials were run and PASS/FAIL thresholds had not been established. Since there was no target, there was never an attempt to adjust input parameters or replace parts as long as there was a high degree of repeatability.

Thus, the assessments of *Test Reproducibility* and *Dummy Reproducibility* should be viewed as conservative assessments. That is, the number of trials that would ultimately be considered FAILs is higher than what would be expected when the dummy is put into service. In practice, we would expect labs to take appropriate actions, as described here, if an initial trial produces a FAIL.

Also, our design of experiments did not provide a means to assess *Dummy Repeatability* and *Test Repeatability* separately. Thus, our quantitative assessment of repeatability is reported here as a combined measure of *Dummy/Test Repeatability*. However, in cases where the coefficient of variation (CV) for *Dummy/Test Repeatability* was high we investigated the root cause further (see Methods for definition of CV). There, we were usually able to deduce whether it was due to a test fixture problem (i.e., a *Test Repeatability* issue) or whether a part on the dummy became deformed, dislodged, or otherwise caused test-to-test variations (i.e., a *Dummy Repeatability* issue). Details of such investigations are provided here.

Qualification Targets. For each qualification requirement, a target response ±10 percent is specified (see Table 2-1). The target responses were determined from the exercise described here.

Table 2-1. THOR-50M Qualification Tests and Requirements

Test	Measurement	Units	Nominal Target	Acceptance Interval
1. Head Impact	Peak Probe Force	N	5580	5022 - 6138
	Peak Head CG Resultant Acceleration	G	117.0	105.3 – 128.7
2. Face Impact	Peak Probe Force	N	7098	6378 - 7796
	Peak Head CG Resultant Acceleration	G	138	124 - 152
3. Neck – Flexion	Peak Upper Neck My	N-m	31.0	27.9 – 34.1
	Upper Neck Fz Most Positive Value Prior to 40 ms	N	860	774 - 946
	Peak Head Angular Velocity ω_y (relative to earth)	deg/sec	1975	1777 - 2172
	Peak Head Rotation (relative to pendulum)	deg	64.5	58.1 – 71.0
4. Neck – Extension	Peak Upper Neck My	N-m	23.0	20.7 – 25.3
	Peak Upper Neck Fz	N	2918	2626 – 3210
	Peak Head Angular Velocity ω_y (relative to earth)	deg/sec	2061	1855 – 2267
	Peak Head Rotation (relative to pendulum)	deg	65.0	58.5 – 71.5
5. Neck – Lateral	Upper Neck Mx first peak After 40.0 ms	N-m	49.7	44.8 – 54.7
	First Peak Head Angular Velocity ω_x (relative to earth)	deg/sec	1362	1226 – 1498
	Peak Head Rotation (relative to pendulum)	deg	41.7	37.6 – 45.9
6. Neck – Torsion	Peak Upper Neck Mz	N-m	41.4	37.3 – 45.6
	First Peak Upper Neck Angular Velocity ω_z (relative to earth)	deg/sec	1390	1251 - 1529
	Peak Neck Fixture Rotation	deg	47.9	43.1 – 52.7
7. Upper thorax	Peak Probe Force	N	3039	0 – 3039
	Peak Upper Resultant Deflection	mm	53.6	48.3 – 59.0
	Difference Between Peak Left & Right Resultant Deflections	mm	0	-5 to 5
	Force at Peak Resultant Deflection	N	2677	2409 – 2944
8. Lower thorax	Peak Probe Force	N	3484	3136 – 3832
	Resultant Deflection at Peak Force	mm	50.9	45.8 – 56.0
9. Lower abdomen	Peak Probe Force	N	2918	2626 – 3210
	Lower Abdomen X-axis Deflection at Time of Peak Force	N	83.0	74.4 – 91.3
	Difference Between Peak Left & Right X-axis Deflections	mm	0	-8 to 8
10. Upper leg	Peak Probe Force	N	8333	7500 – 9166
	Peak Femur Force, Fz	N	4920	4428 – 5412
	Peak Resultant Acetabulum Force	N	2738	2464 – 3012
11. Knee	Peak Femur Z-axis Force	N	6506	5855 – 7156
	Knee Deflection at Peak Femur Force	mm	20.2	18.2 – 22.2
12. Ankle inversion	Peak Lower Tibia Fz	N	505	454 – 555
	Peak Ankle Resistive Moment	N-m	39.1	35.2 – 43.0
	Peak Ankle X-axis Rotation	deg	34.5	31.0 – 37.9
13. Ankle eversion	Peak Lower Tibia Fz	N	571	514 – 629
	Peak Ankle Resistive Moment	N-m	43.0	38.7 – 47.3
	Peak Ankle X-axis Rotation	deg	29.6	26.6 – 32.5
14. Ball of foot	Peak Lower Tibia Fz	N	3170	2853 – 3487
	Peak Ankle Resistive Moment	N-m	55.3	49.8 – 60.8
	Peak Ankle Y-axis Rotation (in dorsiflexion)	deg	33.8	30.4 – 37.2
15. Heel	Peak Lower Tibia Fz	N	3162	2846 - 3478

Note: For comparison purposes, unless otherwise noted, only positive values are shown for the Nominal Target and Acceptance Range. Some targets, such as Neck Flexion Angular Velocity (ω_y = -1362 deg/sec), are defined by negative values.

3 Methodology

The tests for each body region were performed according to the qualification test procedures described in the *THOR-50M Qualification Procedures Manual*. The THORs used in this study were manufactured by Humanetics, delivered in approximately 2014, and have been updated along the way to correct minor design issues (e.g., IR-TRACCs were pinned to prevent erroneous movement). As tested, these THORs meet the requirements of the *THOR-50M Drawing Package* (NHTSA, 2018). All test data in this report was collected in compliance with SAE J211 polarity specifications.

Unless mentioned otherwise in the subsequent sections, THOR S/Ns 9207, 9798, and 9799 were tested at NHTSA's Vehicle Research and Test Center (VRTC), and then 9799 was tested at Humanetics[1] and Calspan[2]; however, there are some exceptions such as the face, lower abdomen, and upper leg test modes, described in more detail in those sections. For neck tests, the necks utilized were new at the time of testing to ensure that they were straight and undamaged; as such, the neck serial numbers, rather than the ATD serial number, were used to describe the tests.

As previously stated, three dummies were subjected to repeat tests in each test condition at VRTC, and one of the three dummies was tested at two other labs, Humanetics and Calspan. The upper leg test procedures were revised after these labs originally tested the dummies; therefore, in addition to VRTC, TRC Inc.[3] and Karco[4] provided the data for test reproducibility for the upper leg. The data acquired from these tests was used to assess repeatability and reproducibility; this data was also used to generate the qualification targets for each response requirement.

Results were assessed using the following criteria for the CV, where CV is defined as the percentage of the standard deviation divided by the mean of the data set:

Below 5 percent: No further investigation needed

Between 5 percent and 10 percent: Sources of variability investigated; outliers may exist

Greater than 10 percent: Test procedure thoroughly reviewed, and dummies inspected.

A set of responses with a CV below 5 percent indicates a highly repeatable and reproducible condition. In this study, the responses in all tests with a CV below 5 percent were also within ±10 percent of the target response, and no further examination of the data or test condition was carried out.

When a test condition produced a CV above 5 percent, a response in at least one test was outside the ±10 percent limits, and when the CV exceeded 10 percent, several tests were outside the limits. In these instances, a close examination of the data and procedure was performed to pinpoint the source of the variability. We provided an explanation (where possible) for the likely source of the variation.

[1] Humanetics Innovative Solutions, 23300 Haggerty Rd., Farmington Hills, MI 48335
[2] Calspan, 4455 Genesee Street, Buffalo, NY 14225
[3] Transportation Research Center Inc., 10820 OH-347, East Liberty, OH 43319
[4] KARCO Engineering, LLC, Automotive Research Center, 9270 Holly Road, Adelanto, CA 92301

Only data collected through this analysis were used to compute the target responses. Although only a limited number of units and test laboratories were included in this analysis, and data from other laboratories and dummies may exist, exclusively using the data from this report to compute the target responses ensures integrity of the process. By limiting the analysis to our own data, we were better able to control test variables that could confound our ability to assess the uniformity of the dummy. These test variables include the configuration of the dummy (older versions, or otherwise modified versions of the 2018 NHTSA version) and other variations associated with lab-to-lab test equipment and procedures.

At the end of each section under the heading of "Corridor Development," a table of all tests provides a glimpse at how well particular dummies or labs were able to achieve a uniform response. The table highlights any test that was outside the ±10 percent limits, and a discussion is provided on the circumstances associated with the non-conforming tests.

The CV and standard deviation for all tests combined are also listed in the table. The CV may be interpreted as the basis for considering alternate qualification limits set at ± 2*CV in lieu of ±10 percent. Thus, when CVs are below 5 percent it may be feasible to narrow them. However, doing so would assume that data from other labs and other dummies are consistent with the data reported here. Likewise, when CVs are above 5 percent, widening the limits beyond ±10 percent may be considered. But doing so would ignore any reductions in CVs that could be attained by improving repeatability and reproducibility as discussed at the end of each section.

4 Head

4.1 Methodology

Repeatability and reproducibility tests were performed using the head qualification procedures described in the *THOR-50M Qualification Procedures Manual*. 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 4-1). During these tests, the probe force and the head center of gravity (CG) resultant acceleration were measured.

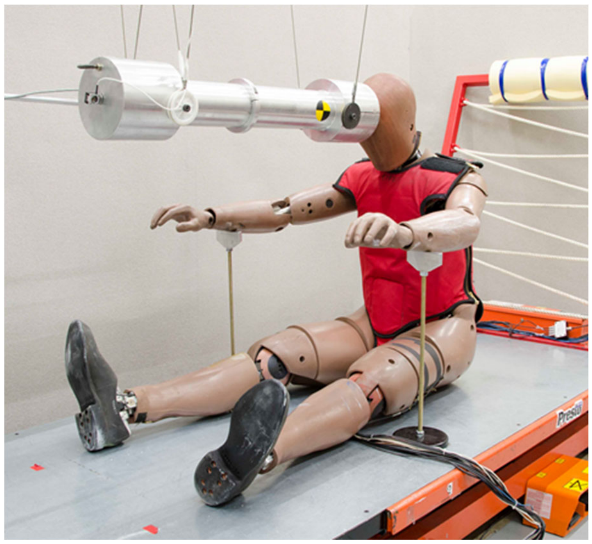

Figure 4-1. Head impact test setup

4.2 Head Impact Repeatability Results

Sections 4.2.1 to 4.2.5 illustrate the results of the head impact repeatability tests. Each section contains a table providing the test data, followed by plot overlays of the five repeat tests conducted at all three labs. Note that the data in the tables containing the results of each test series are listed sequentially, with the test at the top of the table beginning the test series.

4.2.1 THOR-50M DL9207 Testing at VRTC

Repeatability results at VRTC for DL9207 displayed CV values below 5 percent (Table 4-1, Figure 4-2, and Figure 4-3).

Table 4-1. VRTC THOR-50M DL9207 Head Impact Repeatability Results

Test Number	Peak Probe Force (N)	Peak Head CG Resultant Acceleration (G)
082814_01	5578	113.2
082814_02	5557	118.0
082814_03	5570	116.4
082814_04	5602	114.9
082814_05	5580	114.3
Mean	**5578**	**115.4**
Std. Dev.	**16**	**1.9**
CV	**0.3%**	**1.6%**

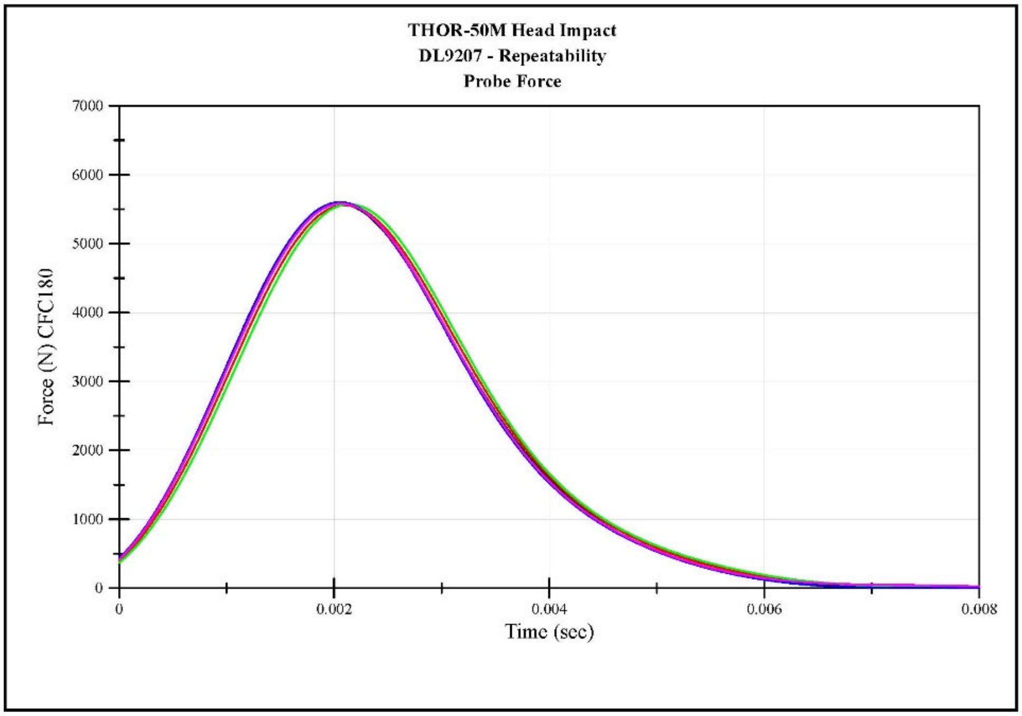

Figure 4-2. VRTC head impact probe force repeatability for DL9207

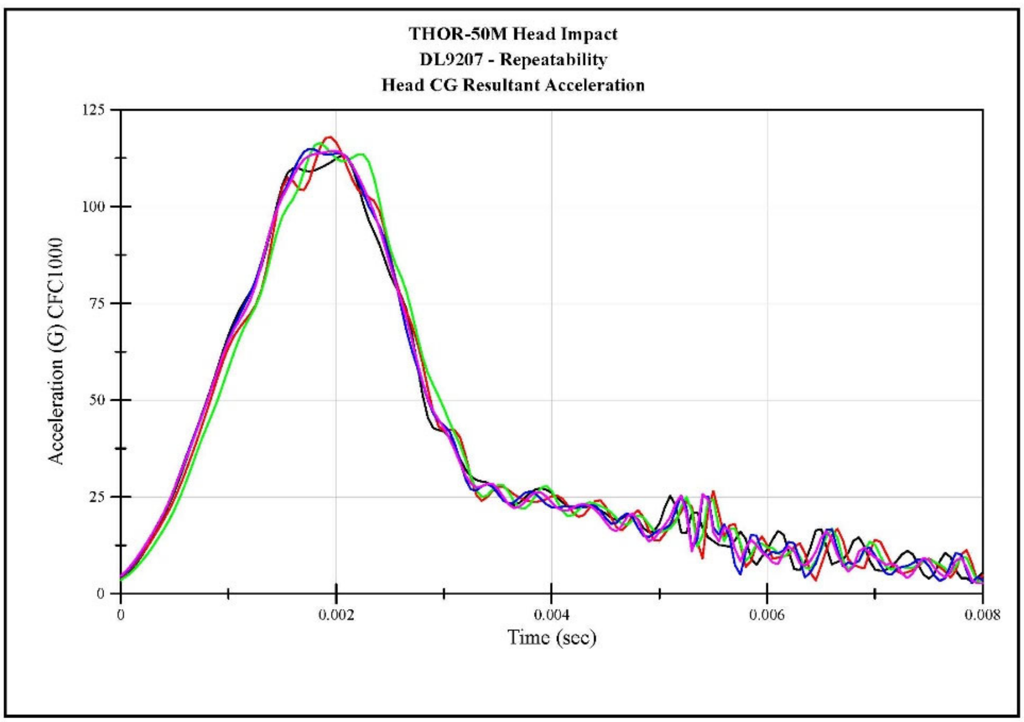

Figure 4-3. VRTC head impact head resultant CG acceleration repeatability for DL9207

4.2.2 THOR-50M DL9798 Testing at VRTC

Repeatability results at VRTC for DO9798 displayed CV values below 5 percent (Table 4-2, Figure 4-4, and Figure 4-5).

Table 4-2. VRTC THOR-50M DO9798 Head Impact Repeatability Results

Test Number	Peak Probe Force (N)	Peak Head CG Resultant Acceleration (G)
082714_01	5586	116.7
082714_02	5605	116.9
082714_03	5525	116.3
082714_04	5553	116.5
082714_05	5522	115.2
Mean	**5558**	**116.3**
Std. Dev.	**37**	**0.7**
CV	**0.7%**	**0.6%**

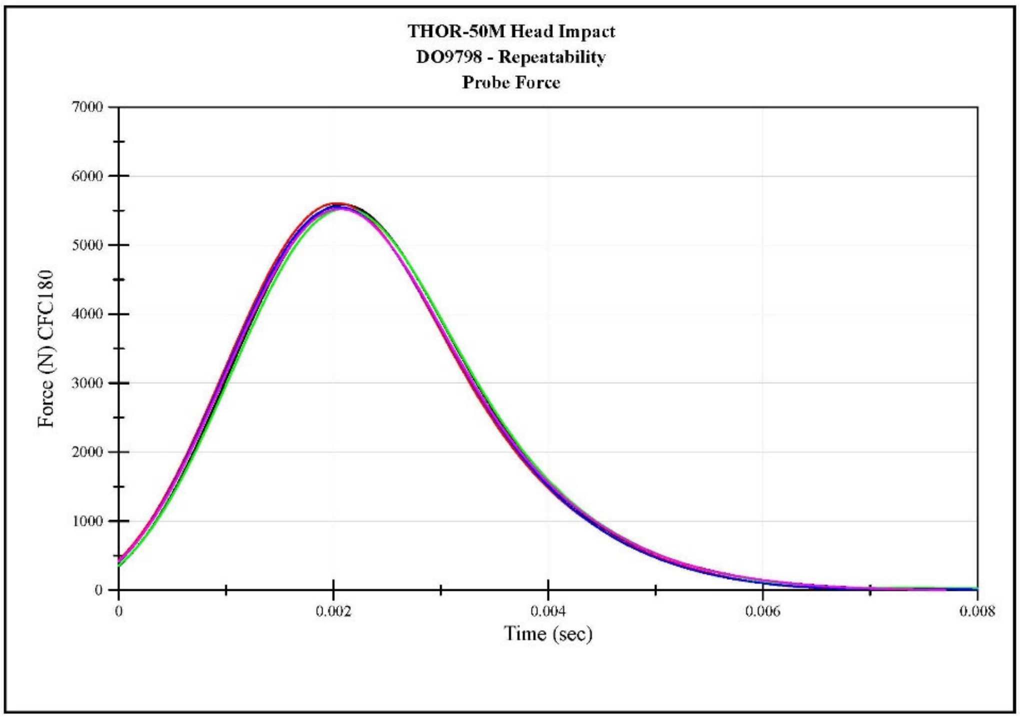

Figure 4-4. VRTC head impact probe force repeatability for DO9798

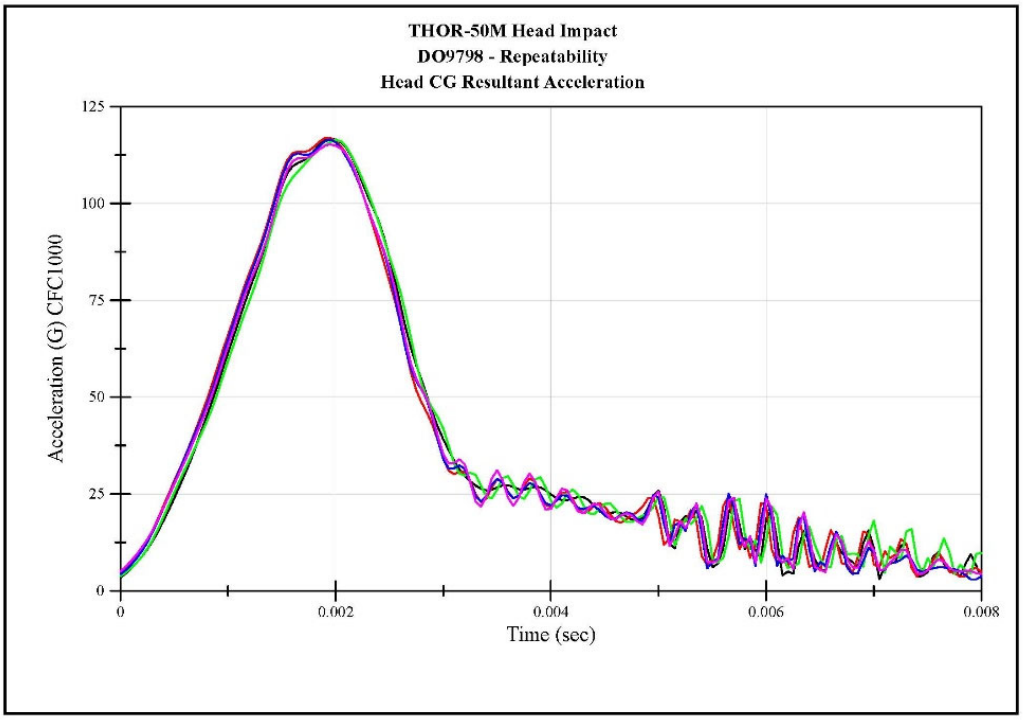

Figure 4-5. VRTC head impact head resultant CG acceleration repeatability for DO9798

4.2.3 THOR-50M DO9799 Testing at VRTC

Repeatability results at VRTC for DO9799 displayed CV values below 5 percent (Table 4-3, Figure 4-6, and Figure 4-7).

Table 4-3. VRTC THOR-50M DO9799 Head Impact Repeatability Results

Test Number	Peak Probe Force (N)	Peak Head CG Resultant Acceleration (G)
082714_01_9799	5520	111.8
082714_02_9799	5614	117.3
082714_03_9799	5601	115.1
082714_04_9799	5567	115.1
082714_05_9799	5584	114.9
Mean	**5577**	**114.8**
Std. Dev.	**36**	**1.9**
CV	**0.7%**	**1.7%**

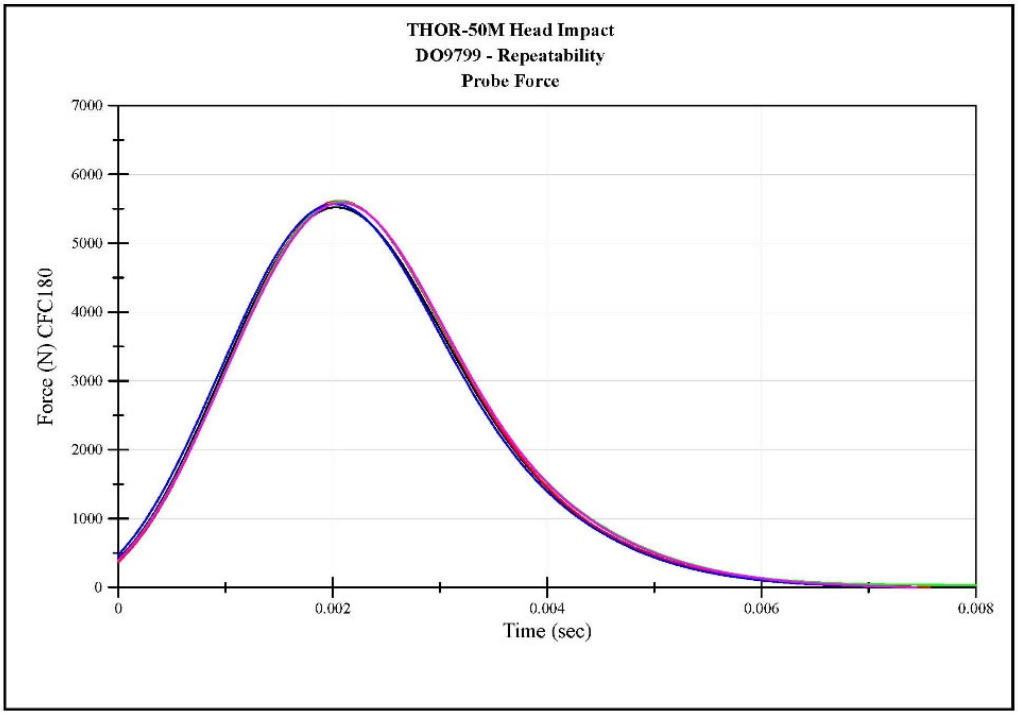

Figure 4-6. VRTC head impact probe force repeatability for DO9799

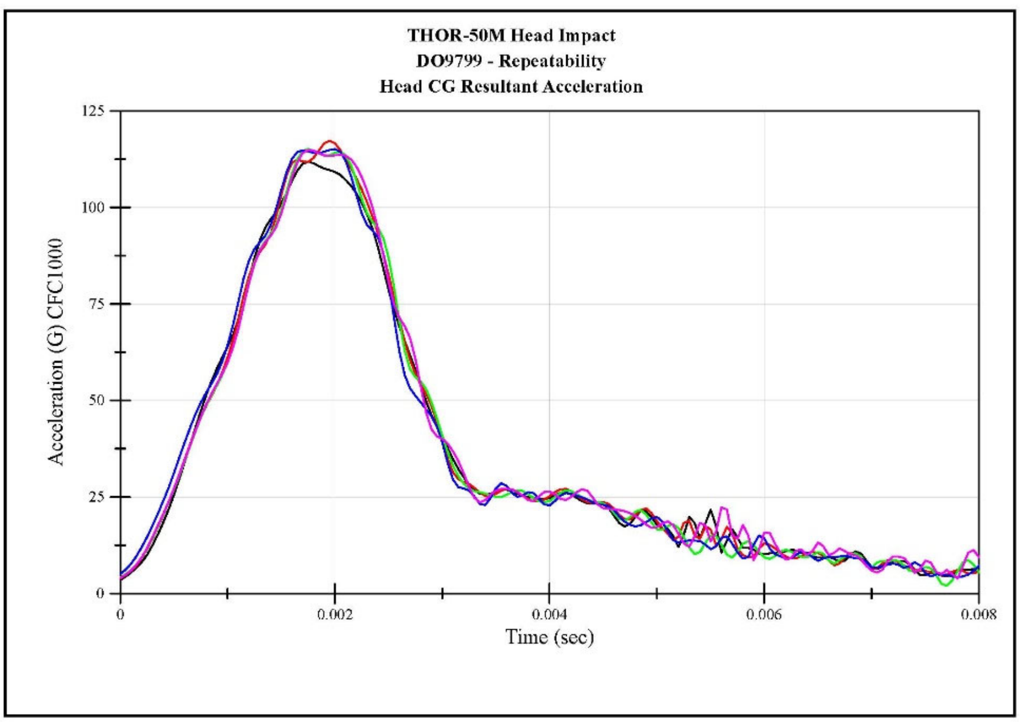

Figure 4-7. VRTC head impact head resultant CG acceleration repeatability for DO9799

4.2.4 THOR-50M DO9799 Testing at Humanetics

Repeatability results at Humanetics for DO9799 displayed CV values below 5 percent (Table 4-4, Figure 4-8, and Figure 4-9).

Table 4-4. Humanetics THOR-50M DO9799 Head Impact Repeatability Results

Test Number	Peak Probe Force (N)	Peak Head CG Resultant Acceleration (G)
249	5569	118.2
251	5595	118.4
253	5572	118.8
255	5529	117.4
256	5544	118.6
258	5534	131.3
Mean	**5557**	**120.5**
Std. Dev.	**26**	**5.3**
CV	**0.5%**	**4.4%**

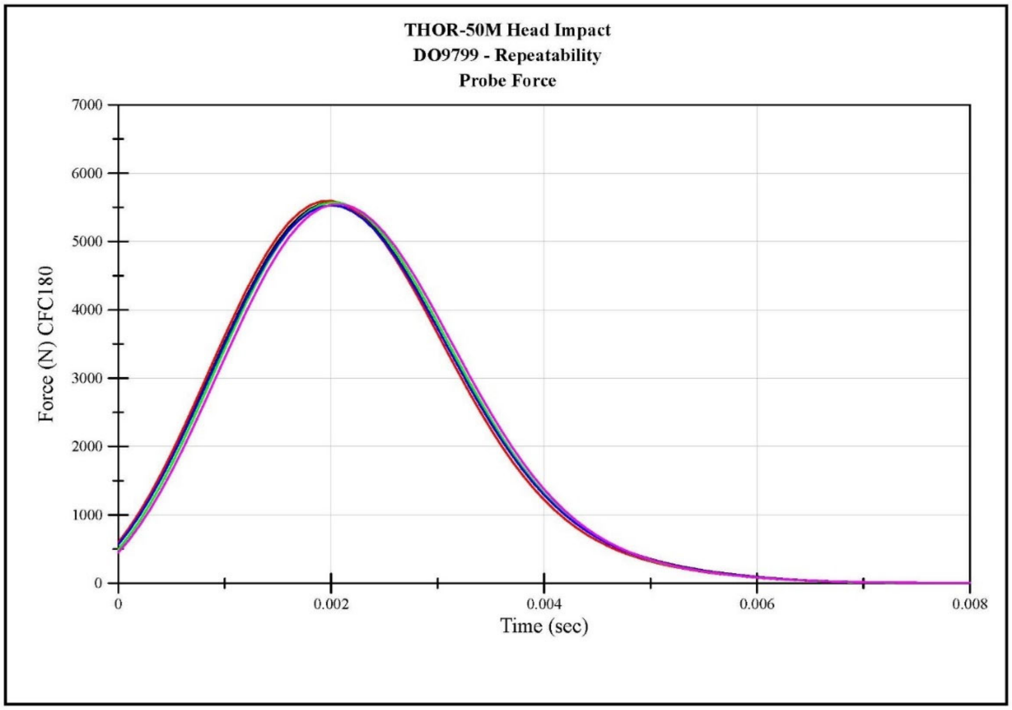

Figure 4-8. Humanetics head impact probe force repeatability for DO9799

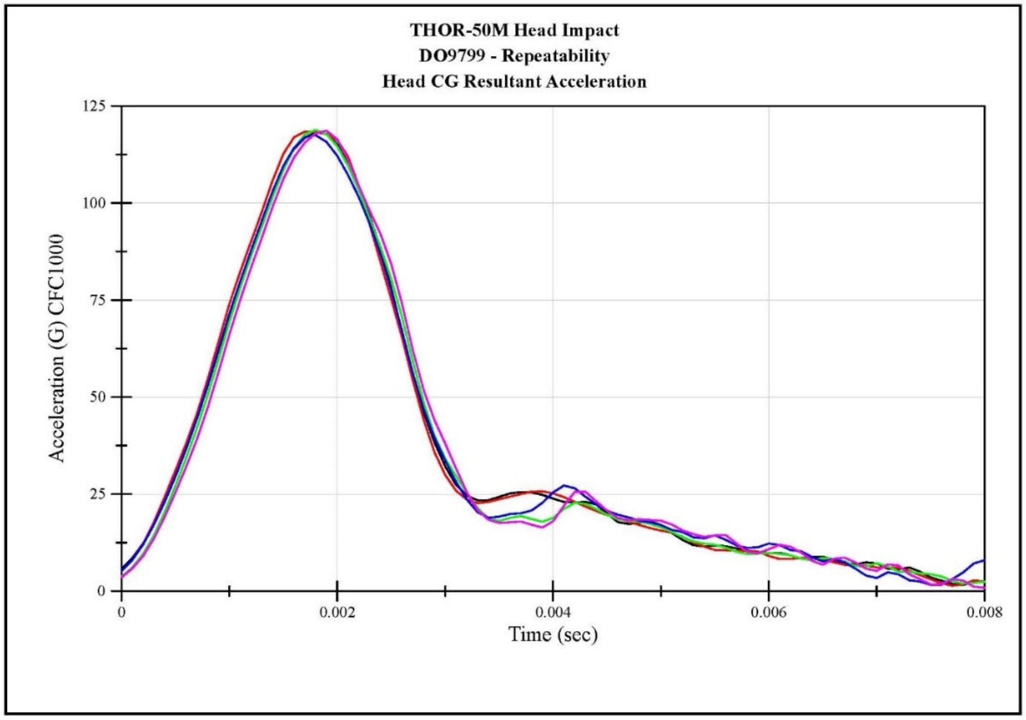

Figure 4-9. Humanetics head impact head resultant CG acceleration repeatability for DO9799

4.2.5 THOR-50M DO9799 Testing at Calspan

Repeatability results at Calspan for DO9799 displayed CV values below 5 percent (Table 4-5, Figure 4-10, and Figure 4-11).

Table 4-5. Calspan THOR-50M DO9799 Head Impact Repeatability Results

Test Number	Peak Probe Force (N)	Peak Head CG Resultant Acceleration (G)
20160629100136	5711	121.6
20160629112922	5700	117.5
20160629123310	5618	117.8
20160629133449	5522	112.4
20160629143613	5618	116.8
Mean	**5634**	**117.2**
Std. Dev.	**77**	**3.3**
CV	**1.4%**	**2.8%**

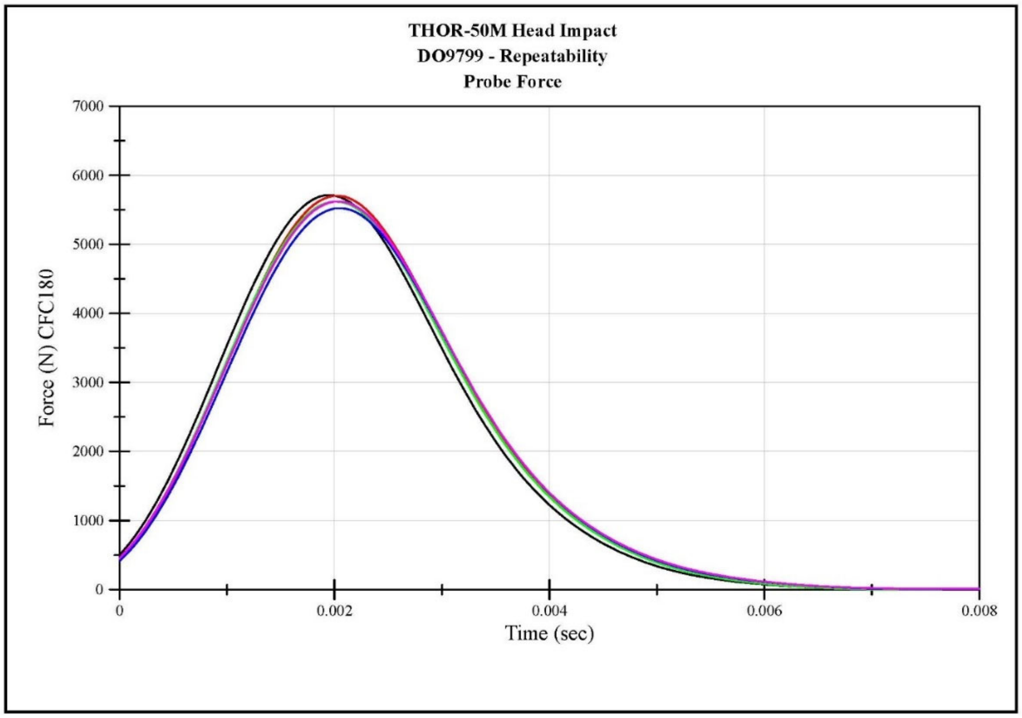

Figure 4-10. Calspan head impact probe force repeatability for DO9799

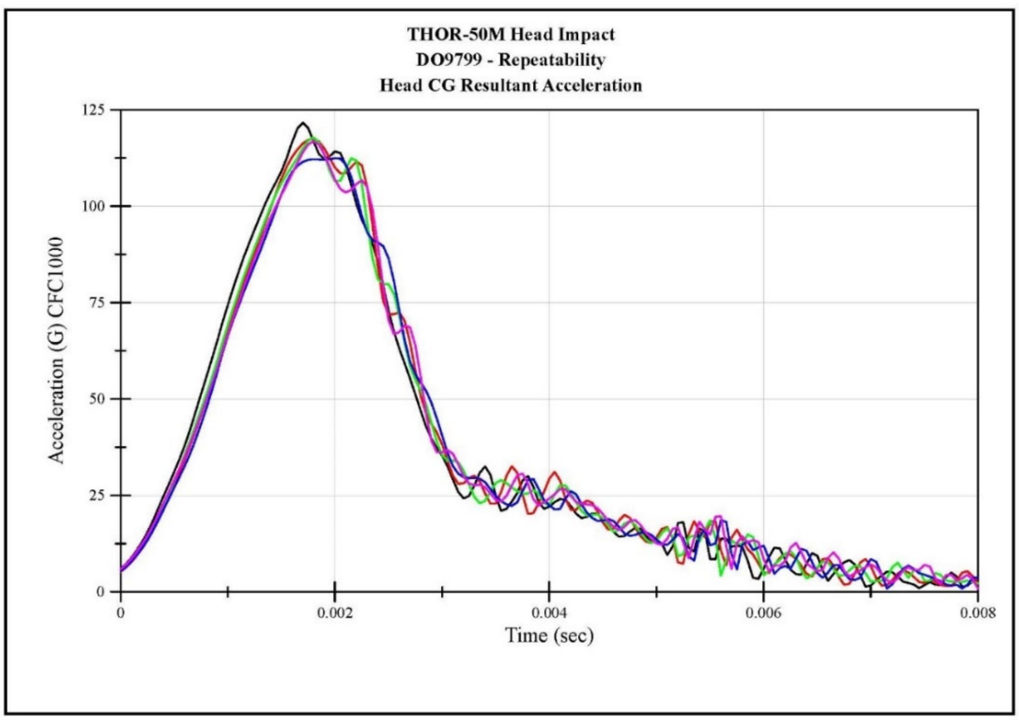

Figure 4-11. Calspan head impact head resultant CG acceleration repeatability for DO9799

4.3 THOR-50M Head Impact Dummy Reproducibility Results at VRTC

Dummy Reproducibility results at VRTC for the head impact qualification tests yielded CV values all below 5 percent (Table 4-6).

Table 4-6. THOR-50M Head Impact Dummy Reproducibility Results

Dummy	Test Number	Peak Probe Force (N)	Peak Head CG Resultant Acceleration (G)
VRTC DL9207	**082814_01**	5578	113.2
	082814_02	5557	118.0
	082814_03	5570	116.4
	082814_04	5602	114.9
	082814_05	5580	114.3
VRTC DO9798	**082714_01**	5586	116.7
	082714_02	5605	116.9
	082714_03	5525	116.3
	082714_04	5553	116.5
	082714_05	5522	115.2
VRTC DO9799	**082714_01**	5520	111.8
	082714_02	5614	117.3
	082714_03	5601	115.1
	082714_04	5567	115.1
	082714_05	5584	114.9
Mean		**5571**	**115.5**
Std. Dev.		**30**	**1.6**
CV		**0.5%**	**1.4%**

4.4 Lab-to-Lab Variability Analysis

The results of the head qualification tests from each lab are presented in Table 4-7. The repeatability within each lab is indicated by CV values below 5 percent. The last four rows of the table show the *Test Reproducibility* results when data from all three labs are combined.

Table 4-7. THOR-50M Head Impact Lab-to-Lab Variability Results

Dummy	Peak Probe Force (N)	Peak Head CG Resultant Acceleration (G)
VRTC DO9799	5520	111.8
	5614	117.3
	5601	115.1
	5567	115.1
	5584	114.9
Humanetics DO9799	5569	118.2
	5595	118.4
	5572	118.8
	5529	117.4
	5544	118.6
	5534	131.3
Calspan DO9799	5711	121.6
	5700	117.5
	5618	117.8
	5522	112.4
	5618	116.8
Test Reproducibility DO9799 ALL Labs		
Mean	**5587**	**117.7**
Std. Dev.	**57**	**4.4**
CV	**1.0%**	**3.7%**

4.5 Corridor Development

All the data used to determine the head qualification corridors is shown in Table 4-8. The qualification corridors were calculated using the mean plus or minus 10 percent of the peak for the specified measured or calculated channels (Table 4-9).

Table 4-8. THOR-50M Head Impact Qualification Corridor Results

Dummy	Test Number	Peak Probe Force (N)	Peak Head CG Resultant Acceleration (G)
VRTC DL9207	**082814_01**	5578	113.2
	082814_02	5557	118.0
	082814_03	5570	116.4
	082814_04	5602	114.9
	082814_05	5580	114.3
VRTC DO9798	**082714_01**	5586	116.7
	082714_02	5605	116.9
	082714_03	5525	116.3
	082714_04	5553	116.5
	082714_05	5522	115.2
VRTC DO9799	**082714_01**	5520	111.8
	082714_02	5614	117.3
	082714_03	5601	115.1
	082714_04	5567	115.1
	082714_05	5584	114.9
Humanetics DO9799	**249**	5569	118.2
	251	5595	118.4
	253	5572	118.8
	255	5529	117.4
	256	5544	118.6
	258	5534	131.3
Calspan DO9799	**20160629100136**	5711	121.6
	20160629112922	5700	117.5
	20160629123310	5618	117.8
	20160629133449	5522	112.4
	20160629143613	5618	116.8
Mean		**5580**	**117.0**
Std. Dev.		**48**	**3.6**
CV		**0.9%**	**3.1%**

Table 4-9. Head Impact Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Impact Velocity	**m/s**	1.95	2.05	2.00	
Peak Probe Force	**N**	5022	6138	5580	10%
Peak Head CG Resultant Acceleration	**g**	105.3	128.7	117.0	10%

Discussion. There were no instances in which a test did not achieve the target response ± 10%. All CVs were below 5 percent. There are no indications that there are problems with repeatability or reproducibility for this test condition.

5 Face

5.1 Methodology

Repeatability and reproducibility tests were performed using the face impact qualification procedures described in the *THOR-50M Qualification Procedures Manual*. The face rigid disk qualification test examines facial impact response to loading by a rigid 152.7 mm diameter circular disk face of the 13.00 kg impactor at a velocity of 6.73 ± 0.05 m/s (Figure 5-1).

The face rigid disk qualification test follows the same procedure as the face rigid disk biofidelity test; for the biofidelity test, the peak probe force range is 4400N to 8200N; there are no biofidelity requirements for the head CG resultant acceleration. For this test series, face impact tests were conducted on new, unused, face foams. The face foam is constructed of Confor foam, which is a memory foam that necessitates an extensive recovery period after dynamic impact. As specified in the *THOR-50M Qualification Procedures Manual*, at least 24 hours of recovery was allowed between tests; this was an extended recovery period due to the "memory" nature of the face foam. However, there was no additional conditioning performed on the face foams between tests. As the response changes with subsequent tests, the series was complete once the peak probe force exceeded the upper biofidelity limit of 8200 N; only those tests which fell within the peak probe force biofidelity range were then included in the test matrix results. This testing was performed using the same dummy, including head and face skin; since the force and acceleration of the face test increases with each subsequent test, any dummy response variations would be masked by the significant variations caused by the foam. Furthermore, the responses were limited to fit between the biofidelity limits, effectively forcing the qualification corridors to be a subset of the biofidelity limits. For these reasons, using a different dummy to evaluate each foam wasn't necessary. Therefore, THOR-50M serial number DO9799 was used with three different face foams installed. During these tests, the probe force and the head CG resultant acceleration were measured.

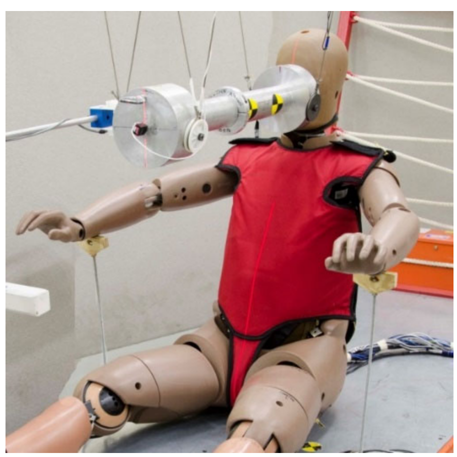

Figure 5-1. Face impact test setup

5.2 Face Impact Repeatability Results

Sections 5.2.1 to 5.2.4 illustrate the results of the face impact repeatability tests. Each section contains a table providing the test data, followed by plot overlays of tests performed at VRTC conducted on THOR-50M DO9799 with each face foam. Note that the data in the tables containing the results of each test series are listed sequentially, with the test at the top of the table beginning the test series.

5.2.1 THOR-50M DO9799, Foam #010, Testing at VRTC

Repeatability results at VRTC for Face Foam #010 revealed that the CV values for peak probe force and head CG resultant acceleration are above 5 percent but less than 10 percent (Table 5-1, Figure 5-2, and Figure 5-3). Nine tests were conducted before the face foam exceeded the 8200N upper biofidelity limit for peak probe force. As shown in Table 5-1, for the most part, progressive increases in both peak probe force and head CG resultant acceleration were evident with each successive test as the test matrix proceeded.

Table 5-1. VRTC THOR-50M DO9799 With Face Foam #010 Face Impact Repeatability Results

Test Number	Peak Probe Force (N)	Peak Head CG Resultant Acceleration (G)
161102-4	6495	124
161107-1	6277	125
161108-2	6619	128
161109-1	7065	136
161110-1	6908	131
161114-3	7463	144
161115-8	7743	153
161117-2	7884	153
161121-1	7832	155
Mean	**7143**	**138.9**
Std. Dev.	**612**	**12.6**
CV	**8.6%**	**9.1%**

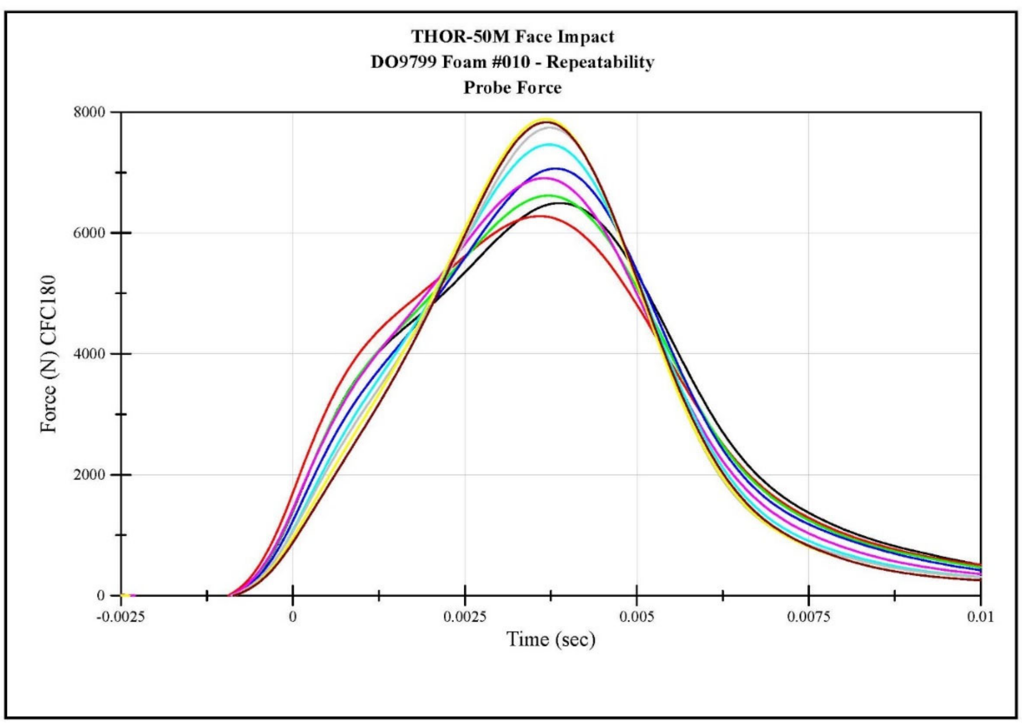

Figure 5-2. VRTC face impact probe force repeatability for THOR DO9799 with Face Foam #010

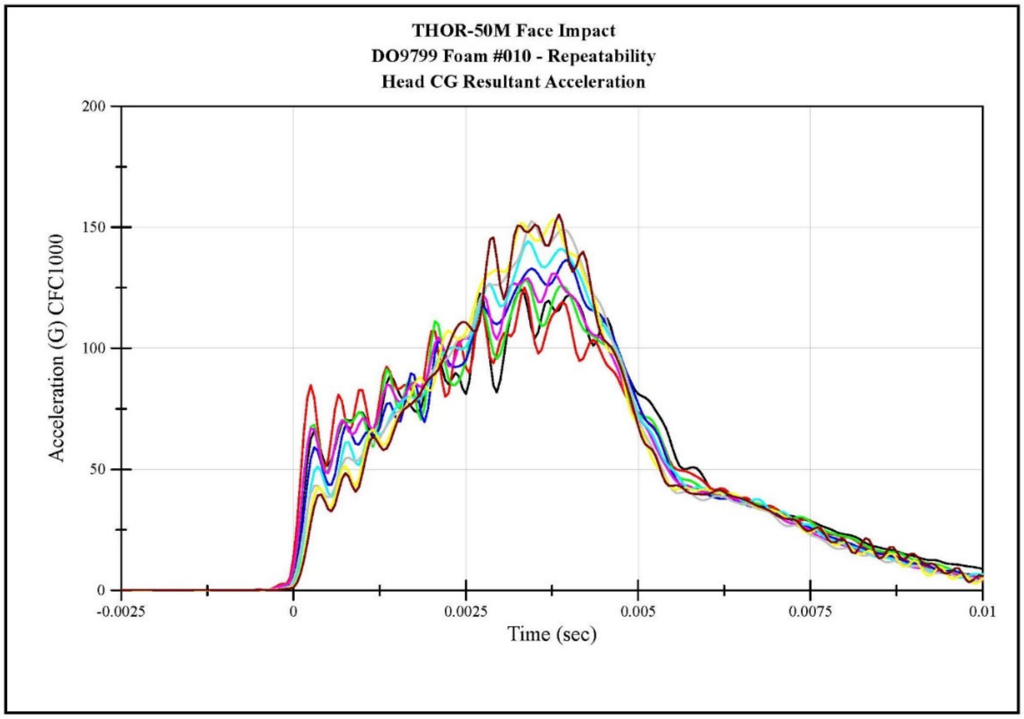

Figure 5-3. VRTC face impact head CG resultant acceleration repeatability for THOR DO9799 with Face Foam #010

5.2.2 THOR-50M DO9799, Foam #011, Testing at VRTC

Repeatability results at VRTC for Face Foam #011 revealed that the CV values for peak probe force and head CG resultant acceleration are above 10 percent (Table 5-2, Figure 5-4, and Figure 5-5). Eight tests were conducted before the face foam exceeded the 8200N upper biofidelity limit for peak probe force. For the most part, progressive increases in both peak probe force and head CG resultant acceleration were evident with each successive test as the test matrix proceeded.

Table 5-2. VRTC THOR-50M DO9799 With Face Foam #011 Face Impact Repeatability Results

Test Number	Peak Probe Force (N)	Peak Head CG Resultant Acceleration (G)
161102-5	6750	127
161107-2	6094	113
161108-3	6564	126
161109-2	6744	130
161110-2	6529	126
161114-4	7149	138
161115-9	8037	158
161117-3	8017	159
Mean	**6986**	**134.5**
Std. Dev.	**706**	**16.2**
CV	**10.1%**	**12.1%**

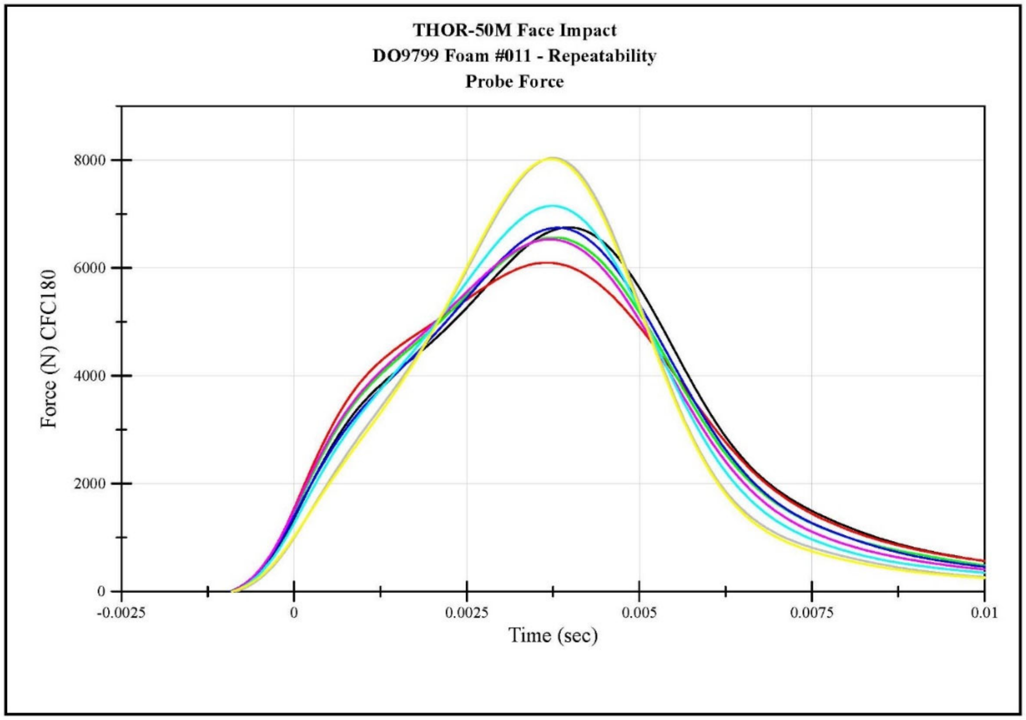

Figure 5-4. VRTC face impact probe force repeatability for THOR DO9799 with Face Foam #011

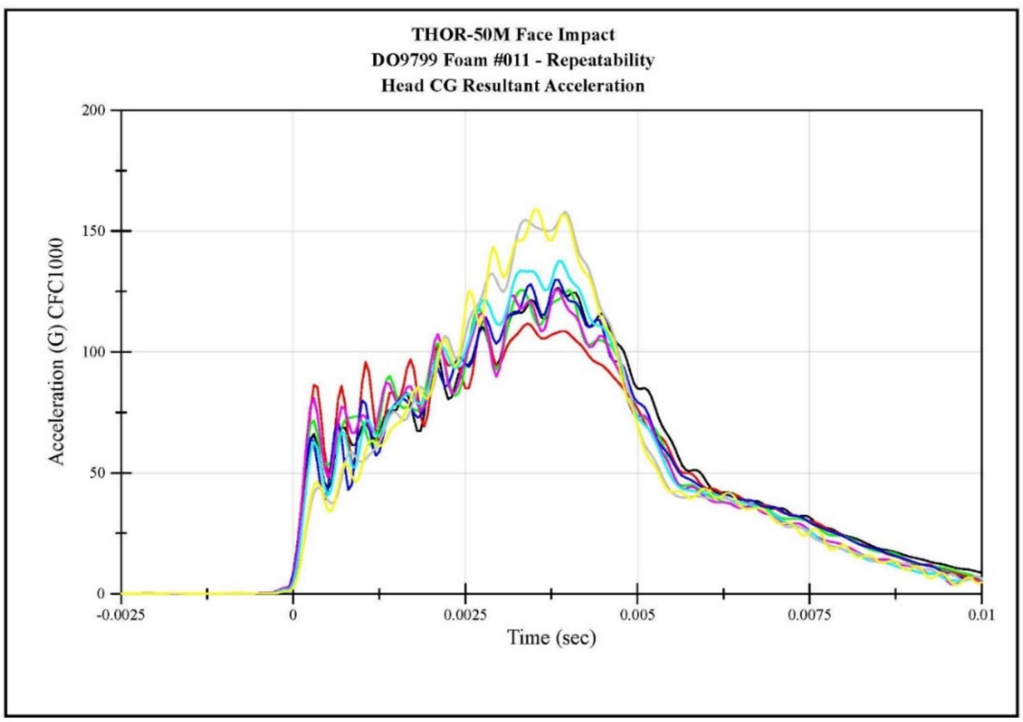

Figure 5-5. VRTC face impact head CG resultant acceleration repeatability for THOR DO9799 with Face Foam #011

5.2.3 THOR-50M DO9799, Foam #012, Testing at VRTC

Repeatability results at VRTC for Face Foam #012 revealed that CV values for peak probe force and head CG resultant acceleration are above 5 percent but less than 10 percent (Table 5-3, Figure 5-6, and Figure 5-7). As shown in Table 5-3, nine tests were conducted before the face foam exceeded the 8200N upper biofidelity limit for peak probe force. For the most part, progressive increases in both peak probe force and head CG resultant acceleration were evident with each successive test as the test matrix proceeded.

Table 5-3. VRTC THOR-50M DO9799 With Face Foam #012 Face Impact Repeatability Results

Test Number	Peak Probe Force (N)	Peak Head CG Resultant Acceleration (G)
161102-6	6801	132
161107-3	6249	125
161108-4	6693	128
161109-3	7105	138
161110-3	6874	135
161114-5	7260	143
161116-1	7546	148
161117-4	8012	156
161121-3	7552	151
Mean	**7121**	**139.7**
Std. Dev.	**534**	**10.6**
CV	**7.5%**	**7.6%**

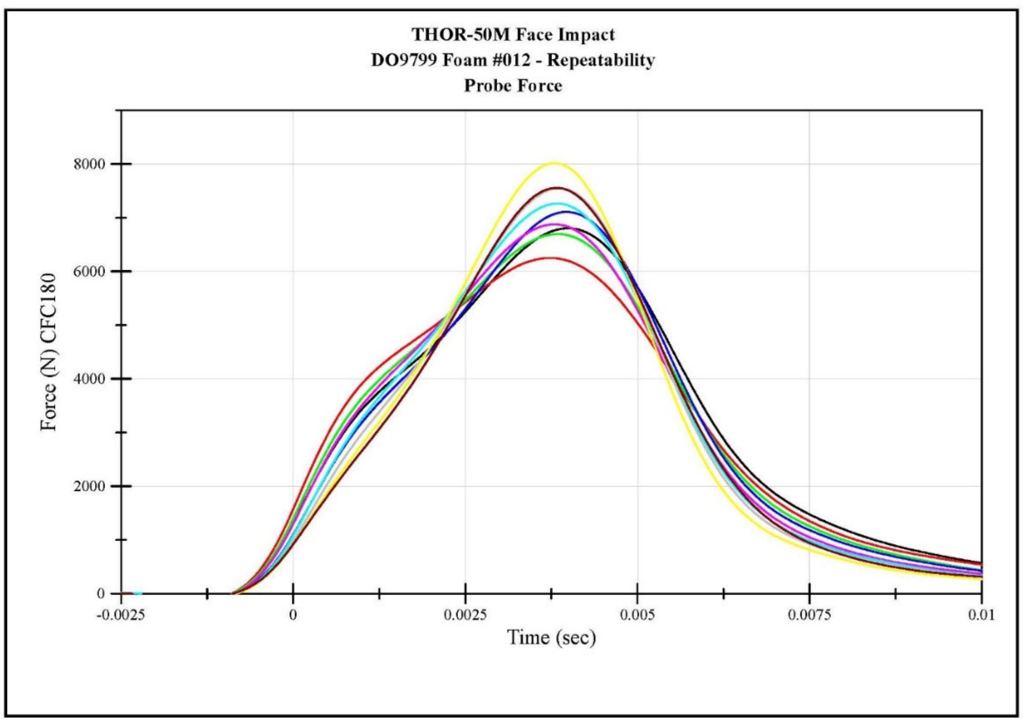

Figure 5-6. VRTC face impact probe force repeatability for THOR DO9799 with Face Foam #012

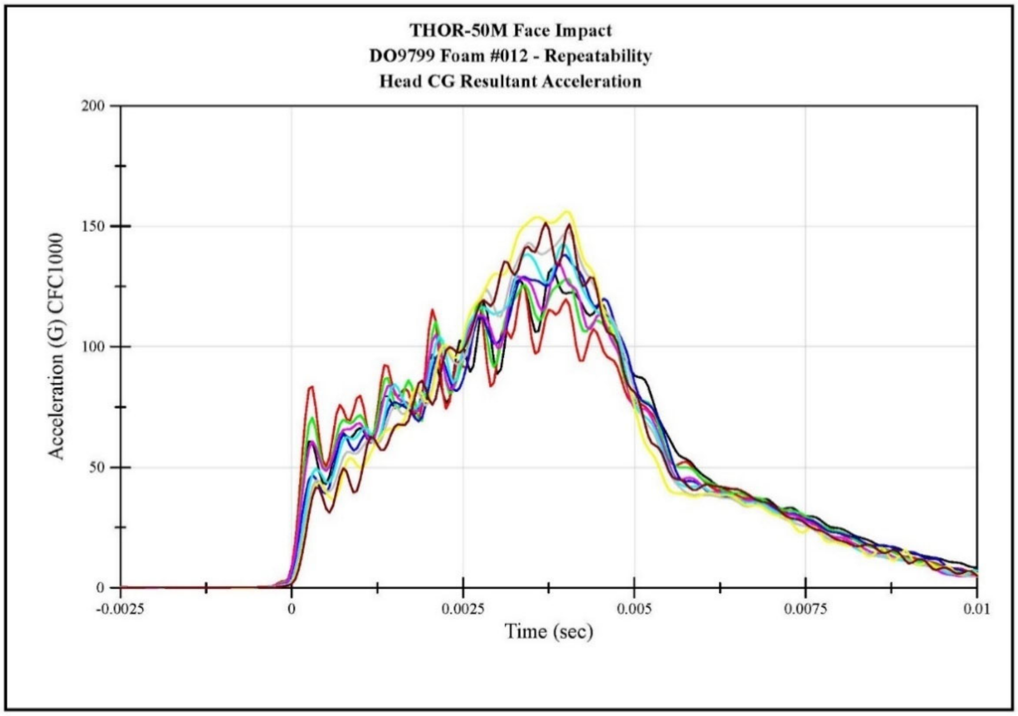

Figure 5-7. VRTC face impact head CG resultant acceleration repeatability for THOR DO9799 with Face Foam #012

5.2.4 Humanetics and Calspan Face Repeatability

Since results from the VRTC tests revealed that the foam progressively degrades without full recovery after multiple impacts, the face impact qualification tests on the same foams were not performed at other labs; therefore, no results were assessed for the face foam at Humanetics or Calspan.

5.3 THOR-50M Face Impact Dummy Reproducibility Results

Dummy Reproducibility results at VRTC for the face impact qualification tests revealed that the CV values for peak probe force and head CG resultant acceleration are above 5 percent, but less than 10 percent (Table 5-4). The dummy reproducibility performed at VRTC was conducted on THOR-50M DO9799 with each face foam.

Table 5-4. THOR-50M Face Impact Dummy Reproducibility Results

Dummy	Test Number	Peak Probe Force (N)	Peak Head CG Resultant Acceleration (G)
VRTC DO9799 Face Foam #010	**161102-4**	6495	124
	161107-1	6277	125
	161108-2	6619	128
	161109-1	7065	136
	161110-1	6908	131
	161114-3	7463	144
	161115-8	7743	153
	161117-2	7884	153
	161121-1	7832	155
VRTC DO9799 Face Foam #011	**161102-5**	6750	127
	161107-2	6094	113
	161108-3	6564	126
	161109-2	6744	130
	161110-2	6529	126
	161114-4	7149	138
	161115-9	8037	158
	161117-3	8017	159
VRTC DO9799 Face Foam #012	**161102-6**	6801	132
	161107-3	6249	125
	161108-4	6693	128
	161109-3	7105	138
	161110-3	6874	135
	161114-5	7260	143
	161116-1	7546	148
	161117-4	8012	156
	161121-3	7552	151
Mean		**7087**	**138**
Std. Dev.		**596**	**13**
CV		**8.4%**	**9.3%**

5.4 Lab-to-Lab Variability Analysis

As mentioned in Section 5.4, the foam progressively degrades without full recovery after multiple impacts; as such, the face impact qualification tests on the same foams were not performed at other labs so *Test Reproducibility* was not assessed.

5.5 Corridor Development

Only data from the tests performed at VRTC (Section 5.2) were used to develop the qualification test corridors. All the data used to determine the face qualification corridors are shown in Table 5-5. The qualification corridors were calculated using the mean plus or minus 10 percent of the peak for the specified measured or calculated channels (Table 5-6).

Table 5-5. THOR-50M Face Impact Qualification Corridor Results

Dummy	Test Number	Peak Probe Force (N)	Peak Head CG Resultant Acceleration (G)
DO9799 Face Foam #010	**161102-4**	6495	124
	161107-1	6277	125
	161108-2	6619	128
	161109-1	7065	136
	161110-1	6908	131
	161114-3	7463	144
	161115-8	7743	153
	161117-2	7884	153
	161121-1	7832	155
DO9799 Face Foam #011 (Cont.)	**161102-5**	6750	127
	161107-2	6094	113
	161108-3	6564	126
	161109-2	6744	130
	161110-2	6529	126
	161114-4	7149	138
	161115-9	8037	158
	161117-3	8017	159
DO9799 Face Foam #012	**161102-6**	6801	132
	161107-3	6249	125
	161108-4	6693	128
	161109-3	7105	138
	161110-3	6874	135
	161114-5	7260	143
	161116-1	7546	148
	161117-4	8012	156
	161121-3	7552	151
Mean		**7087**	**138**
Std. Dev.		**596**	**13**
CV		**8.4%**	**9.3%**

Table 5-6. Face Impact Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Impact Velocity	**m/s**	6.68	6.78	6.73	
Peak Probe Force	**N**	6378	7796	7087	10%
Peak Head CG Resultant Acceleration	**g**	124	152	138	10%

Discussion. The *Dummy Repeatability* assessment reveals that the response of the face foam changes from one impact to the next, which drove the CV above 5 percent. This condition was observed for all three foams. Because of this, the CV for *Dummy Reproducibility* also exceeded 5 percent.

Table 5-5 shows all trials. As seen in the table, the force and acceleration show fairly gradual and predictable increases from one test to the next, which indicates that the same foam may be used for multiple applications of the dummy.

Instances in which the target response ± 10 percent was not met are marked by yellow cells. The failures always occurred early in the test series (too low) or the in the later tests (too high). When a new foam is installed, the peak probe force for the second test in a series is lower than the first test. This is a characteristic of many ATD foam components. The first impact to the foam causes initial breakdown of the foam cells, so the first test often appears much different from subsequent tests in the series. Thereafter, foam characteristics become more predictable from test-to-test.

In the field, qualification tests are typically performed on a regular basis to identify worn or damaged parts. These include foam parts as well as vinyl parts that may shrink over time and molded rubber parts that may tear or stiffen. This practice applies to all ATDs.

For the THOR-50M in particular, end-users may need to track the responses of the foam from one qualification test to the next in order to make an informed decision on whether to replace the foam. If a response is too low, the foam may simply need an additional test to qualify. If a response is near the upper limit, the foam may need to be replaced soon.

In summary, the predictable nature of the foam response and the relative ease of replacing a new face foam greatly alleviate any concerns over *Dummy Repeatability* and *Dummy Reproducibility*. This situation is readily manageable and represents only a minor impediment to achieving the qualification targets.

Despite the elevated *Dummy Repeatability*, a high level of *Test Repeatability* was observed because the same sequence of responses (second trial highest; progressive increase thereafter) was observed in the trials for all three sets of foams. *Test Reproducibility* was not assessed (all tests were run at a single lab).

6 Neck Flexion

6.1 Methodology

Repeatability and reproducibility tests were performed using the neck flexion qualification procedures described in the *THOR-50M 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 6-1). For the flexion qualification 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 the aluminum honeycomb. During these tests the upper neck Y-axis moment (My), upper neck Z-axis force (Fz), head angular rate, and head rotation were measured.

Figure 6-1. Neck flexion test setup

6.2 Neck Flexion Repeatability Results

Sections 6.2.1 to Section 6.2.5 illustrate the results of the neck flexion repeatability tests. Each section contains a table providing the quantified test data, followed by plot overlays of the five repeat tests conducted at all three labs. Note that the data in the tables containing the results of each test series are listed sequentially, with the test at the top of the table beginning the test series.

6.2.1 THOR-50M Neck EB6007 Testing at VRTC

Repeatability results at VRTC for neck EB6007 in the neck flexion qualification yielded CV values below 5 percent in most instances (Table 6-1 and Table 6-2, and Figure 6-2 to Figure 6-5); the only exceptions were My and Fz, which were above 5 percent but less than 10 percent.

Table 6-1. VRTC THOR-50M Neck EB6007 Frontal Flexion Pulse Repeatability Results

Test Number	Pendulum Velocity at 8 ms After T0 (m/s)	Pendulum Velocity at 16 ms After T0 (m/s)	Pendulum Velocity at 24 ms After T0 (m/s)
170328-1	1.72	3.43	4.89
170328-2	1.82	3.54	4.98
170328-4	1.75	3.46	4.85
170328-8	1.72	3.45	4.80
170328-9	1.81	3.50	4.82
Mean	**1.76**	**3.48**	**4.87**
Std. Dev.	**0.05**	**0.04**	**0.07**
CV	**2.8%**	**1.3%**	**1.5%**

Table 6-2. VRTC THOR-50M Neck EB6007 Frontal Flexion Repeatability Results

Test Number	Peak Upper Neck My (N-m)	Upper Neck Fz Most Positive Value Prior to 40 ms (N)	Peak Head Angular Velocity ω_y (relative to earth) (deg/s)	Peak Head Rotation (relative to pendulum) (deg)
170328-1	34.4	928	-1962	-64.7
170328-2	31.0	908	-1985	-64.4
170328-4	30.9	851	-1954	-63.7
170328-8	30.2	815	-1941	-64.8
170328-9	29.7	818	-1957	-63.9
Mean	**31.3**	**864**	**-1960**	**-64.3**
Std. Dev.	**1.8**	**52**	**16**	**0.5**
CV	**5.8%**	**6.0%**	**0.8%**	**0.8%**

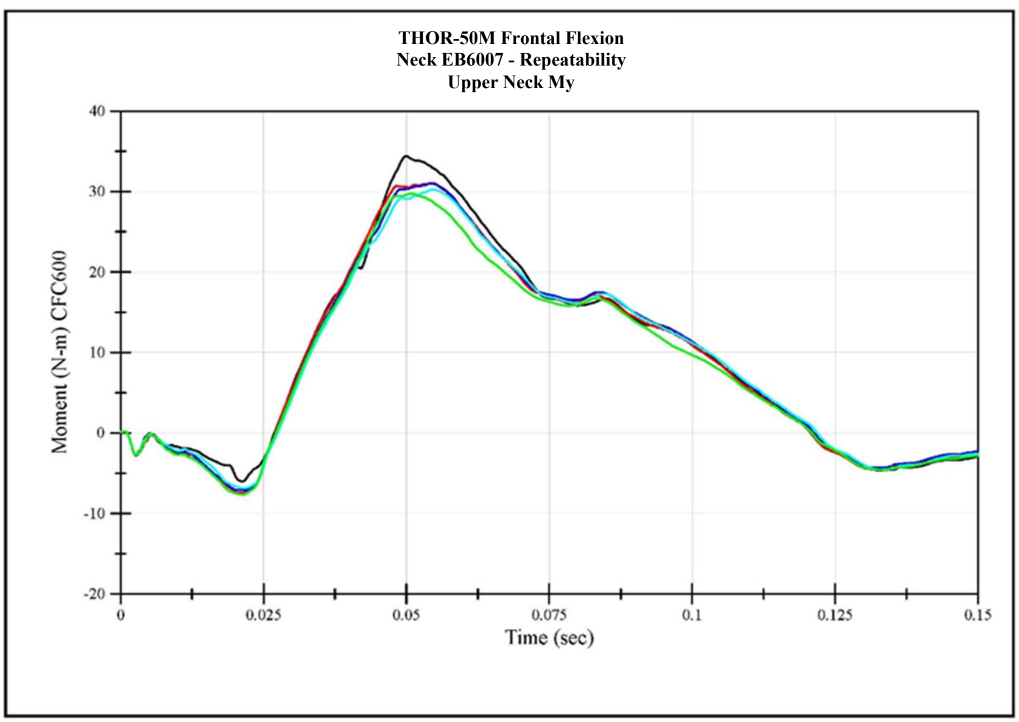

Figure 6-2. VRTC neck frontal flexion upper neck Y-moment repeatability for Neck EB6007

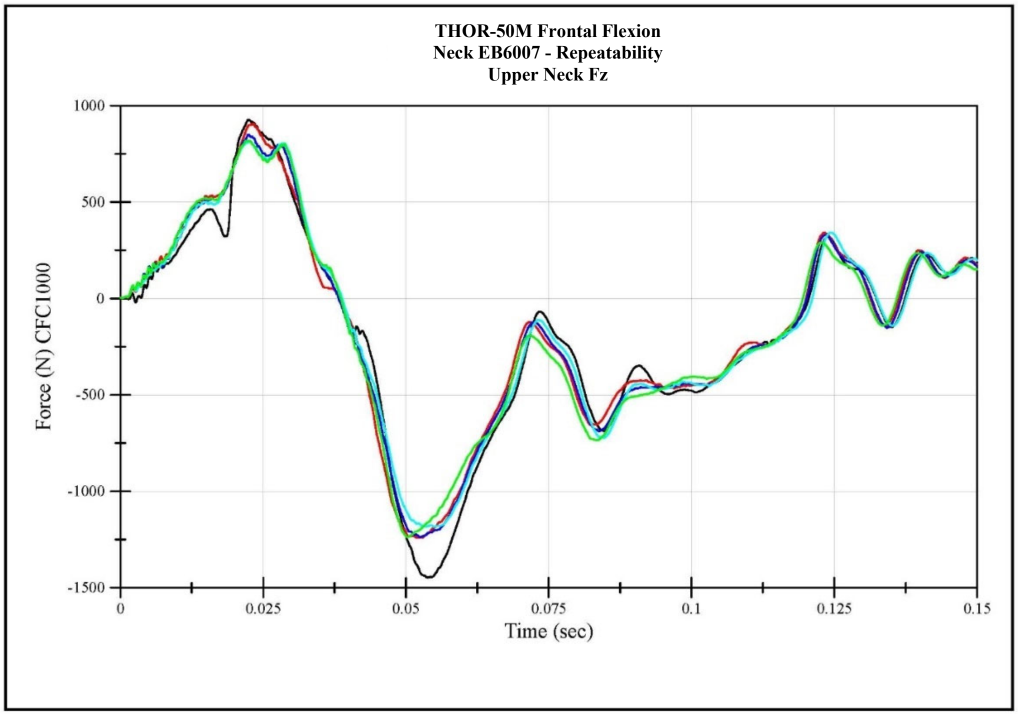

Figure 6-3. VRTC neck frontal flexion upper neck Z-force repeatability for Neck EB6007

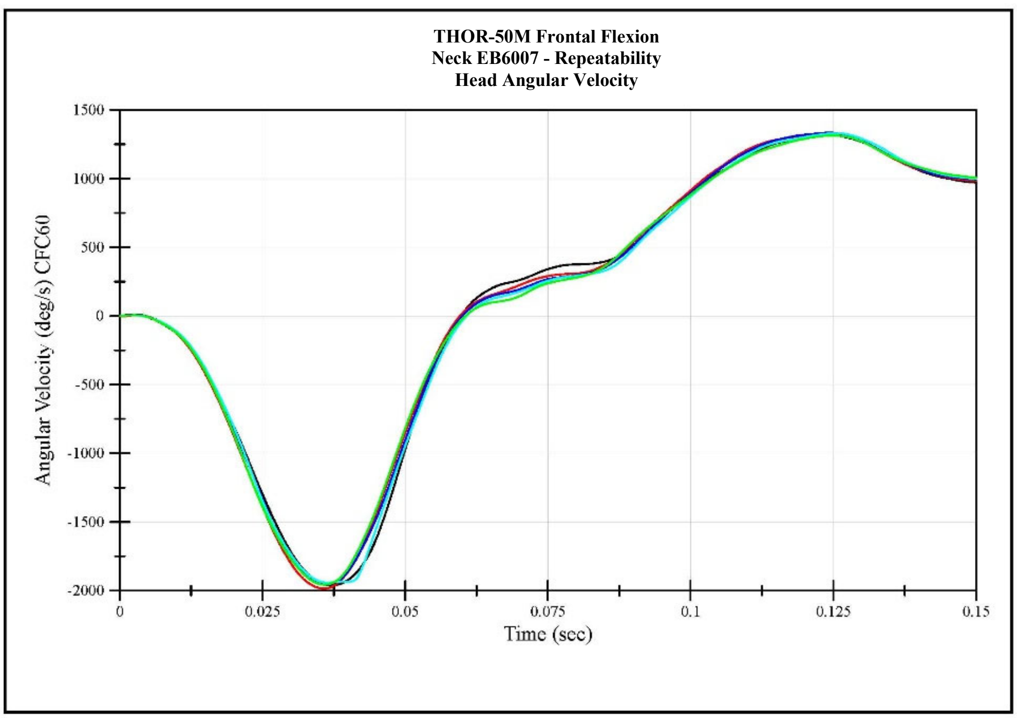

Figure 6-4. VRTC neck frontal flexion angular velocity repeatability for Neck EB6007

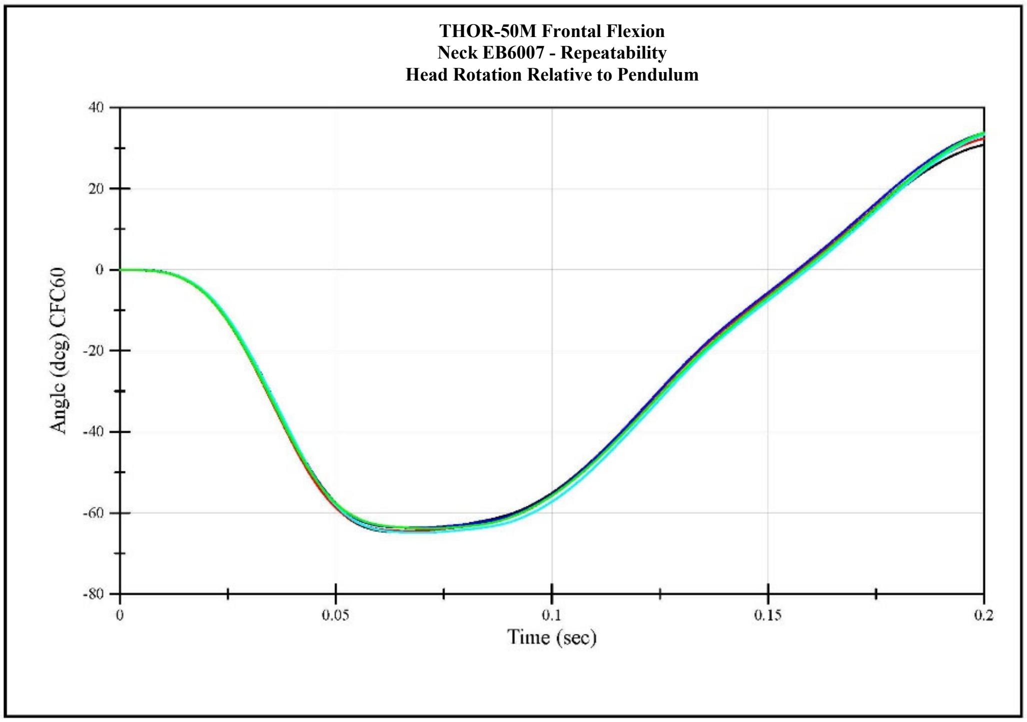

Figure 6-5. VRTC neck frontal flexion head rotation repeatability for Neck EB6007

6.2.2 THOR-50M Neck EB6006 Testing at VRTC

Repeatability results at VRTC for Neck EB6006 in the neck flexion qualification yielded CV values all below 5 percent with the exception of My which was above 5 percent but less than 10 percent (Table 6-3 and Table 6-4, and Figure 6-6 to Figure 6-9).

Table 6-3. VRTC THOR-50M Neck EB6006 Frontal Flexion Pulse Repeatability Results

Test Number	**Pendulum Velocity at 8 ms After T0 (m/s)**	**Pendulum Velocity at 16 ms After T0 (m/s)**	**Pendulum Velocity at 24 ms After T0 (m/s)**
170315-1	1.70	3.32	4.66
170315-3	1.67	3.33	4.71
170315-4	1.67	3.29	4.62
170315-5	1.72	3.43	4.76
170315-6	1.72	3.43	4.84
Mean	**1.70**	**3.36**	**4.72**
Std. Dev.	**0.03**	**0.06**	**0.09**
CV	**1.5%**	**1.9%**	**1.8%**

Table 6-4. VRTC THOR-50M Neck EB6006 Frontal Flexion Repeatability Results

Test Number	Peak Upper Neck My (N-m)	Upper Neck Fz Most Positive Value Prior to 40 ms (N)	Peak Head Angular Velocity ω_y (relative to earth) (deg/s)	Peak Head Rotation (relative to pendulum) (deg)
170315-1	36.2	804	-1960	-65.5
170315-3	32.8	858	-1959	-67.5
170315-4	32.2	849	-1939	-67.7
170315-5	32.4	839	-1971	-68.0
170315-6	32.3	840	-1989	-68.1
Mean	**33.2**	**838**	**-1964**	**-67.3**
Std. Dev.	**1.7**	**20.6**	**18**	**1.1**
CV	**5.1%**	**2.5%**	**0.9%**	**1.6%**

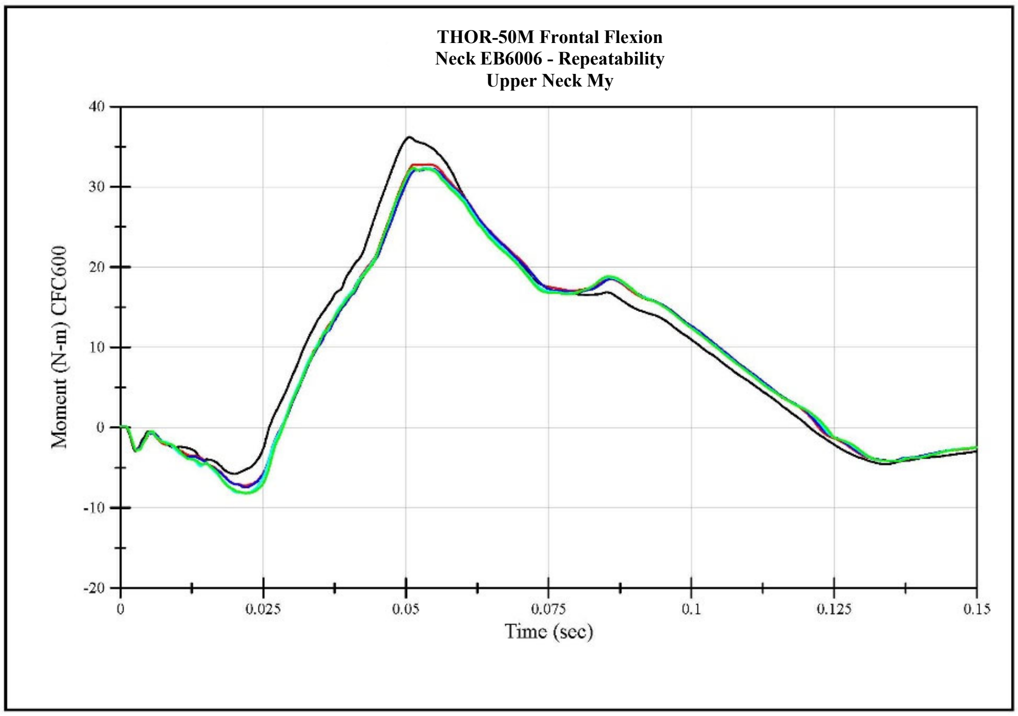

Figure 6-6. VRTC neck frontal flexion upper neck Y-moment repeatability for Neck EB6006

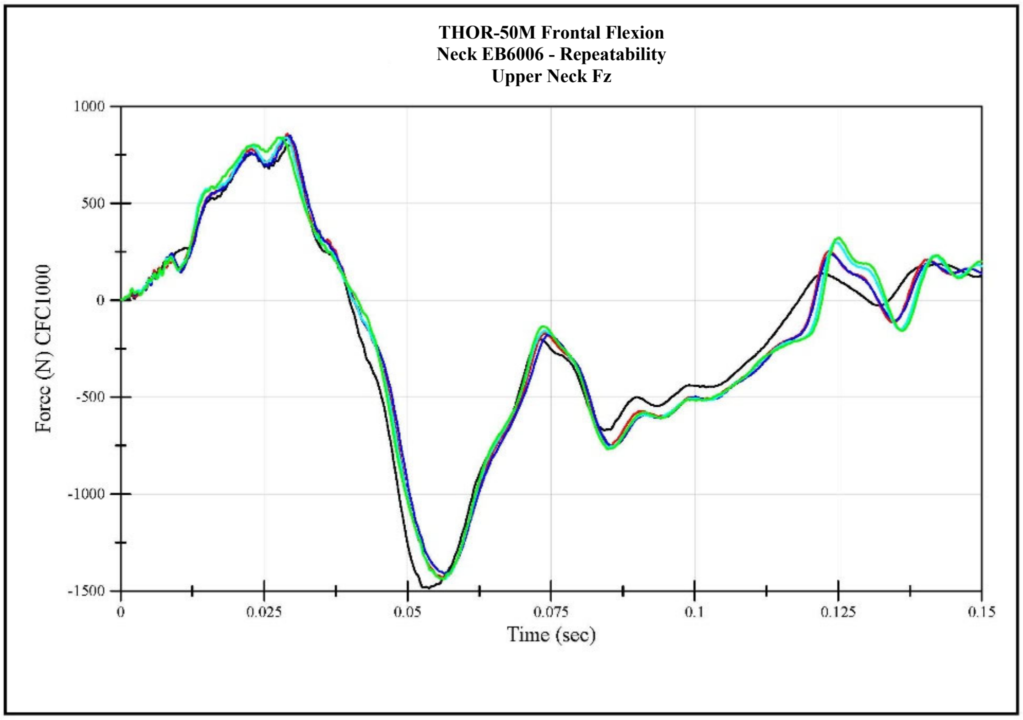

Figure 6-7. VRTC neck frontal flexion upper neck Z-force repeatability for Neck EB6006

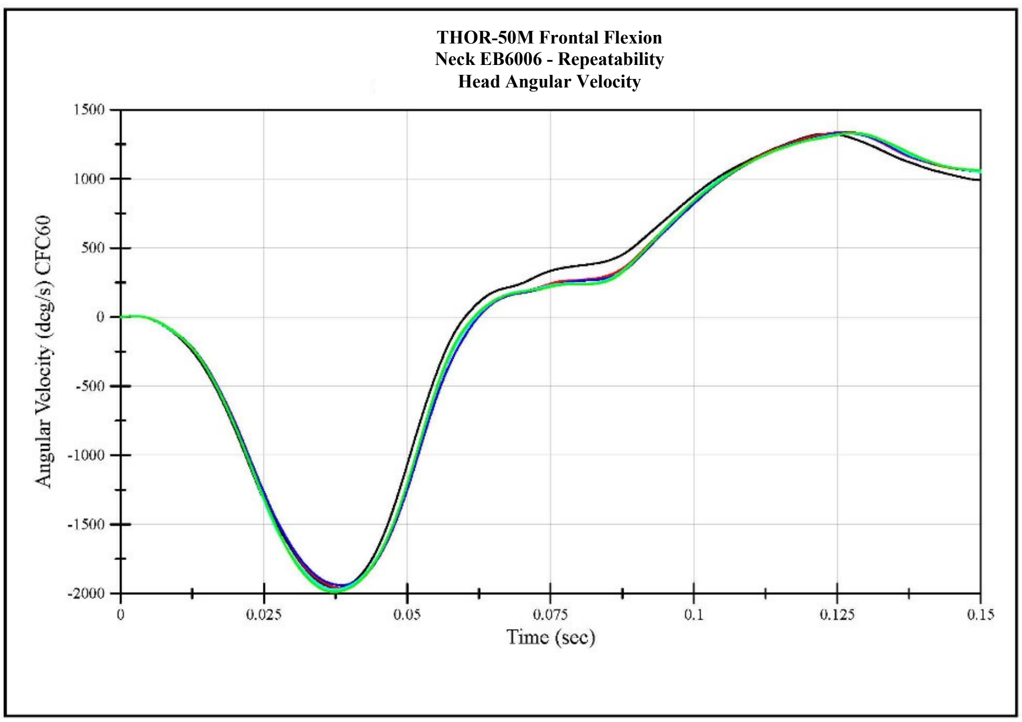

Figure 6-8. VRTC neck frontal flexion head angular velocity repeatability for Neck EB6006

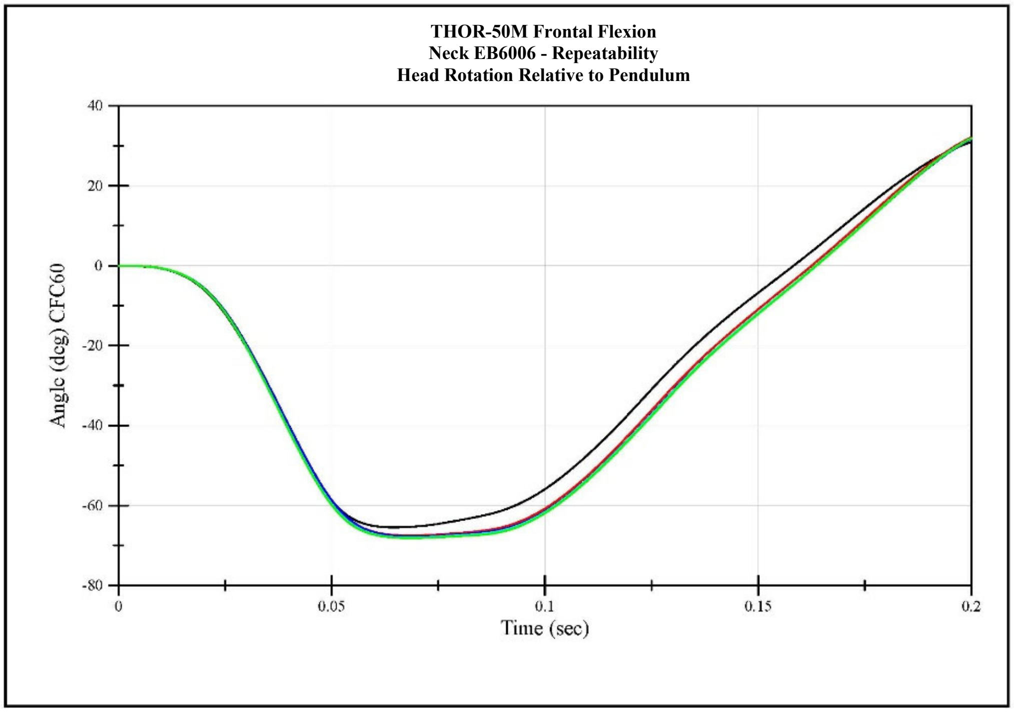

Figure 6-9. VRTC neck frontal flexion head rotation repeatability for Neck EB6006

6.2.3 THOR-50M Neck EB6005 Testing at VRTC

Repeatability results at VRTC for Neck EB6005 in the neck flexion qualification yielded CV values all below 5 percent (Table 6-5 and Table 6-6, and Figure 6-10 to Figure 6-13).

Table 6-5. VRTC THOR-50M Neck EB6005 Frontal Flexion Pulse Repeatability Results

Test Number	**Pendulum Velocity at 8 ms After T0 (m/s)**	**Pendulum Velocity at 16 ms After T0 (m/s)**	**Pendulum Velocity at 24 ms After T0 (m/s)**
170321-8	1.79	3.56	5.03
170321-9	1.81	3.56	4.95
170322-8	1.84	3.62	5.01
170322-10	1.83	3.61	5.00
170322-11	1.81	3.58	4.98
Mean	**1.82**	**3.59**	**4.99**
Std. Dev.	**0.02**	**0.03**	**0.03**
CV	**1.0%**	**0.8%**	**0.6%**

Table 6-6. VRTC THOR-50M Neck EB6005 Frontal Flexion Repeatability Results

Test Number	Peak Upper Neck My (N-m)	Upper Neck Fz Most Positive Value Prior to 40 ms (N)	Peak Head Angular Velocity ω_y (relative to earth) (deg/s)	Peak Head Rotation (relative to pendulum) (deg)
170321-8	32.0	905	-1960	-66.2
170321-9	31.8	872	-2019	-66.3
170322-8	31.3	893	-2011	-66.5
170322-10	30.0	855	-2002	-66.9
170322-11	30.1	867	-2083	-67.9
Mean	**31.0**	**878**	**-2015**	**-66.8**
Std. Dev.	**0.9**	**21**	**44**	**0.7**
CV	**3.0%**	**2.3%**	**2.2%**	**1.0%**

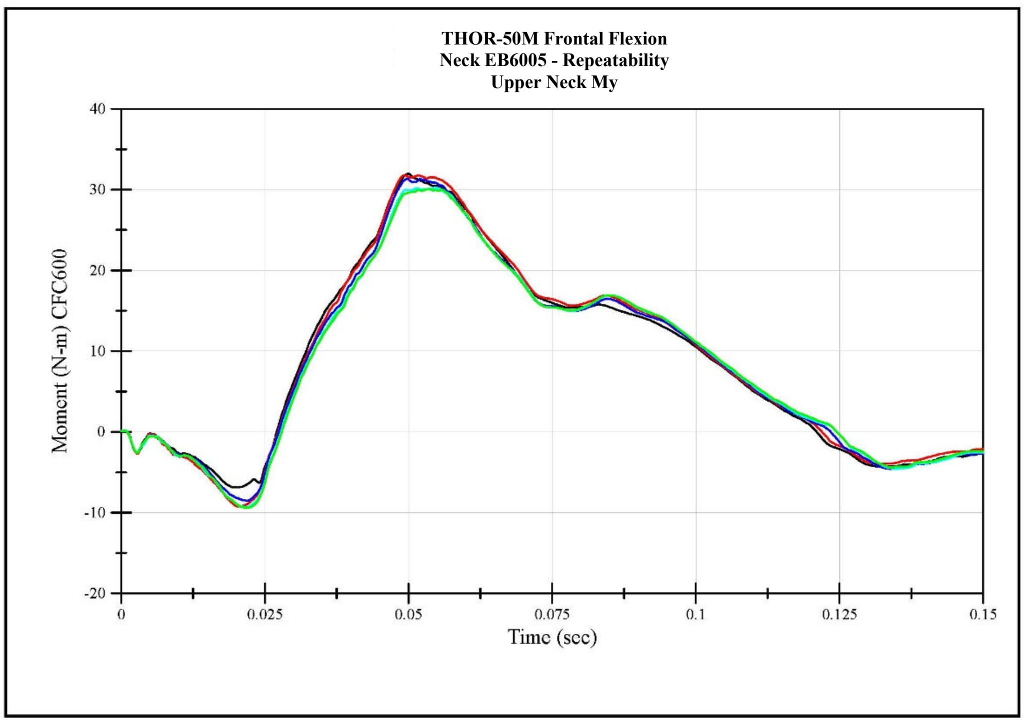

Figure 6-10. VRTC neck frontal flexion upper neck Y-moment repeatability for Neck EB6005

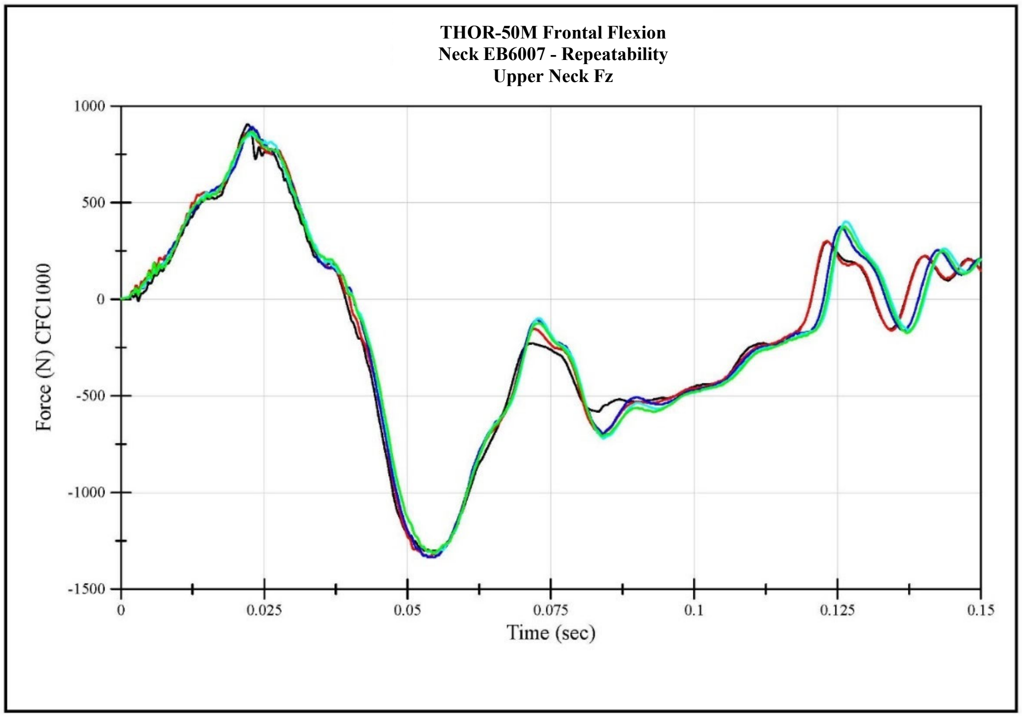

Figure 6-11. VRTC neck frontal flexion upper neck Z-force repeatability for Neck EB6005

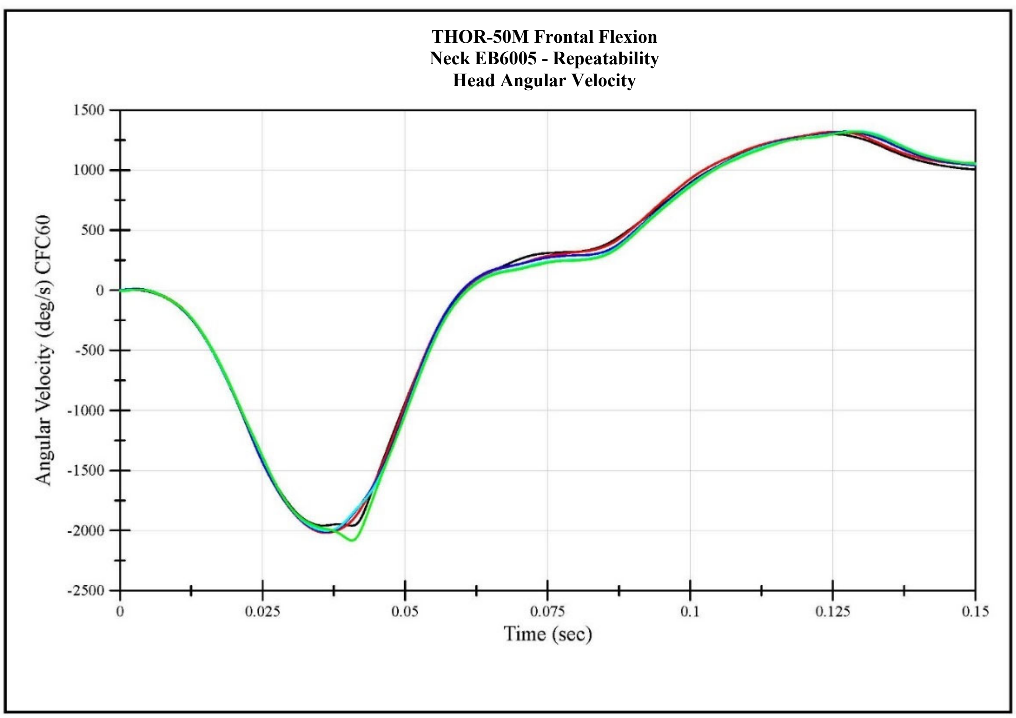

Figure 6-12. VRTC neck frontal flexion head angular velocity repeatability for Neck EB6005

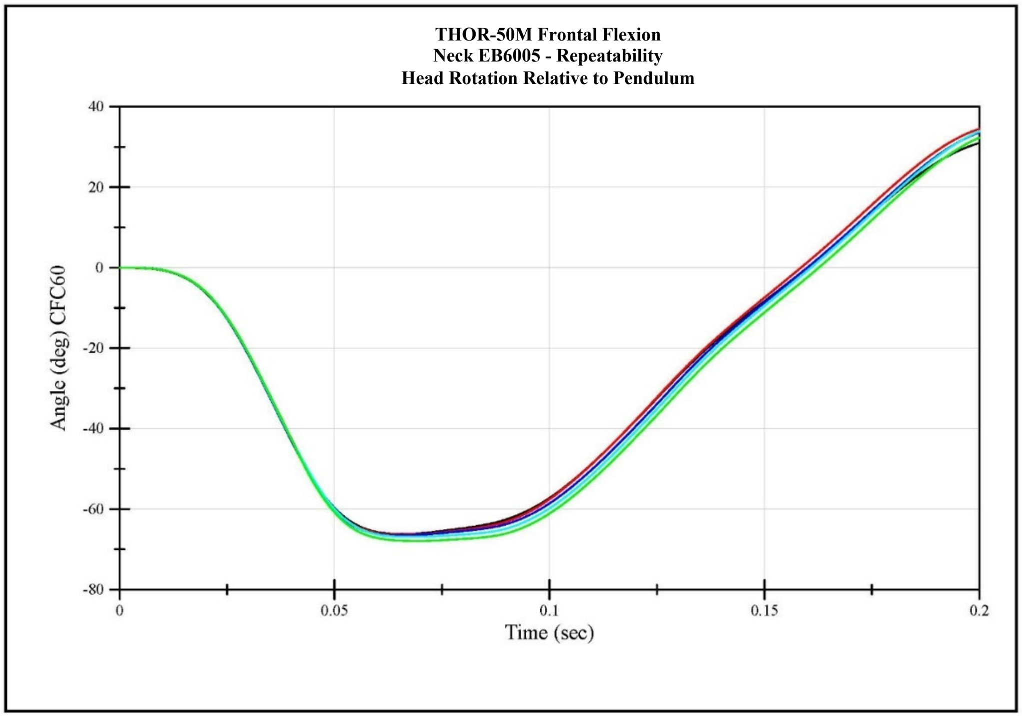

Figure 6-13. VRTC neck frontal flexion head rotation repeatability for Neck EB6005

6.2.4 THOR-50M Neck EB6007 Testing at Humanetics

Repeatability results at Humanetics for Neck EB6007 in the neck flexion qualification yielded CV values all below 5 percent with the exception of Fz which was above 5 percent but less than 10 percent (Table 6-7 and Table 6-8, Figure 6-14 to Figure 6-17).

Table 6-7. Humanetics THOR-50M Neck EB6007 Frontal Flexion Pulse Repeatability Results

Test Number	Pendulum Velocity at 8 ms After T0 (m/s)	Pendulum Velocity at 16 ms After T0 (m/s)	Pendulum Velocity at 24 ms After T0 (m/s)
370503	1.60	3.19	4.61
370507	1.68	3.38	4.87
370508	1.81	3.58	5.05
370509	1.72	3.44	4.94
370512	1.74	3.43	4.86
Mean	**1.71**	**3.40**	**4.87**
Std. Dev.	**0.08**	**0.14**	**0.16**
CV	**4.6%**	**4.2%**	**3.3%**

Table 6-8. Humanetics THOR-50M Neck EB6007 Frontal Flexion Repeatability Results

Test Number	Peak Upper Neck My (N-m)	Upper Neck Fz Most Positive Value Prior to 40 ms (N)	Peak Head Angular Velocity ω_y (relative to earth) (deg/s)	Peak Head Rotation (relative to pendulum) (deg)
370503	30.5	825	-2090	-64.6
370507	30.0	937	-1951	-62.8
370508	30.3	974	-1989	-63.1
370509	30.0	936	-1945	-63.4
370512	29.9	914	-1945	-63.0
Mean	**30.1**	**917**	**-1984**	**-63.4**
Std. Dev.	**0.2**	**56**	**62**	**0.7**
CV	**0.8%**	**6.1%**	**3.1%**	**1.1%**

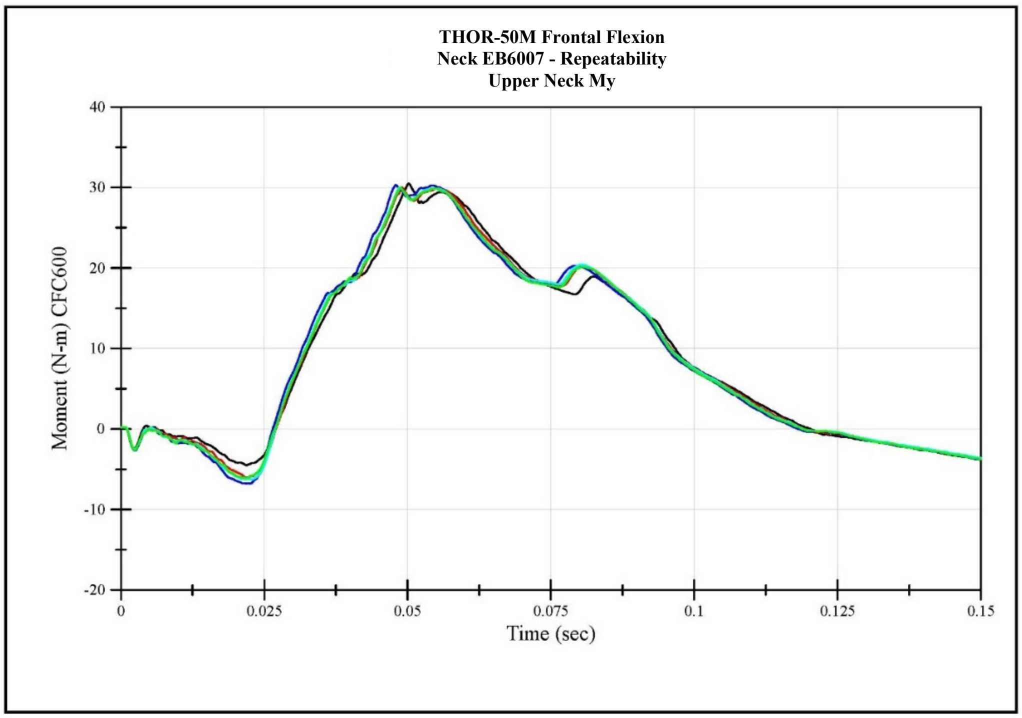

Figure 6-14. Humanetics neck frontal flexion upper neck Y-moment repeatability for Neck EB6007

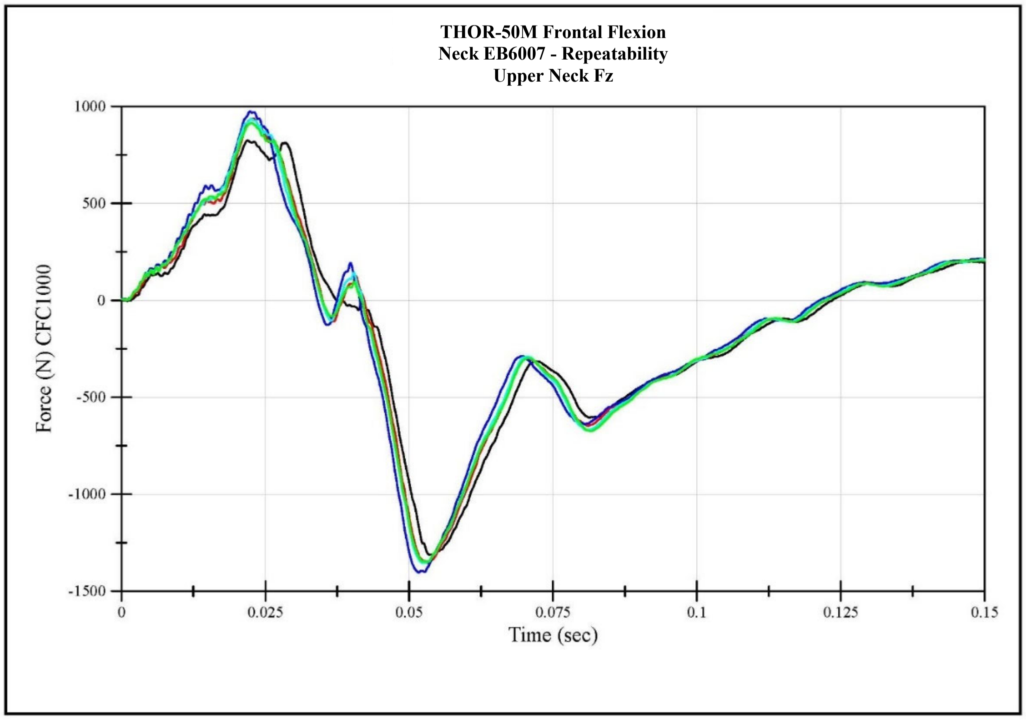

Figure 6-15. Humanetics neck frontal flexion upper neck Z-force repeatability for Neck EB6007

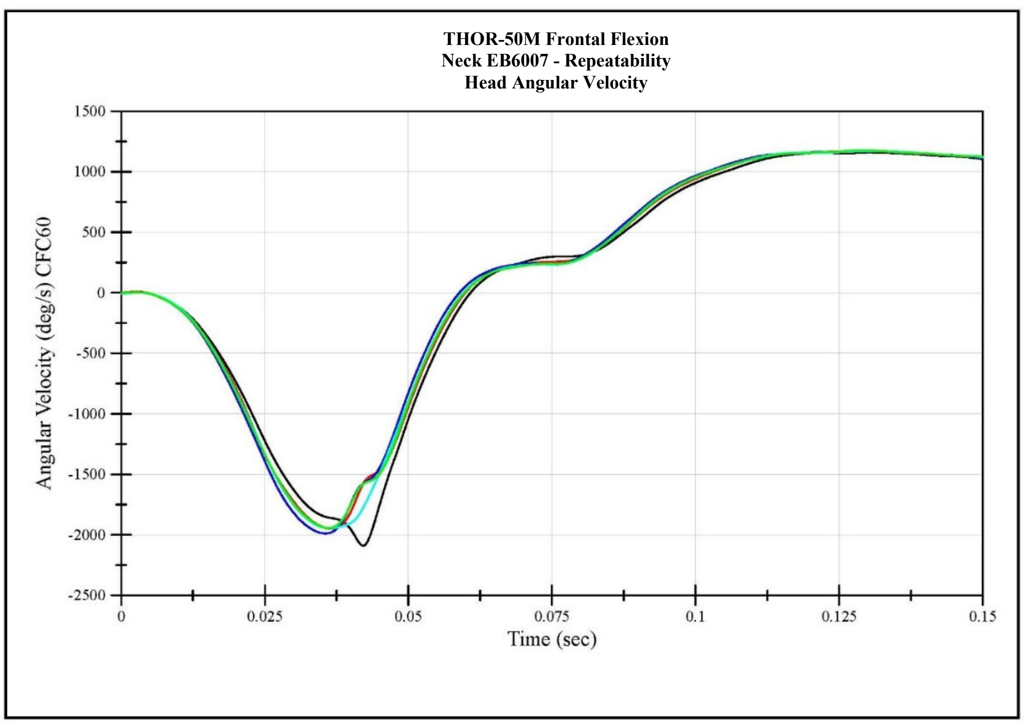

Figure 6-16. Humanetics neck frontal flexion angular velocity repeatability for Neck EB6007

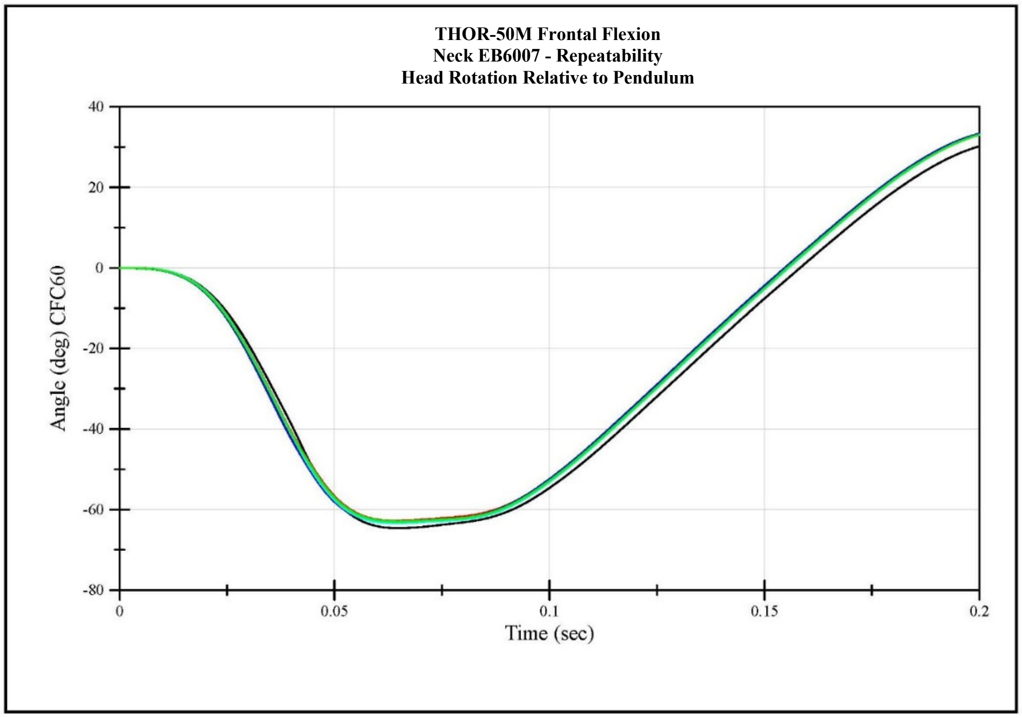

Figure 6-17. Humanetics neck frontal flexion head rotation repeatability for Neck EB6007

6.2.5 THOR-50M Neck EB6007 Testing at Calspan

Repeatability results at Calspan for Neck EB6007 in the neck flexion qualification yielded CV values all below 5 percent (Table 6-9 and Table 6-10, Figure 6-18 to Figure 6-21).

Table 6-9. Calspan THOR-50M Neck EB6007 Frontal Flexion Pulse Repeatability Results

Test Number	Pendulum Velocity at 8 ms After T0 (m/s)	Pendulum Velocity at 16 ms After T0 (m/s)	Pendulum Velocity at 24 ms After T0 (m/s)
20170523131703	1.76	3.62	5.21
20170523135220	1.74	3.60	5.09
20170523142255	1.68	3.47	5.07
20170523145453	1.70	3.50	5.14
20170524062529	1.73	3.50	5.12
Mean	**1.72**	**3.54**	**5.13**
Std. Dev.	**0.03**	**0.06**	**0.05**
CV	**1.8%**	**1.8%**	**1.0%**

Table 6-10. Calspan THOR-50M Neck EB6007 Frontal Flexion Repeatability Results

Test Number	Peak Upper Neck My (N-m)	Upper Neck Fz Most Positive Value Prior to 40 ms (N)	Peak Head Angular Velocity ω_y (relative to earth) (deg/s)	Peak Head Rotation (relative to pendulum) (deg)
20170523131703	29.8	809	-1997	-60.7
20170523135220	29.3	773	-1940	-61.3
20170523142255	29.0	797	-1930	-60.9
20170523145453	29.1	811	-1946	-60.9
20170524062529	28.4	812	-1944	-60.9
Mean	**29.1**	**801**	**-1951**	**-60.9**
Std. Dev.	**0.5**	**16**	**26**	**0.2**
CV	**1.8%**	**2.1%**	**1.3%**	**0.4%**

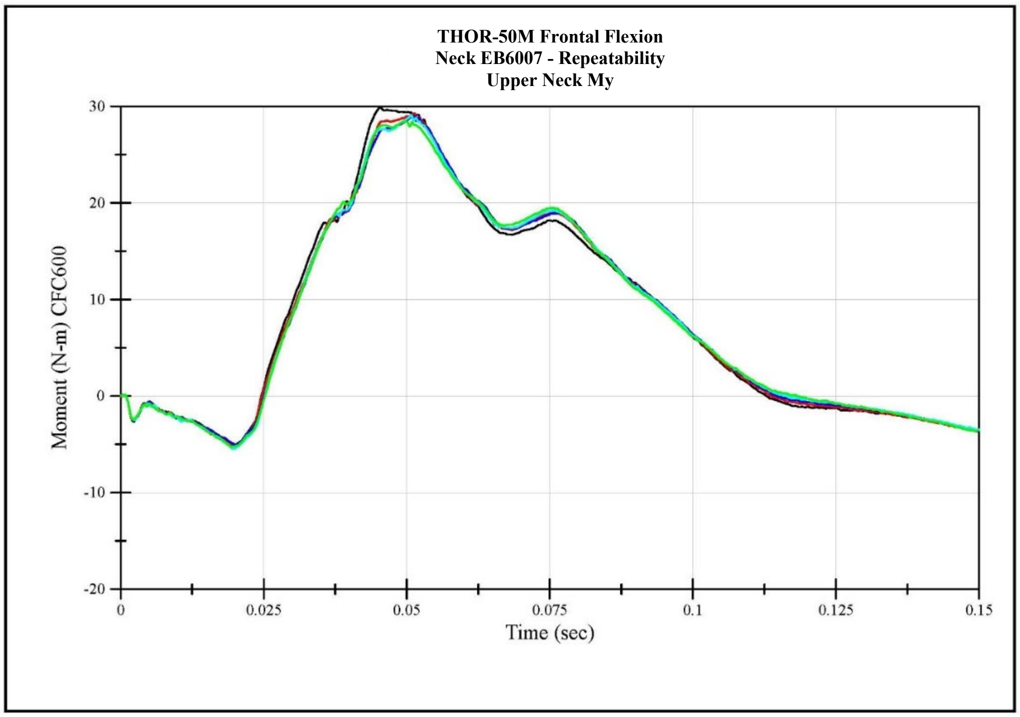

Figure 6-18. Calspan neck frontal flexion upper neck Y-moment repeatability for Neck EB6007

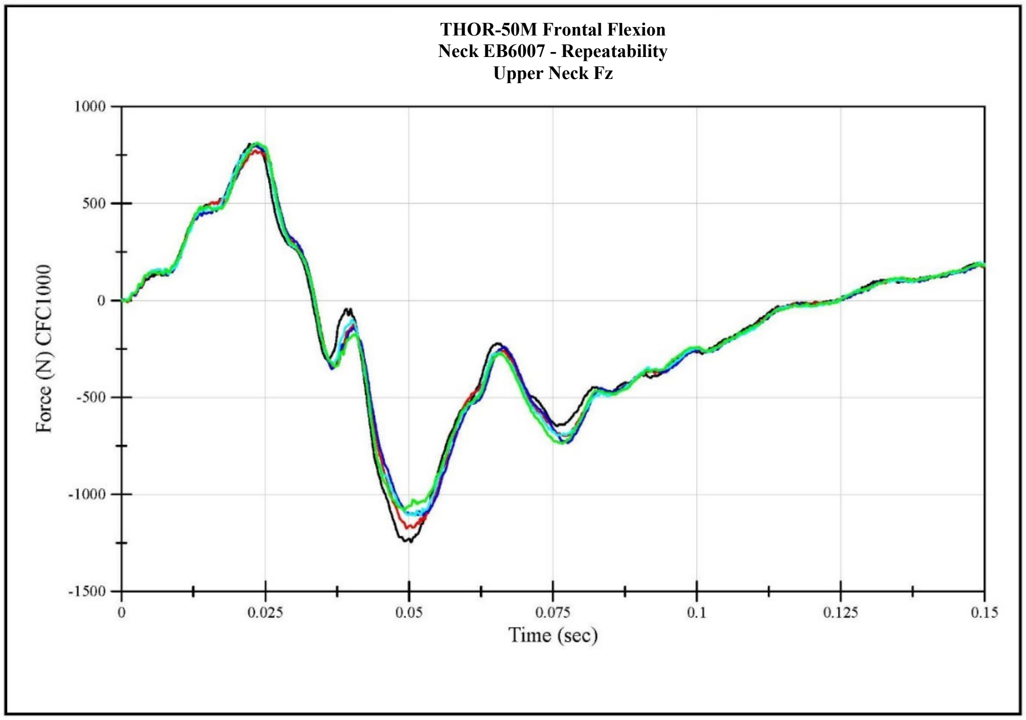

Figure 6-19. Calspan neck frontal flexion upper neck Z-force repeatability for Neck EB6007

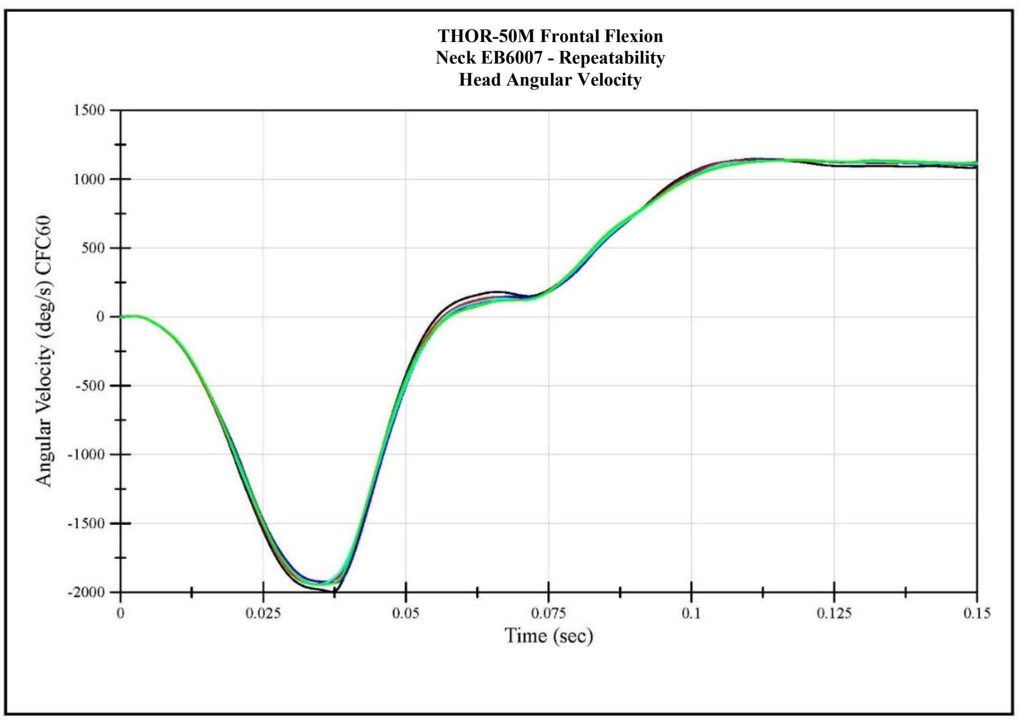

Figure 6-20. Calspan neck frontal flexion angular velocity repeatability for Neck EB6007

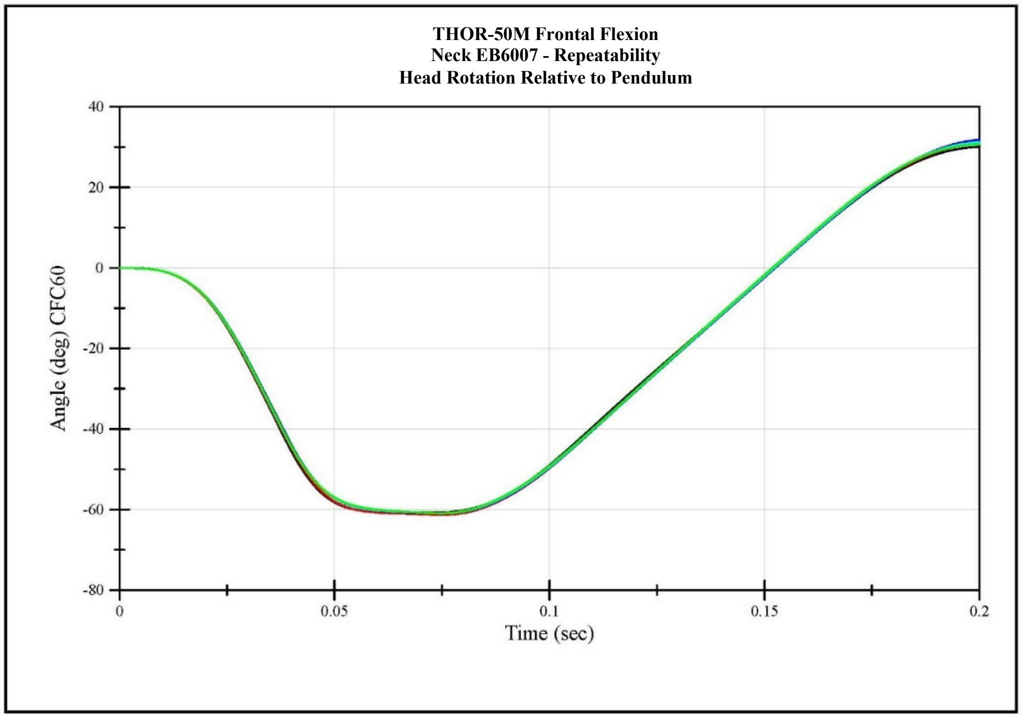

Figure 6-21. Calspan neck frontal flexion head rotation repeatability for Neck EB6007

6.3 Neck Flexion Dummy Reproducibility Results

Dummy Reproducibility results at VRTC for the three THOR-50M necks yielded CV values all below 5 percent, with the exception of My which was above 5 percent but less than 10 percent (Table 6-11 and Table 6-12).

Table 6-11. THOR-50M Neck Frontal Flexion Pulse Dummy Reproducibility Corridors Results

Neck Number	Test Number	Pendulum Velocity at 8 ms After T0 (m/s)	Pendulum Velocity at 16 ms After T0 (m/s)	Pendulum Velocity at 24 ms After T0 (m/s)
VRTC Neck EB6007	**170328-1**	1.72	3.43	4.89
	170328-2	1.82	3.54	4.98
	170328-4	1.75	3.46	4.85
	170328-8	1.72	3.45	4.80
	170328-9	1.81	3.50	4.82
VRTC Neck EB6006	**170315-1**	1.70	3.32	4.66
	170315-3	1.67	3.33	4.71
	170315-4	1.67	3.29	4.62
	170315-5	1.72	3.43	4.76
	170315-6	1.72	3.43	4.84
VRTC Neck EB6005	**170321-8**	1.79	3.56	5.03
	170321-9	1.81	3.56	4.95
	170322-8	1.84	3.62	5.01
	170322-10	1.83	3.61	5.00
	170322-11	1.81	3.58	4.98
Mean		**1.76**	**3.47**	**4.86**
Std. Dev.		**0.06**	**0.11**	**0.13**
CV		**3.3%**	**3.0%**	**2.7%**

Table 6-12. THOR-50M Neck Frontal Flexion Reproducibility Results

Test Number	Test Number	Peak Upper Neck My (N-m)	Upper Neck Fz Most Positive Value Prior to 40 ms (N)	Peak Head Angular Velocity ω_y (relative to earth) (deg/s)	Peak Head Rotation (relative to pendulum) (deg)
VRTC Neck EB6007	**170328-1**	34.4	928	-1962	-64.7
	170328-2	31.1	908	-1985	-64.4
	170328-4	31.0	851	-1954	-63.7
	170328-8	30.3	815	-1941	-64.8
	170328-9	29.7	818	-1957	-63.9
VRTC Neck EB6006	**170315-1**	36.2	804	-1960	-65.5
	170315-3	32.8	858	-1959	-67.5
	170315-4	32.2	849	-1939	-67.7
	170315-5	32.4	839	-1971	-68.0
	170315-6	32.3	840	-1989	-68.1
VRTC Neck EB6005	**170321-8**	32.0	905	-1960	-66.2
	170321-9	31.8	872	-2019	-66.3
	170322-8	31.3	893	-2011	-66.5
	170322-10	30.0	855	-2002	-66.9
	170322-11	30.1	867	-2083	-67.9
Mean		**31.8**	**860**	**-1979**	**-66.1**
Std. Dev.		**1.7**	**36**	**38**	**1.6**
CV		**5.4%**	**4.2%**	**1.9%**	**2.3%**

6.4 THOR-50M Neck EB6007 Lab-to-Lab Variability Analysis

The results for the neck frontal flexion qualification tests from each lab are presented in Table 6-13 and Table 6-14. The last rows of the tables show the *Test Reproducibility* results when data from all three labs are combined. For the pulse, the CV values are all below 5 percent (Table 6-13). For the dummy metrics (Table 6-14), the CV values were all below 5 percent with the exception of Fz which was above 5 percent but less than 10 percent.

Table 6-13. THOR-50M Neck Frontal Flexion Pulse Lab-to-Lab Variability Results

Neck Number	Pendulum Velocity at 8 ms After T0 (m/s)	Pendulum Velocity at 16 ms After T0 (m/s)	Pendulum Velocity at 24 ms After T0 (m/s)
VRTC Neck EB6007	1.72	3.43	4.89
	1.82	3.54	4.98
	1.75	3.46	4.85
	1.72	3.45	4.80
	1.81	3.50	4.82
Humanetics Neck EB6007	1.60	3.19	4.61
	1.68	3.38	4.87
	1.81	3.58	5.05
	1.72	3.44	4.94
	1.74	3.43	4.86
Calspan Neck EB6007	1.76	3.62	5.21
	1.74	3.60	5.09
	1.68	3.47	5.07
	1.70	3.50	5.14
	1.73	3.50	5.12
Test Reproducibility EB6007 ALL Labs			
Mean	**1.73**	**3.47**	**4.95**
Std. Dev.	**0.06**	**0.10**	**0.16**
CV	**3.3%**	**3.0%**	**3.2%**

Table 6-14. THOR-50M Neck Frontal Flexion Lab-to-Lab Variability Results

Neck Number	Peak Upper Neck My (N-m)	Upper Neck Fz Most Positive Value Prior to 40 ms (N)	Peak Head Angular Velocity ω_y (relative to earth) (deg/s)	Peak Head Rotation (relative to pendulum) (deg)
VRTC Neck EB6007	34.4	928	-1962	-64.7
	31.1	908	-1985	-64.4
	31.0	851	-1954	-63.7
	30.3	815	-1941	-64.8
	29.7	818	-1957	-63.9
Humanetics Neck EB6007	30.5	825	-2090	-64.6
	30.0	937	-1951	-62.8
	30.3	974	-1989	-63.1
	30.0	936	-1945	-63.4
	29.9	914	-1945	-63.0
Calspan Neck EB6007	29.8	809	-1997	-60.7
	29.3	773	-1940	-61.3
	29.0	797	-1930	-60.9
	29.1	811	-1946	-60.9
	28.4	812	-1944	-60.9
Test Reproducibility EB6007 ALL Labs				
Mean	**30.2**	**861**	**-1965**	**-62.9**
Std. Dev.	**1.4**	**65**	**40**	**1.5**
CV	**4.5%**	**7.5%**	**2.0%**	**2.5%**

6.5 Corridor Development

All the data used to determine the neck frontal flexion qualification corridors are shown in Table 6-15 and Table 6-16. The qualification corridors were calculated using the mean plus or minus 10 percent of the peak for the specified measured or calculated channels (Table 6-17).

Table 6-15. THOR-50M Neck Frontal Flexion Pulse Qualification Corridor Results

Neck Number	Test Number	Pendulum Velocity at 8 ms After T0 (m/s)	Pendulum Velocity at 16 ms After T0 (m/s)	Pendulum Velocity at 24 ms After T0 (m/s)
VRTC Neck EB6007	**170328-1**	1.72	3.43	4.89
	170328-2	1.82	3.54	4.98
	170328-4	1.75	3.46	4.85
	170328-8	1.72	3.45	4.80
	170328-9	1.81	3.50	4.82
VRTC Neck EB6006 (Cont.)	**170315-1**	1.70	3.32	4.66
	170315-3	1.67	3.33	4.71
	170315-4	1.67	3.29	4.62
	170315-5	1.72	3.43	4.76
	170315-6	1.72	3.43	4.84
VRTC Neck EB6005	**170321-8**	1.79	3.56	5.03
	170321-9	1.81	3.56	4.95
	170322-8	1.84	3.62	5.01
	170322-10	1.83	3.61	5.00
	170322-11	1.81	3.58	4.98
Humanetics EB6007	**370503**	1.60	3.19	4.61
	370507	1.68	3.38	4.87
	370508	1.81	3.58	5.05
	370509	1.72	3.44	4.94
	370512	1.74	3.43	4.86
Calspan EB6007	**20170523131703**	1.76	3.62	5.21
	20170523135220	1.74	3.60	5.09
	20170523142255	1.68	3.47	5.07
	20170523145453	1.70	3.50	5.14
	20170524062529	1.73	3.50	5.12
Mean		**1.74**	**3.47**	**4.91**
Std. Dev.		**0.06**	**0.11**	**0.16**
CV		**3.5%**	**3.2%**	**3.3%**

Table 6-16. THOR-50M Neck Frontal Flexion Qualification Corridor Results

Test Number	Test Number	Peak Upper Neck My (N-m)	Upper Neck Fz Most Positive Value Prior to 40 ms (N)	Peak Head Angular Velocity ω_y (relative to earth) (deg/s)	Peak Head Rotation (relative to pendulum) (deg)
VRTC Neck EB6007	**170328-1**	34.4	928	-1962	-64.7
	170328-2	31.1	908	-1985	-64.4
	170328-4	31.0	851	-1954	-63.7
	170328-8	30.3	815	-1941	-64.8
	170328-9	29.7	818	-1957	-63.9
VRTC Neck EB6006	**170315-1**	36.2	804	-1960	-65.5
	170315-3	32.8	858	-1959	-67.5
	170315-4	32.2	849	-1939	-67.7
	170315-5	32.4	839	-1971	-68.0
	170315-6	32.3	840	-1989	-68.1
VRTC Neck EB6005	**170321-8**	32.0	905	-1960	-66.2
	170321-9	31.8	872	-2019	-66.3
	170322-8	31.3	893	-2011	-66.5
	170322-10	30.0	855	-2002	-66.9
	170322-11	30.1	867	-2083	-67.9
Humanetics Neck EB6007	**370503**	30.5	825	-2090	-64.6
	370507	30.0	937	-1951	-62.8
	370508	30.3	974	-1989	-63.1
	370509	30.0	936	-1945	-63.4
	370512	29.9	914	-1945	-63.0
Calspan Neck EB6007 (Cont.)	**20170523131703**	29.8	809	-1997	-60.7
	20170523135220	29.3	773	-1940	-61.3
	20170523142255	29.0	797	-1930	-60.9
	20170523145453	29.1	811	-1946	-60.9
	20170524062529	28.4	812	-1944	-60.9
Mean		**31.0**	**860**	**-1975**	**-64.5**
Std. Dev.		**1.8**	**52**	**41**	**2.5**
CV		**5.7%**	**6.1%**	**2.1%**	**3.8%**

Table 6-17. Neck Frontal Flexion Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Pendulum Velocity at 8 ms After T0	**m/s**	1.57	1.92	1.74	10.0%
Pendulum Velocity at 16 ms After T0	**m/s**	3.13	3.82	3.48	10.0%
Pendulum Velocity at 24 ms After T0	**m/s**	4.42	5.41	4.92	10.0%
Impact Velocity	**m/s**	4.95	5.05	5.00	
Peak Upper Neck My	**N-m**	27.9	34.1	31.0	10.0%
Upper Neck Fz Most Positive Value Prior to 40 ms	**N**	774	946	860	10.0%
Peak Head Angular Velocity ω_y (relative to earth)	**deg/s**	-2172	-1777	1975	10.0%
Peak Head Rotation (relative to pendulum)	**deg**	-71.0	-58.1	64.5	10.0%

Discussion. The assessment indicates that the initial test of a series may produce results that are slightly different than subsequent tests, which is considered a *Dummy Repeatability* issue. Three of the six series of repeatability tests yielded slightly elevated CVs for My and Fz. In each of the six series of tests, the initial test always produced the highest My value. This initial response may be a function of the newness of the necks or caused by the fact that the necks were assembled immediately prior to the test series. The discrepancy is most prominent on test 1 at VRTC for serial no. 6007 which produced the highest My of all tests at all labs.

This trend, however, was not repeated when the neck was passed onto Humanetics and Calspan (at Humanetics, the initial test produced a low Fz. However, this may have been related to the input pulse in which the velocity change for test 1 was lower than the other tests). Thus, the slightly elevated CVs for some of the *Dummy Repeatability* and *Dummy Reproducibility* results (all below 10%) do not necessarily indicate that qualification targets within ±10 percent will be difficult to achieve.

There also appears to be variability related to *Test Reproducibility* as seen in Table 6-14, most noticeably for the Fz. Data clusters by test lab are apparent, where the Fz results are all lower at Calspan and higher at Humanetics. The *Test Reproducibility* of the input pulses (shown in Table 6-15) also shows that the Calspan setup always produced higher velocity changes than the other labs.

Nonetheless, only three tests produced results outside of the ±10 percent range: the above initial test at VRTC and one test each at Calspan and Humanetics. The non-conforming test at Humanetics also had an input pulse with a high velocity change relative to the other tests. Thus, results within ± 10 percent for all necks are likely achievable by adjusting the input pulse through the selection of their honeycomb cell configuration.

7 Neck Extension

7.1 Methodology

Repeatability and reproducibility 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 7-1). For the extension 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 aluminum honeycomb. During these tests the upper neck Y-axis moment (My), upper neck Z-axis force (Fz), head angular rate, and head rotation were measured.

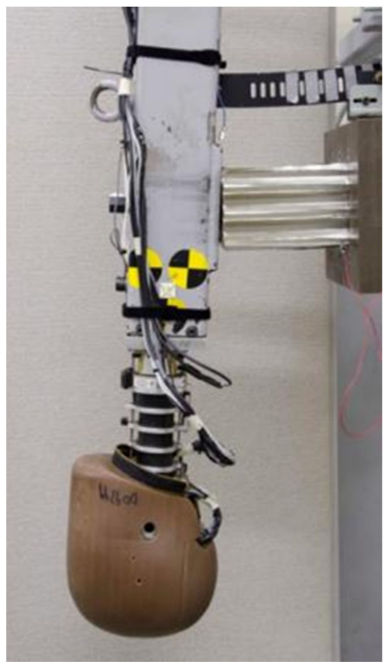

Figure 7-1. Neck extension test setup

7.2 Neck Extension Repeatability Results

Sections 7.2.1 to 7.2.5 illustrate the results of the neck extension repeatability tests. Each section contains a table providing the quantified test data, followed by plot overlays of the five repeat tests conducted at all three labs. Note that the data in the tables containing the results of each test series are listed sequentially, with the test at the top of the table beginning the test series.

7.2.1 THOR-50M Neck EB6007 Testing at VRTC

Repeatability results at VRTC for neck EB6007 in the neck extension qualification yielded CV values all below 5 percent (Table 7-1 and Table 7-2, Figure 7-2 to Figure 7-5).

Table 7-1. VRTC THOR-50M Neck EB6007 Extension Pulse Repeatability Results

Test Number	Pendulum Velocity at 10 ms After T0 (m/s)	Pendulum Velocity at 20 ms After T0 (m/s)	Pendulum Velocity at 30 ms After T0 (m/s)
170215-6	1.95	3.64	4.91
170215-8	1.90	3.59	5.01
170215-9	2.00	3.71	5.01
170215-11	1.97	3.74	5.12
170216-3	1.96	3.69	4.91
Mean	**1.96**	**3.67**	**4.99**
Std. Dev.	**0.04**	**0.06**	**0.09**
CV	**1.9%**	**1.6%**	**1.7%**

Table 7-2. VRTC THOR-50M Neck EB6007 Extension Repeatability Results

Test Number	Peak Upper Neck My (N-m)	Peak Upper Neck Fz (N)	Peak Head Angular Velocity ω_y (relative to earth) (deg/s)	Peak Head Rotation (relative to pendulum) (deg)
170215-6	-21.1	-3043	2048	64.0
170215-8	-22.3	-3080	2070	64.5
170215-9	-22.3	-3108	2090	65.1
170215-11	-22.6	-3143	2121	65.4
170216-3	-22.9	-3040	2058	64.4
Mean	**-22.2**	**-3083**	**2077**	**64.7**
Std. Dev.	**0.7**	**44**	**29**	**0.6**
CV	**3.2%**	**1.4%**	**1.4%**	**0.9%**

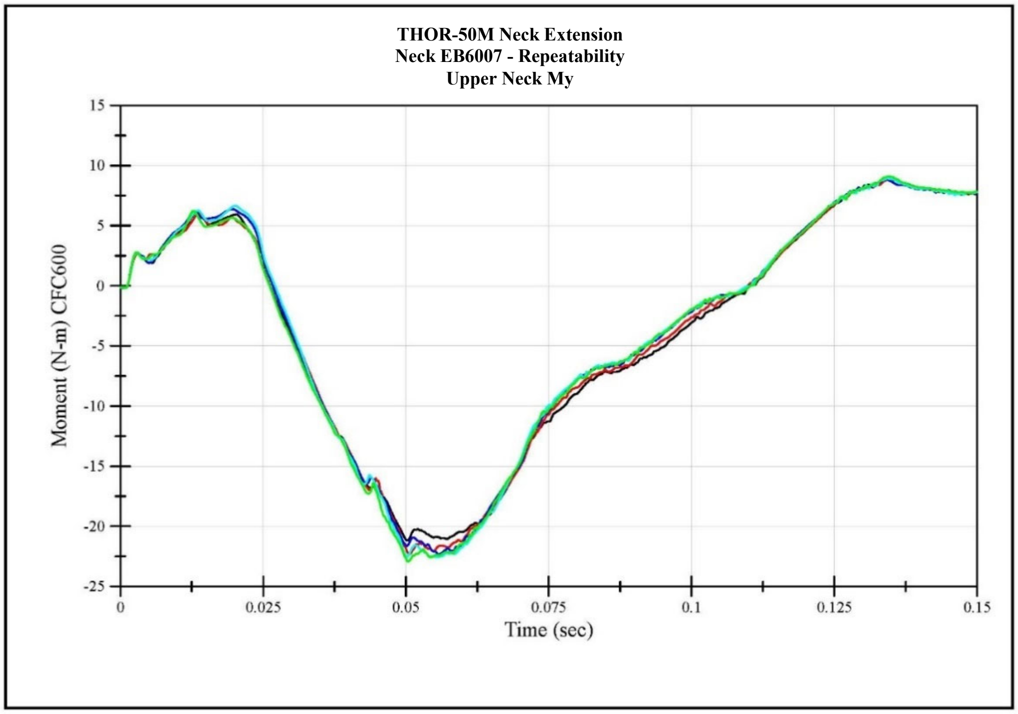

Figure 7-2. VRTC neck extension upper neck Y-moment repeatability for Neck EB6007

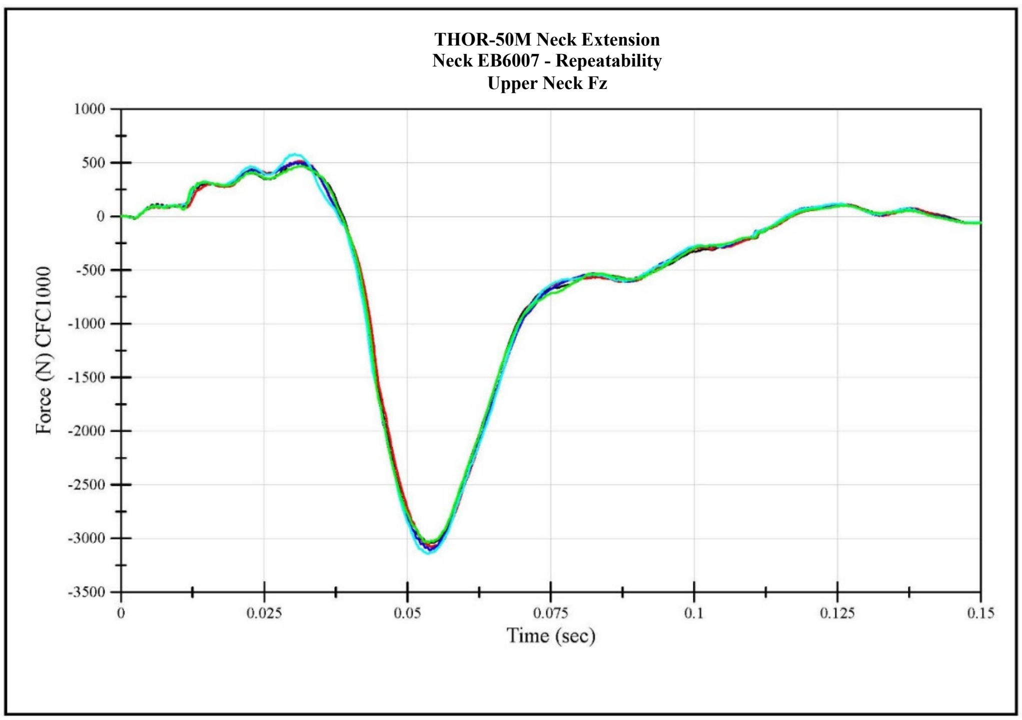

Figure 7-3. VRTC neck extension upper neck Z-force repeatability for Neck EB6007

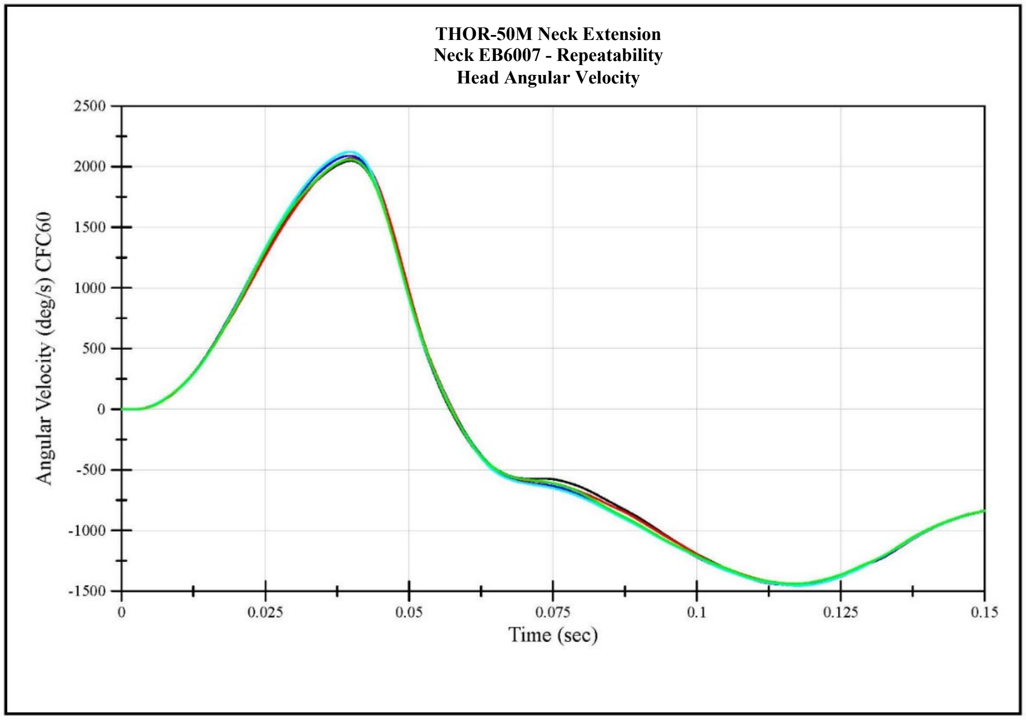

Figure 7-4. VRTC neck extension head angular velocity repeatability for Neck EB6007

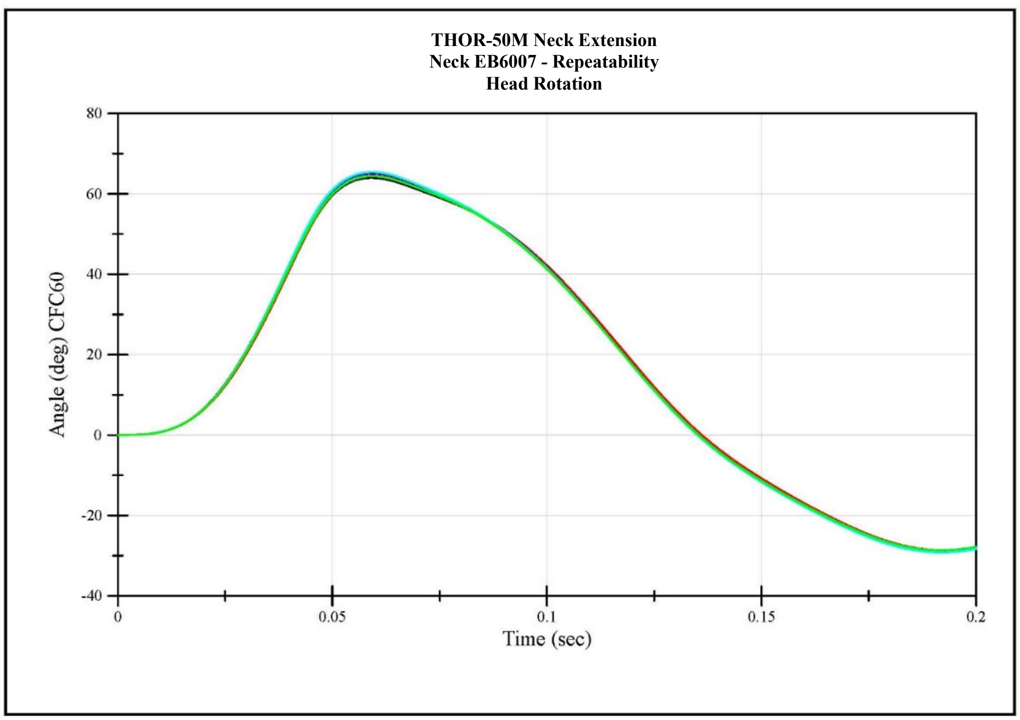

Figure 7-5. VRTC neck extension head rotation repeatability for Neck EB6007

7.2.2 THOR-50M Neck EB6006 Testing at VRTC

Repeatability results at VRTC for neck EB6006 in the neck extension qualification yielded CV values all below 5 percent (Table 7-3 and Table 7-4, Figure 7-6 to Figure 7-9).

Table 7-3. VRTC THOR-50M Neck EB6006 Extension Pulse Repeatability Results

Test Number	Pendulum Velocity at 10 ms After T0 (m/s)	Pendulum Velocity at 20 ms After T0 (m/s)	Pendulum Velocity at 30 ms After T0 (m/s)
170224-2	1.83	3.51	4.94
170227-4	2.04	3.84	5.21
170227-6	1.81	3.51	4.86
170227-8	1.92	3.58	4.90
170227-9	1.89	3.58	4.84
Mean	**1.90**	**3.60**	**4.95**
Std. Dev.	**0.09**	**0.14**	**0.15**
CV	**4.8%**	**3.8%**	**3.0%**

Table 7-4. VRTC THOR-50M Neck EB6006 Extension Repeatability Results

Test Number	Peak Upper Neck My (N-m)	Peak Upper Neck Fz (N)	Peak Head Angular Velocity ω_y (relative to earth) (deg/s)	Peak Head Rotation (relative to pendulum) (deg)
170224-2	-23.2	-2897	1960	64.1
170227-4	-23.2	-3124	2096	66.6
170227-6	-22.4	-2955	2004	66.3
170227-8	-22.1	-2952	2025	66.5
170227-9	-21.9	-2921	2010	66.6
Mean	**-22.5**	**-2970**	**2019**	**66.0**
Std. Dev.	**0.6**	**89**	**49**	**1.1**
CV	**2.7%**	**3.0%**	**2.4%**	**1.6%**

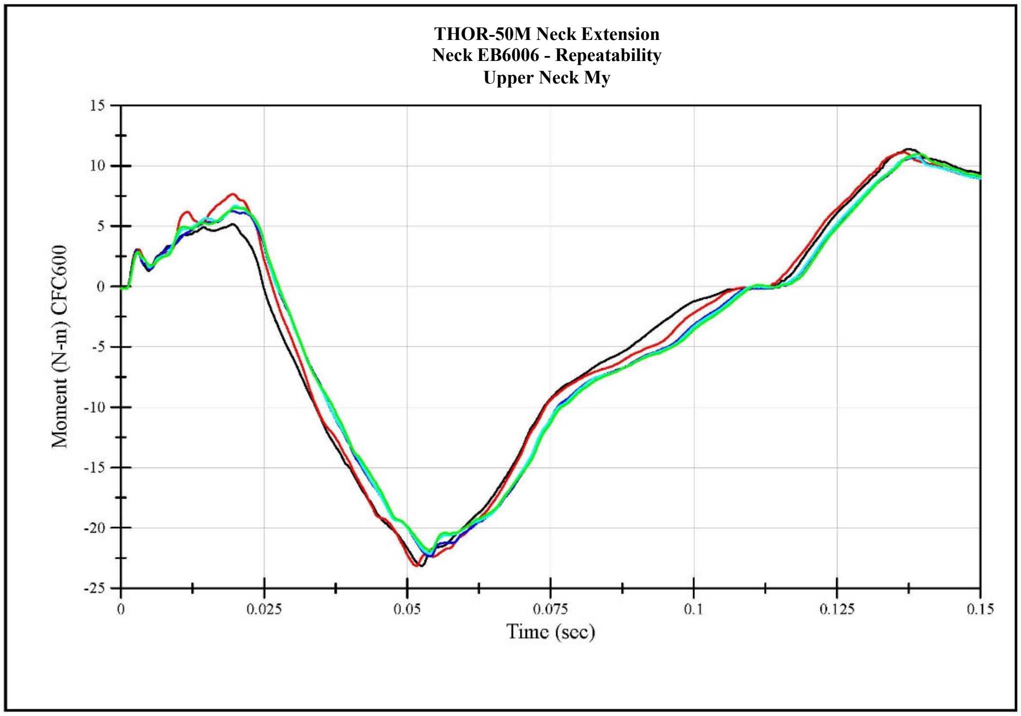

Figure 7-6. VRTC neck extension upper neck Y-moment repeatability for Neck EB6006

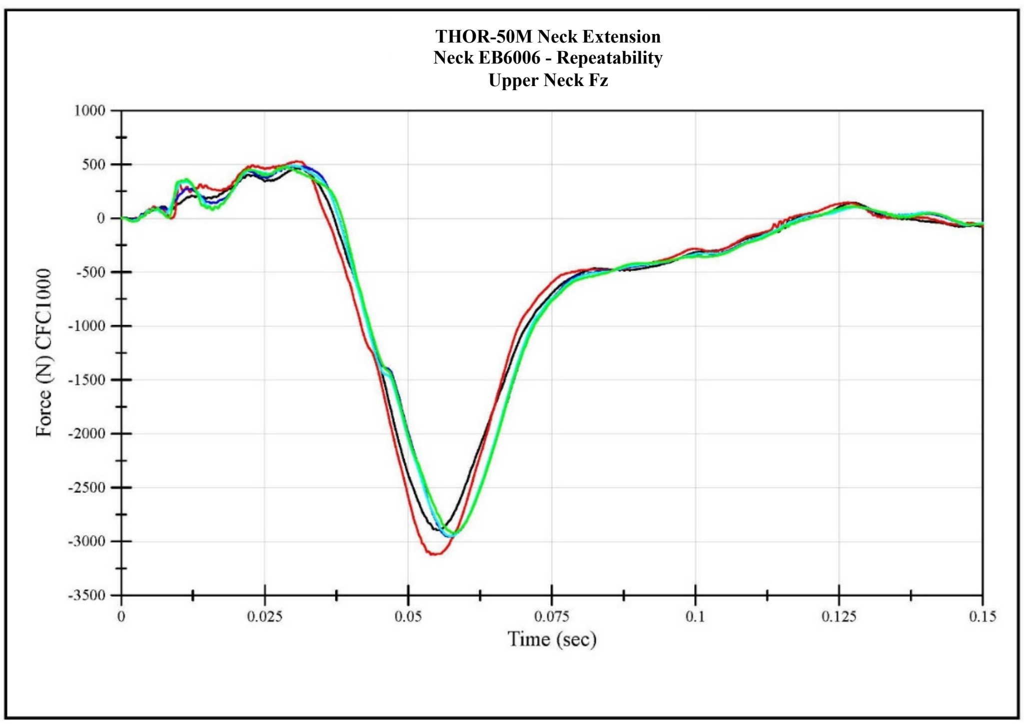

Figure 7-7. VRTC neck extension upper neck Z-force repeatability for Neck EB6006

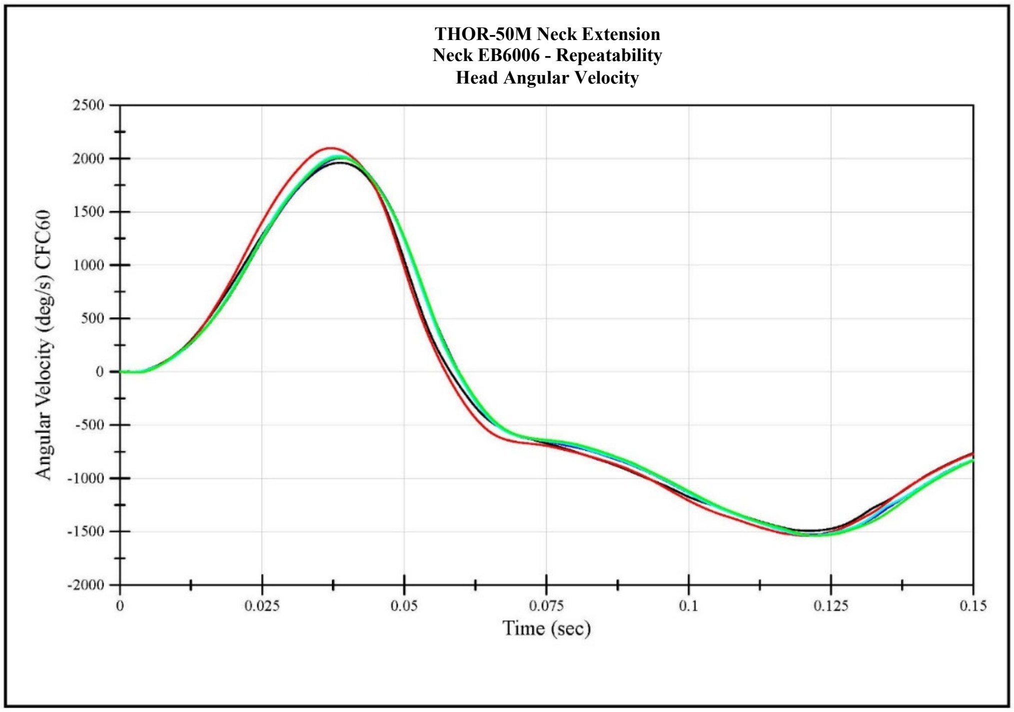

Figure 7-8. VRTC neck extension head angular velocity repeatability for Neck EB6006

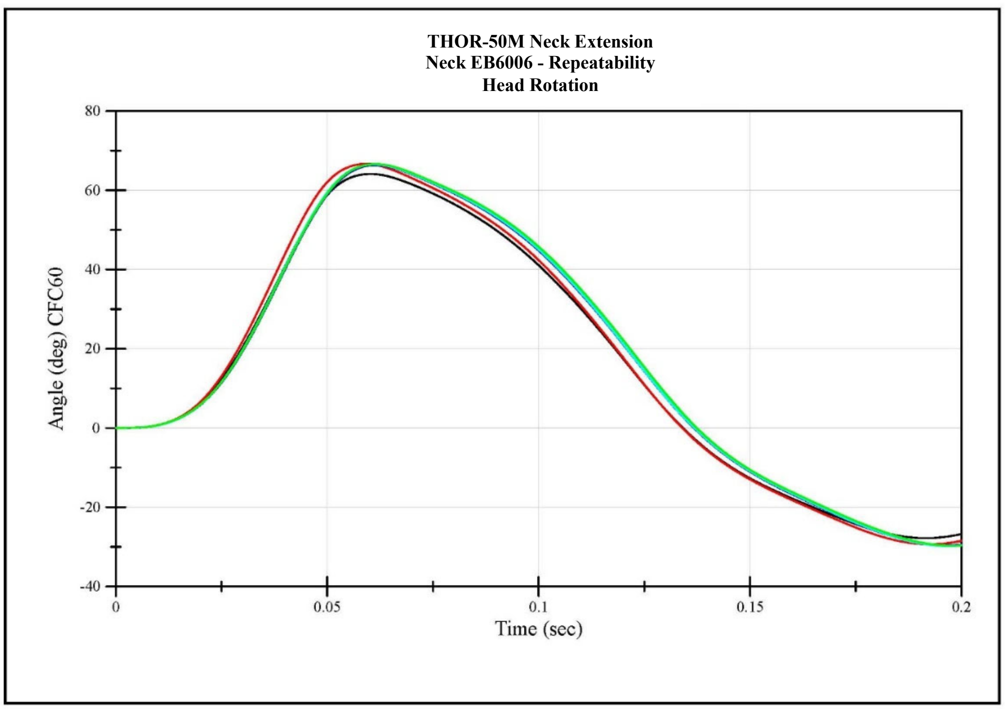

Figure 7-9. VRTC neck extension head rotation repeatability for Neck EB6006

7.2.3 THOR-50M Neck EB6005 Testing at VRTC

Repeatability results at VRTC for Neck EB6005 in the neck extension qualification yielded CV values all below 5 percent (Table 7-5 and Table 7-6, Figure 7-10 to Figure 7-13).

Table 7-5. VRTC THOR-50M Neck EB6005 Extension Pulse Repeatability Results

Test Number	Pendulum Velocity at 10 ms After T0 (m/s)	Pendulum Velocity at 20 ms After T0 (m/s)	Pendulum Velocity at 30 ms After T0 (m/s)
170222-6	2.02	3.73	5.13
170222-7	1.97	3.73	5.10
170222-8	1.90	3.58	4.95
170222-9	1.94	3.59	4.89
170223-1	1.90	3.59	5.00
Mean	**1.95**	**3.64**	**5.01**
Std. Dev.	**0.05**	**0.08**	**0.10**
CV	**2.7%**	**2.2%**	**2.0%**

Table 7-6. VRTC THOR-50M Neck EB6005 Extension Repeatability Results

Test Number	Peak Upper Neck My (N-m)	Peak Upper Neck Fz (N)	Peak Head Angular Velocity ω_y (relative to earth) (deg/s)	Peak Head Rotation (relative to pendulum) (deg)
170222-6	-24.0	-2930	2152	67.1
170222-7	-23.9	-2889	2152	66.9
170222-8	-23.7	-2819	2088	66.6
170222-9	-23.7	-2812	2074	66.3
170223-1	-24.0	-2871	2120	66.4
Mean	**-23.9**	**-2864**	**2117**	**66.7**
Std. Dev.	**0.2**	**49**	**36**	**0.3**
CV	**0.7%**	**1.7%**	**1.7%**	**0.5%**

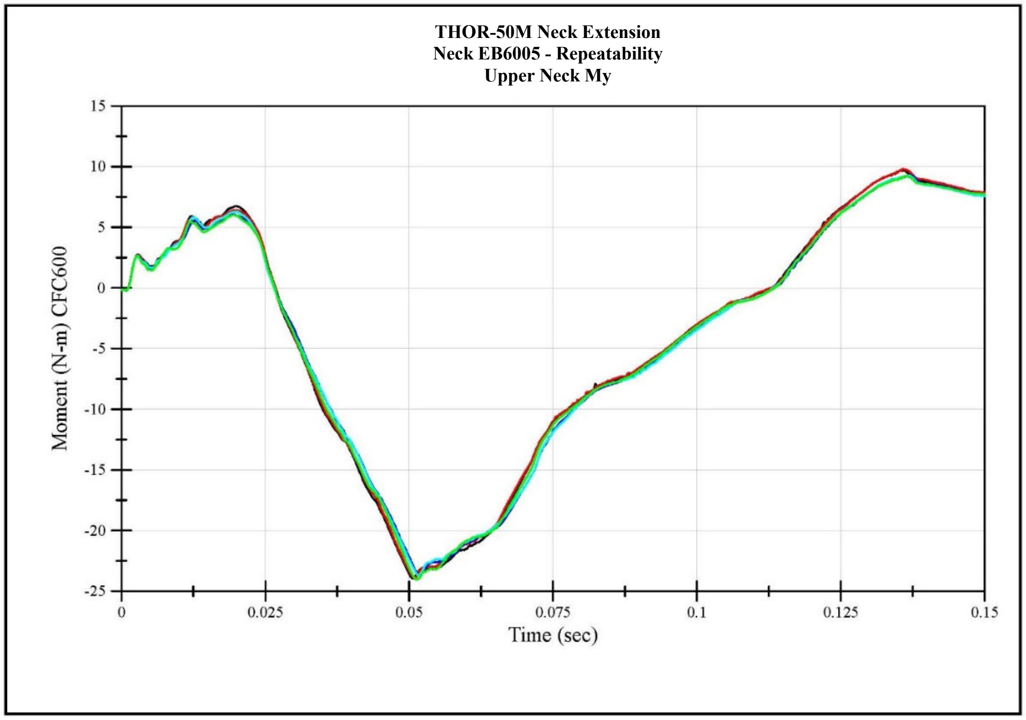

Figure 7-10. VRTC neck extension upper neck Y-moment repeatability for Neck EB6005

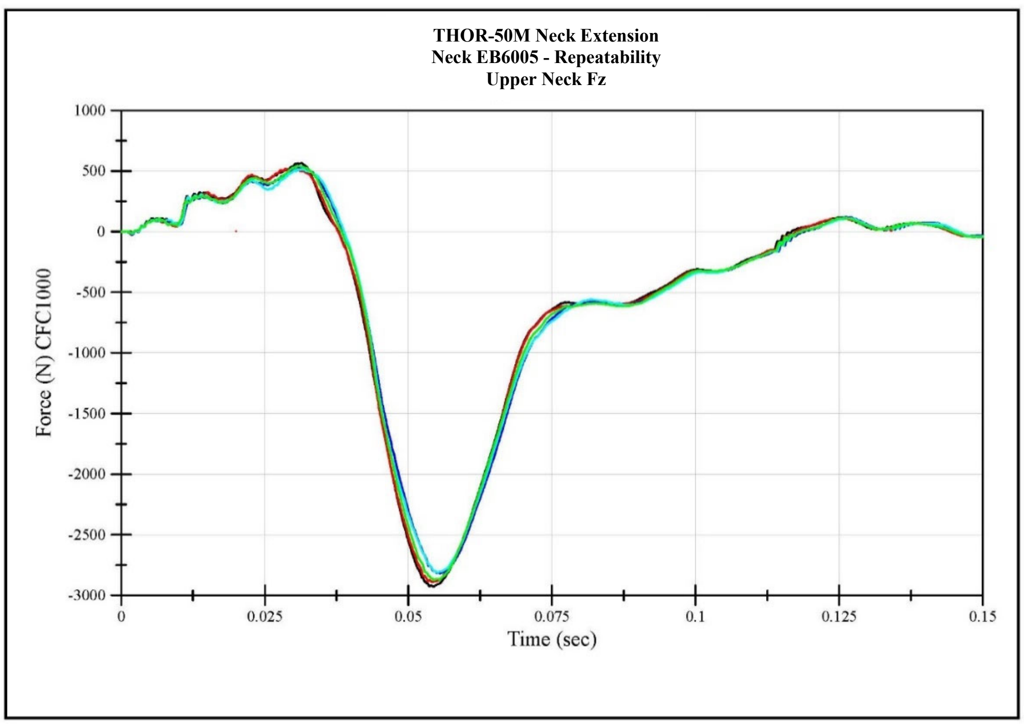

Figure 7-11. VRTC neck extension upper neck Z-force repeatability for Neck EB6005

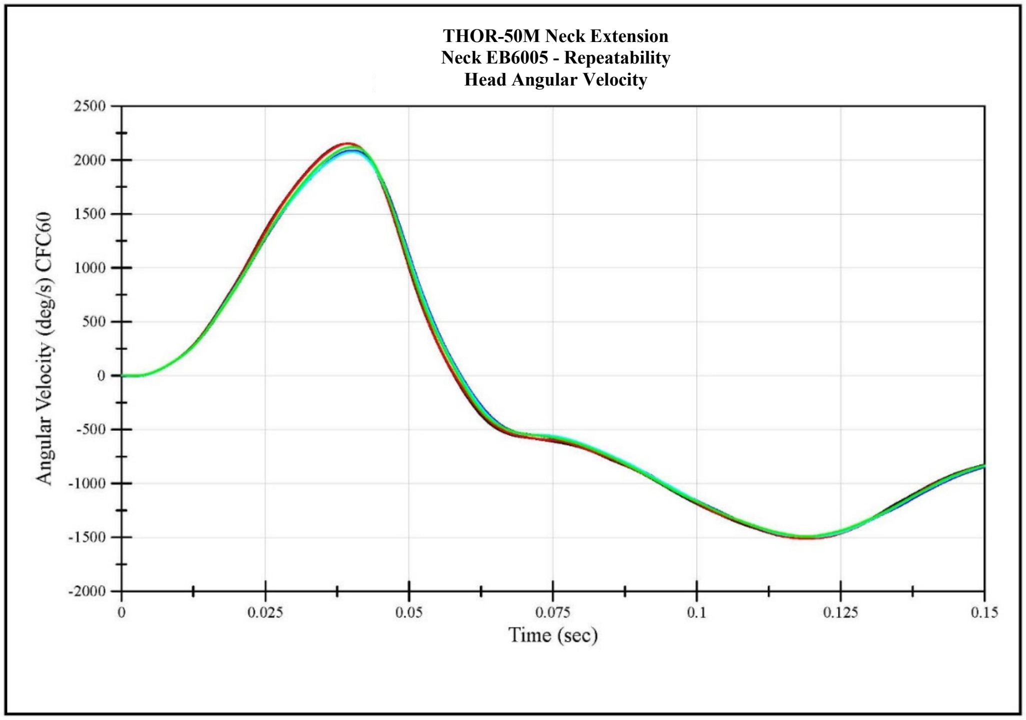

Figure 7-12. VRTC neck extension head angular velocity repeatability for Neck EB6005

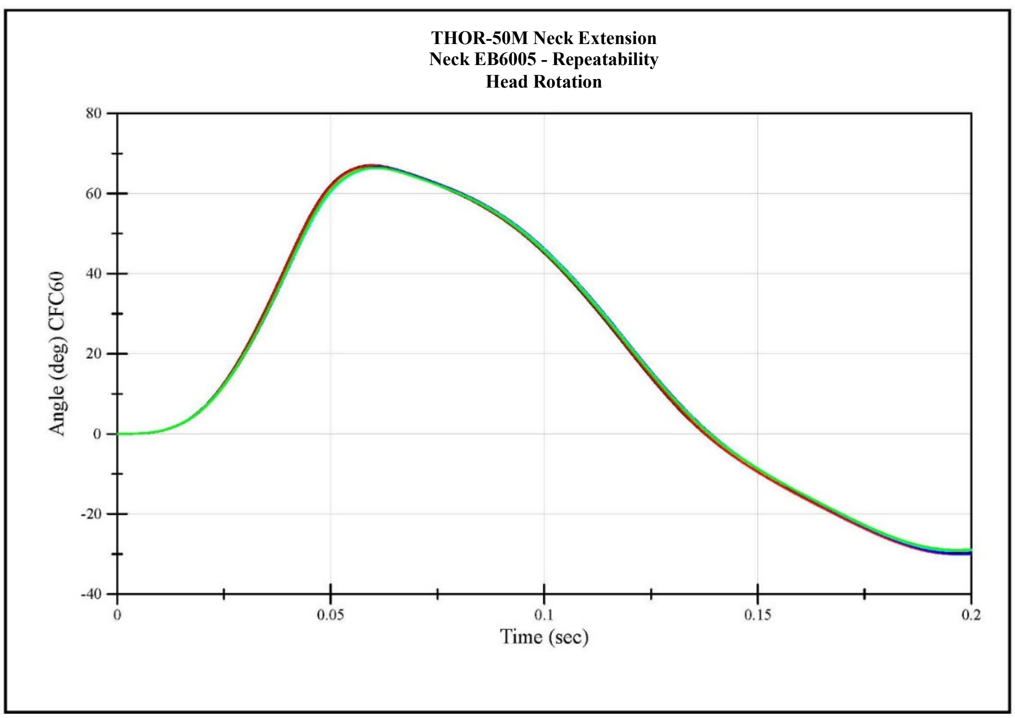

Figure 7-13. VRTC neck extension head rotation repeatability for Neck EB6005

7.2.4 THOR-50M Neck EB6007 Testing at Humanetics

Repeatability results at Humanetics for Neck EB6007 in the neck extension qualification yielded CV values all below 5 percent (Table 7-7 and Table 7-8, Figure 7-14 to Figure 7-17).

Table 7-7. Humanetics THOR-50M Neck EB6007 Extension Pulse Repeatability Results

Test Number	Pendulum Velocity at 10 ms After T0 (m/s)	Pendulum Velocity at 20 ms After T0 (m/s)	Pendulum Velocity at 30 ms After T0 (m/s)
370439.01	1.86	3.63	5.05
370453.01	1.90	3.64	4.99
370500	1.86	3.60	5.00
370501	1.92	3.65	5.04
370502	1.95	3.78	5.13
Mean	**1.90**	**3.66**	**5.04**
Std. Dev.	**0.04**	**0.07**	**0.06**
CV	**2.1%**	**1.9%**	**1.1%**

Table 7-8. Humanetics THOR-50M Neck EB6007 Extension Repeatability Results

Test Number	Peak Upper Neck My (N-m)	Peak Upper Neck Fz (N)	Peak Head Angular Velocity ω_y (relative to earth) (deg/s)	Peak Head Rotation (relative to pendulum) (deg)
370439.01	-22.0	-3241	2139	62.0
370453.01	-22.1	-3239	2154	62.3
370500	-22.2	-3211	2129	62.1
370501	-21.9	-3181	2149	62.7
370502	-22.0	-3242	2193	63.0
Mean	**-22.0**	**-3223**	**2153**	**62.4**
Std. Dev.	**0.1**	**27**	**24**	**0.4**
CV	**0.5%**	**0.8%**	**1.1%**	**0.7%**

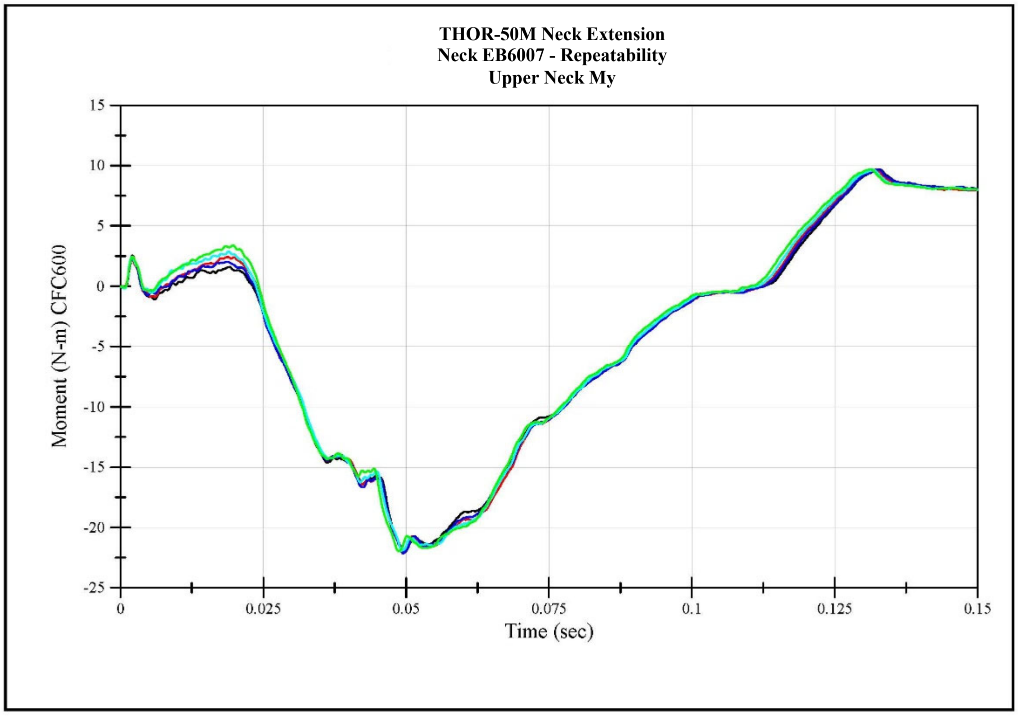

Figure 7-14. Humanetics neck extension upper neck Y-moment repeatability for Neck EB6007

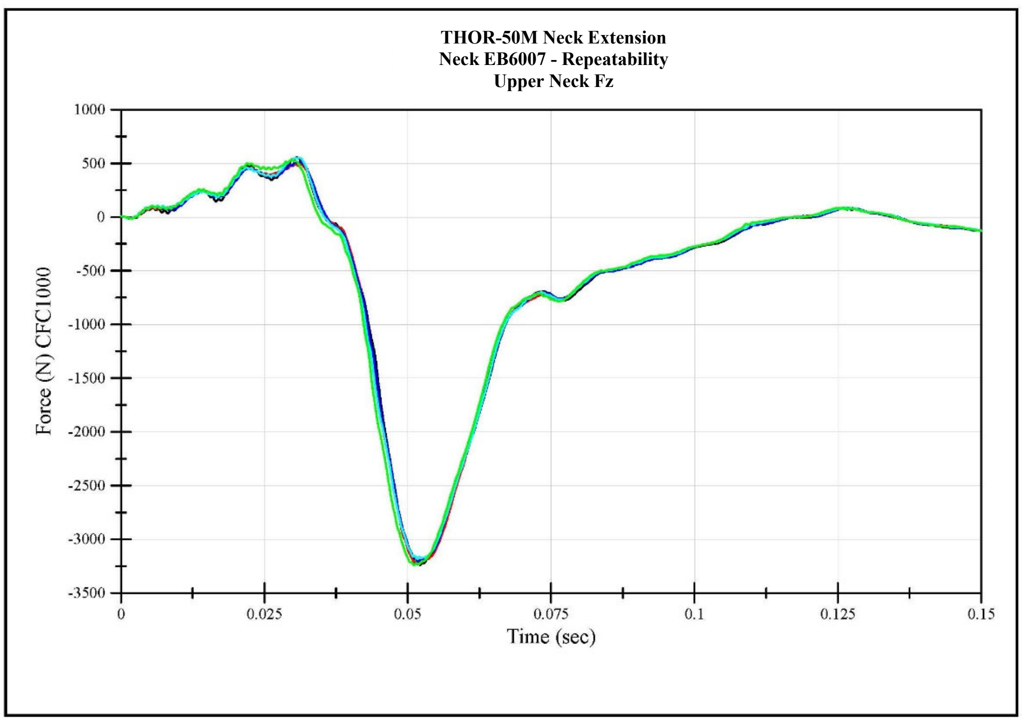

Figure 7-15. Humanetics neck extension upper neck Z-force repeatability for Neck EB6007

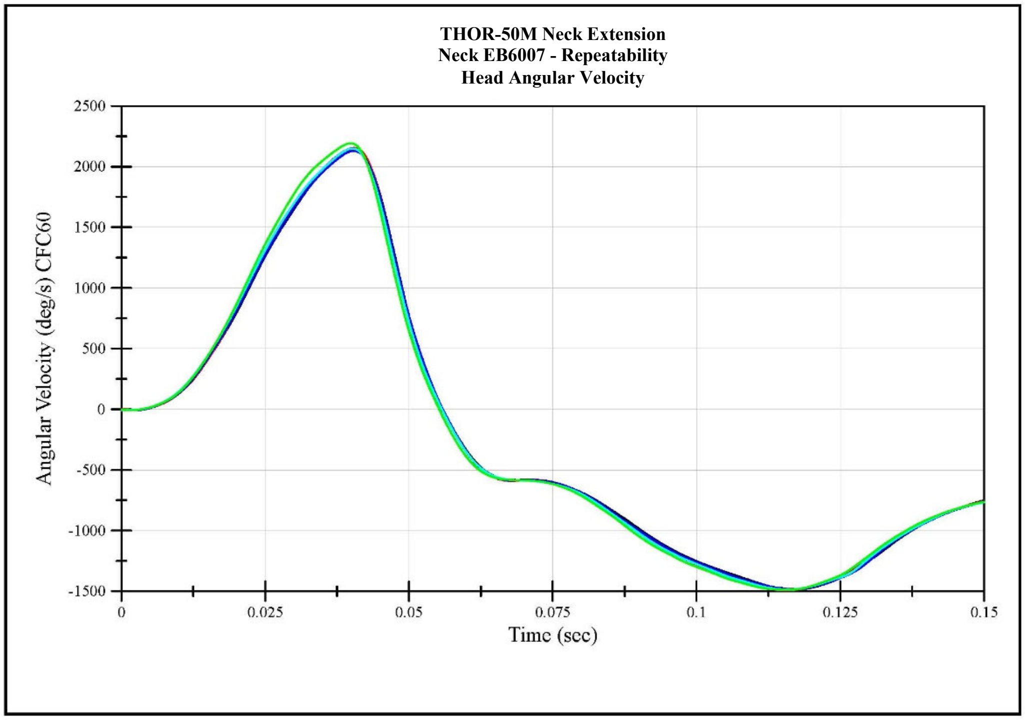

Figure 7-16. Humanetics neck extension head angular velocity repeatability for Neck EB6007

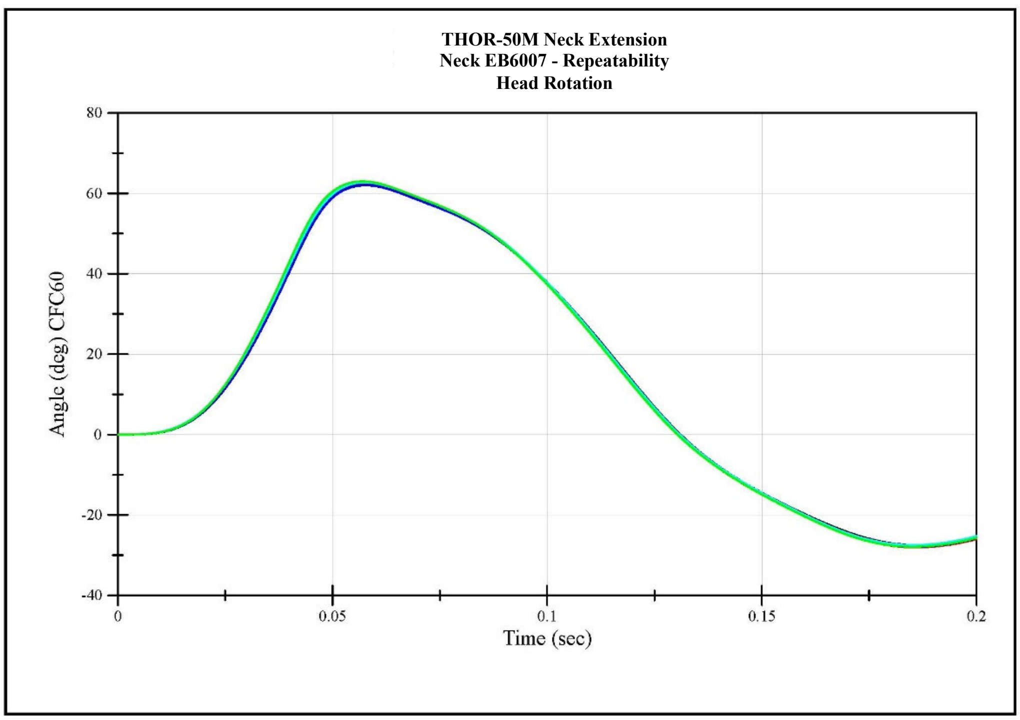

Figure 7-17. Humanetics neck extension head rotation repeatability for Neck EB6007

7.2.5 THOR-50M Neck EB6007 Testing at Calspan

Repeatability results at Calspan for Neck EB6007 in the neck extension qualification yielded CV values all below 5 percent with the exception of Fz which was above 5 percent but less than 10 percent (Table 7-9 and Table 7-10, Figure 7-18 to Figure 7-21).

Table 7-9. Calspan THOR-50M Neck EB6007 Extension Pulse Repeatability Results

Test Number	Pendulum Velocity at 10 ms After T0 (m/s)	Pendulum Velocity at 20 ms After T0 (m/s)	Pendulum Velocity at 30 ms After T0 (m/s)
20170522153239	1.95	3.72	5.11
20170523070934	2.01	3.85	5.25
20170523094141	1.97	3.82	5.22
20170523101341	1.99	3.79	5.22
20170523114925	1.90	3.71	5.17
Mean	**1.96**	**3.78**	**5.19**
Std. Dev.	**0.04**	**0.06**	**0.06**
CV	**2.2%**	**1.6%**	**1.1%**

Table 7-10. Calspan THOR-50M Neck EB6007 Extension Repeatability Results

Test Number	Peak Upper Neck My (N-m)	Peak Upper Neck Fz (N)	Peak Head Angular Velocity ω_y (relative to earth) (deg/s)	Peak Head Rotation (relative to pendulum) (deg)
20170522153239	-22.6	-2311	1894	60.6
20170523070934	-24.2	-2392	1948	62.1
20170523094141	-24.3	-2387	1946	62.4
20170523101341	-25.1	-2537	1950	63.0
20170523114925	-25.5	-2629	1951	63.2
Mean	**-24.3**	**-2451**	**1938**	**62.3**
Std. Dev.	**1.1**	**129**	**25**	**1.0**
CV	**4.5%**	**5.3%**	**1.3%**	**1.7%**

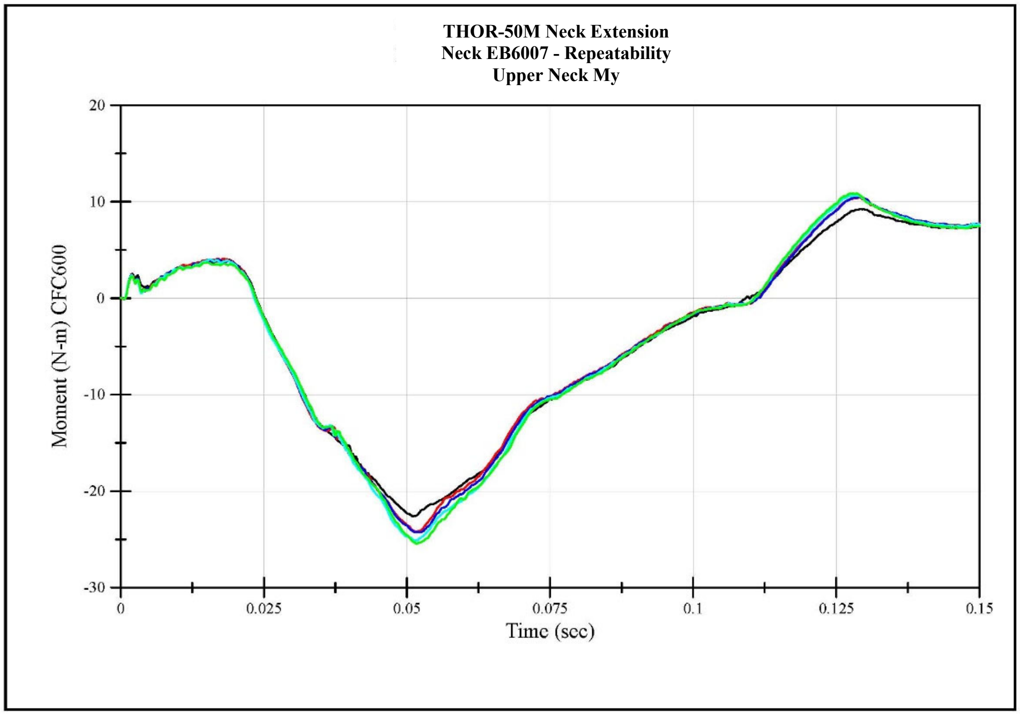

Figure 7-18. Calspan neck extension upper neck Y-moment repeatability for Neck EB6007

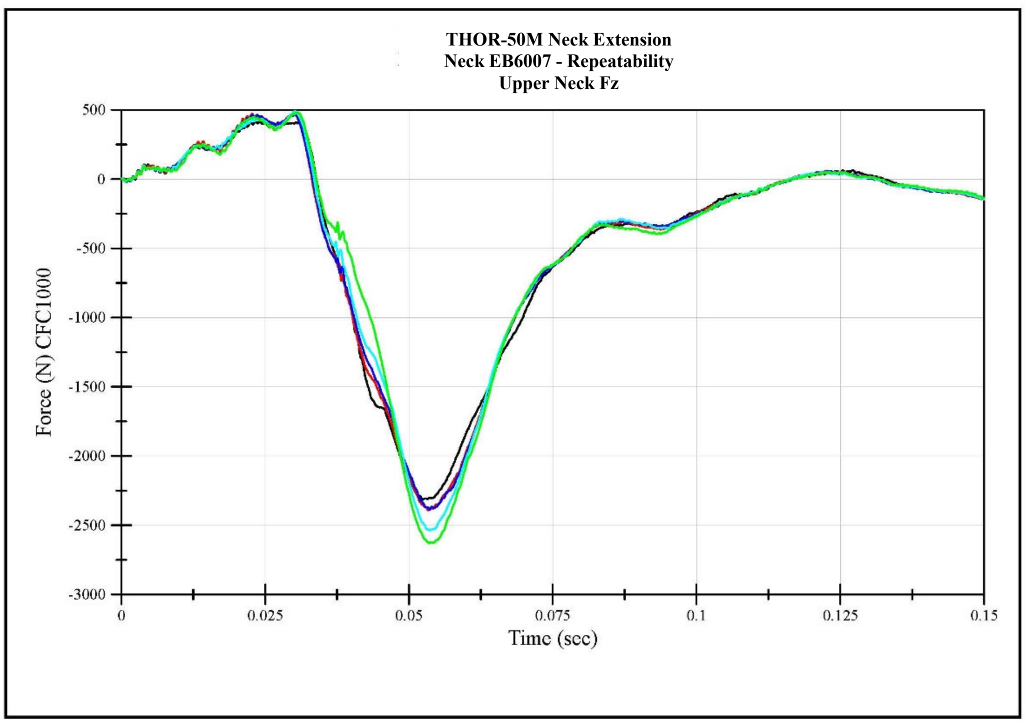

Figure 7-19. Calspan neck extension upper neck Z-force repeatability for Neck EB6007

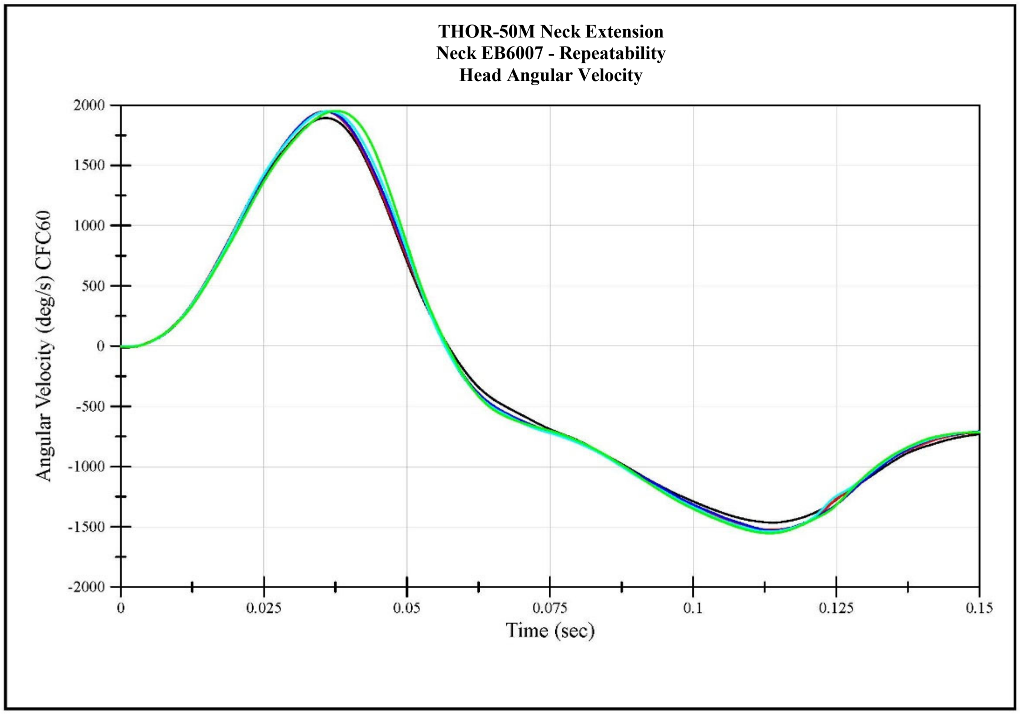

Figure 7-20. Calspan neck extension head angular velocity repeatability for Neck EB6007

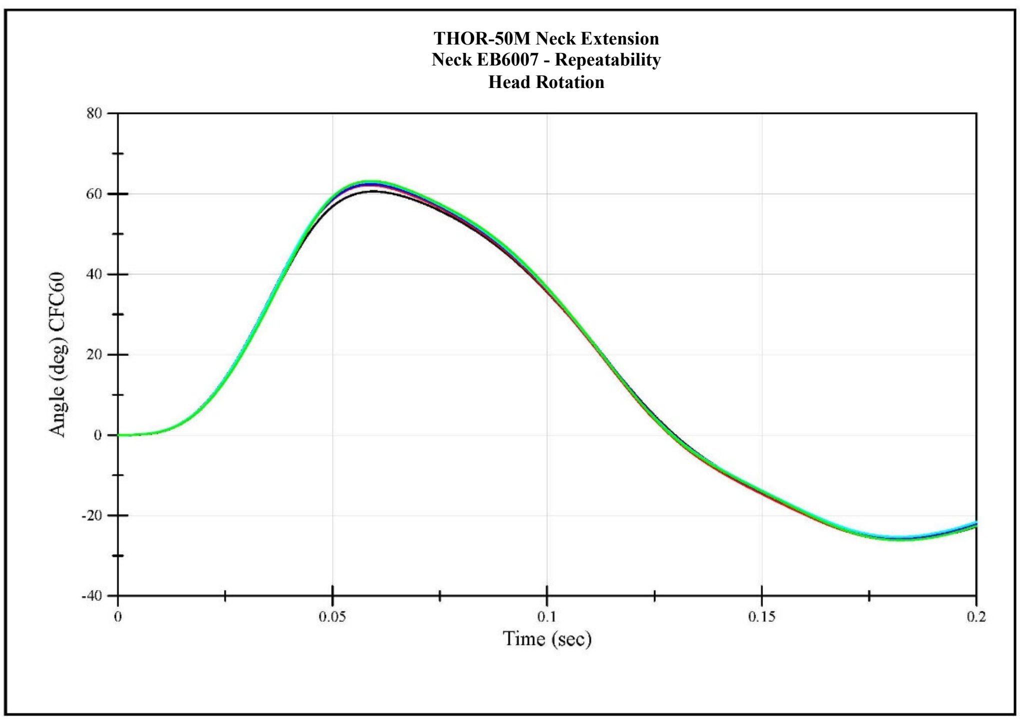

Figure 7-21. Calspan neck extension head rotation repeatability for Neck EB6007

7.3 Neck Extension Dummy Reproducibility Results

Dummy Reproducibility results at VRTC for the three THOR-50M necks yielded CV values all below 5 percent (Table 7-11 and Table 7-12).

Table 7-11. THOR-50M Neck Extension Pulse Dummy Reproducibility Results

Neck Number	Test Number	Pendulum Velocity at 10 ms After T0 (m/s)	Pendulum Velocity at 20 ms After T0 (m/s)	Pendulum Velocity at 30 ms After T0 (m/s)
VRTC Neck EB6007	**170215-6**	1.95	3.64	4.91
	170215-8	1.90	3.59	5.01
	170215-9	2.00	3.71	5.01
	170215-11	1.97	3.74	5.12
	170216-3	1.96	3.69	4.91
VRTC Neck EB6005	**170222-6**	2.02	3.73	5.13
	170222-7	1.97	3.73	5.10
	170222-8	1.90	3.58	4.95
	170222-9	1.94	3.59	4.89
	170223-1	1.90	3.59	5.00
VRTC Neck EB6006	**170224-2**	1.83	3.51	4.94
	170227-4	2.04	3.84	5.21
	170227-6	1.81	3.51	4.86
	170227-8	1.92	3.58	4.90
	170227-9	1.89	3.58	4.84
Mean		**1.93**	**3.64**	**4.98**
Std. Dev.		**0.07**	**0.09**	**0.11**
CV		**3.4%**	**2.6%**	**2.2%**

Table 7-12. THOR-50M Neck Extension Reproducibility Results

Neck Number	Test Number	Peak Upper Neck My (N-m)	Peak Upper Neck Fz (N)	Peak Head Angular Velocity ω_y (relative to earth) (deg/s)	Peak Head Rotation (relative to pendulum) (deg)
VRTC Neck EB6007	**170215-6**	-21.1	-3043	2048	64.0
	170215-8	-22.3	-3080	2070	64.5
	170215-9	-22.3	-3108	2090	65.1
	170215-11	-22.6	-3143	2121	65.4
	170216-3	-22.9	-3040	2058	64.4
VRTC Neck EB6005	**170222-6**	-24.0	-2930	2152	67.1
	170222-7	-23.9	-2889	2152	66.9
	170222-8	-23.7	-2819	2088	66.6
	170222-9	-23.7	-2812	2074	66.3
	170223-1	-24.0	-2871	2120	66.4
VRTC Neck EB6006	**170224-2**	-23.2	-2897	1960	64.1
	170227-4	-23.2	-3124	2096	66.6
	170227-6	-22.4	-2955	2004	66.3
	170227-8	-22.1	-2952	2025	66.5
	170227-9	-21.9	-2921	2010	66.6
Mean		**-22.9**	**-2972**	**2071**	**65.8**
Std. Dev.		**0.9**	**110**	**55**	**1.1**
CV		**3.9%**	**3.7%**	**2.7%**	**1.7%**

7.4 THOR-50M Neck EB6007 Lab-to-Lab Variability Analysis

The results for neck extension qualification tests from each lab are presented in Table 7-13 and Table 7-14. The last four rows of the tables show the *Test Reproducibility* results when data from all three labs are combined. For the pulse, the CV values are all below 5 percent (Table 7-13). The dummy metrics indicate that there was a disparity on neck loads (Table 7-14). In particular, the Fz measurements were clustered at three distinct force levels by test laboratory: levels were highest at Humanetics, and lowest at Calspan. This clustering resulted in a CV greater than 10 percent. The clustering was also prominent in the My results with CV values above 5 percent but less than 10 percent.

Table 7-13. THOR-50M Neck Extension Pulse Lab-to-Lab Variability Results

Neck Number	Pendulum Velocity at 10 ms After T0 (m/s)	Pendulum Velocity at 20 ms After T0 (m/s)	Pendulum Velocity at 30 ms After T0 (m/s)
VRTC Neck EB6007	1.95	3.64	4.91
	1.90	3.59	5.01
	2.00	3.71	5.01
	1.97	3.74	5.12
	1.96	3.69	4.91
Humanetics Neck EB6007	1.86	3.63	5.05
	1.90	3.64	4.99
	1.86	3.60	5.00
	1.92	3.65	5.04
	1.95	3.78	5.13
Calspan Neck EB6007	1.95	3.72	5.11
	2.01	3.85	5.25
	1.97	3.82	5.22
	1.99	3.79	5.22
	1.90	3.71	5.17
Test Reproducibility EB6007 ALL Labs			
Mean	**1.94**	**3.70**	**5.07**
Std. Dev.	**0.05**	**0.08**	**0.11**
CV	**2.4%**	**2.2%**	**2.2%**

Table 7-14. THOR-50M Neck Extension Lab-to-Lab Variability Results

Neck Number	Peak Upper Neck My (N-m)	Peak Upper Neck Fz (N)	Peak Head Angular Velocity ω_y (relative to earth) (deg/s)	Peak Head Rotation (relative to pendulum) (deg)
VRTC Neck EB6007	-21.1	-3043	2048	64.0
	-22.3	-3080	2070	64.5
	-22.3	-3108	2090	65.1
	-22.6	-3143	2121	65.4
	-22.9	-3040	2058	64.4
Humanetics Neck EB6007	-22.0	-3241	2139	62.0
	-22.1	-3239	2154	62.3
	-22.2	-3211	2129	62.1
	-21.9	-3181	2149	62.7
	-22.0	-3242	2193	63.0
Calspan Neck EB6007	-22.6	-2311	1894	60.6
	-24.2	-2392	1948	62.1
	-24.3	-2387	1946	62.4
	-25.1	-2537	1950	63.0
	-25.5	-2629	1951	63.2
Repeatability EB6007 ALL Labs				
Mean	**-22.9**	**-2919**	**2046**	**63.6**
Std. Dev.	**1.3**	**355**	**91**	**1.3**
CV	**5.6%**	**12.2%**	**4.4%**	**2.0%**

7.5 Corridor Development

All the data used to determine the neck extension qualification corridors are shown in Table 7-15 and Table 7-16. The qualification corridors were calculated using the mean plus or minus 10 percent of the peak for the specified measured or calculated channels (Table 7-17).

Table 7-15. THOR-50M Neck Extension Pulse Qualification Corridor Results

Neck Number	Test Number	Pendulum Velocity at 10 ms After T0 (m/s)	Pendulum Velocity at 20 ms After T0 (m/s)	Pendulum Velocity at 30 ms After T0 (m/s)
VRTC Neck EB6007	**170215-6**	1.95	3.64	4.91
	170215-8	1.90	3.59	5.01
	170215-9	2.00	3.71	5.01
	170215-11	1.97	3.74	5.12
	170216-3	1.96	3.69	4.91
VRTC Neck EB6005	**170222-6**	2.02	3.73	5.13
	170222-7	1.97	3.73	5.10
	170222-8	1.90	3.58	4.95
	170222-9	1.94	3.59	4.89
	170223-1	1.90	3.59	5.00
VRTC Neck EB6006	**170224-2**	1.83	3.51	4.94
	170227-4	2.04	3.84	5.21
	170227-6	1.81	3.51	4.86
	170227-8	1.92	3.58	4.90
	170227-9	1.89	3.58	4.84
Humanetics EB6007	**370439.01**	1.86	3.63	5.05
	370453.01	1.90	3.64	4.99
	370500	1.86	3.60	5.00
	370501	1.92	3.65	5.04
	370502	1.95	3.78	5.13
Calspan EB6007	**20170522153239**	1.95	3.72	5.11
	20170523070934	2.01	3.85	5.25
	20170523094141	1.97	3.82	5.22
	20170523101341	1.99	3.79	5.22
	20170523114925	1.90	3.71	5.17
Mean		**1.93**	**3.67**	**5.04**
Std. Dev.		**0.06**	**0.10**	**0.12**
CV		**3.0%**	**2.7%**	**2.4%**

Table 7-16. THOR-50M Neck Extension Qualification Corridor Results

Neck Number	Test Number	Peak Upper Neck My (N-m)	Peak Upper Neck Fz (N)	Peak Head Angular Velocity ω_y (relative to earth) (deg/s)	Peak Head Rotation (relative to pendulum) (deg)
VRTC Neck EB6007	**170215-6**	-21.1	-3043	2048	64.0
	170215-8	-22.3	-3080	2070	64.5
	170215-9	-22.3	-3108	2090	65.1
	170215-11	-22.6	-3143	2121	65.4
	170216-3	-22.9	-3040	2058	64.4
VRTC Neck EB6005	**170222-6**	-24.0	-2930	2152	67.1
	170222-7	-23.9	-2889	2152	66.9
	170222-8	-23.7	-2819	2088	66.6
	170222-9	-23.7	-2812	2074	66.3
	170223-1	-24.0	-2871	2120	66.4
VRTC Neck EB6006	**170224-2**	-23.2	-2897	1960	64.1
	170227-4	-23.2	-3124	2096	66.6
	170227-6	-22.4	-2955	2004	66.3
	170227-8	-22.1	-2952	2025	66.5
	170227-9	-21.9	-2921	2010	66.6
Humanetics Neck EB6007	**370439.01**	-22.0	-3241	2139	62.0
	370453.01	-22.1	-3239	2154	62.3
	370500	-22.2	-3211	2129	62.1
	370501	-21.9	-3181	2149	62.7
	370502	-22.0	-3242	2193	63.0
Calspan Neck EB6007	**20170522153239**	-22.6	-2311	1894	60.6
	20170523070934	-24.2	-2392	1948	62.1
	20170523094141	-24.3	-2387	1946	62.4
	20170523101341	-25.1	-2537	1950	63.0
	20170523114925	-25.5	-2629	1951	63.2
Mean		**-23.0**	**-2918**	**2061**	**65.0**
Std. Dev.		**1.1**	**277**	**83**	**1.8**
CV		**4.8%**	**9.5%**	**4.0%**	**2.7%**

Table 7-17. Neck Extension Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Pendulum Velocity at 10 ms After T0	**m/s**	1.74	2.12	1.93	10.0%
Pendulum Velocity at 20 ms After T0	**m/s**	3.30	4.04	3.67	10.0%
Pendulum Velocity at 30 ms After T0	**m/s**	4.53	5.54	5.04	10.0%
Impact Velocity	**m/s**	4.95	5.05	5.00	
Peak Upper Neck M_y	**N-m**	-25.3	-20.7	-23.0	10.0%
Peak Upper Neck F_z	**N**	-3210	-2626	-2918	10.0%
Peak Head Angular Velocity ω_y (relative to earth)	**deg/s**	1855	2267	2061	10.0%
Peak Head Rotation (relative to pendulum)	**deg**	58.5	71.5	65.0	10.0%

Discussion. The results indicate that *Dummy/Test Repeatability*, and *Dummy Reproducibility* were all sufficient. Thus, the variability appears mostly related to the T*est Reproducibility*, which was the apparent source of the data clusters that led to the high CV values for Fz (>10%) seen in Table 7-14. As seen in Table 7-16, all tests at Calspan were outside of the ±10 limits for either My (1 test) or Fz (4 tests).

In tests at all labs, there is an inverse relationship between My and Fz. At all three labs, the shapes of the My and Fz pulses are very similar, but the higher My values (and lower Fz values) always occurred at Calspan. The *Test Reproducibility* of the input pulses (shown in Table 7-15) also show clustering in which the Calspan setup produced higher velocities than the other labs.

Thus, this situation appears similar to the one for Neck Flexion. That is, a result at Calspan within ± 10 percent probably could have been achieved by adjusting the input pulse through the selection of their honeycomb cell configuration.

8 Neck Lateral Flexion

8.1 Methodology

Repeatability and reproducibility 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”) aluminum honeycomb for pendulum deceleration from an impact velocity of 3.40 ± 0.05 m/s (Figure 8-1). For the lateral neck flexion 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 the aluminum honeycomb. During these tests the upper neck X-axis moment (Mx), head angular rate, and head rotation were measured.

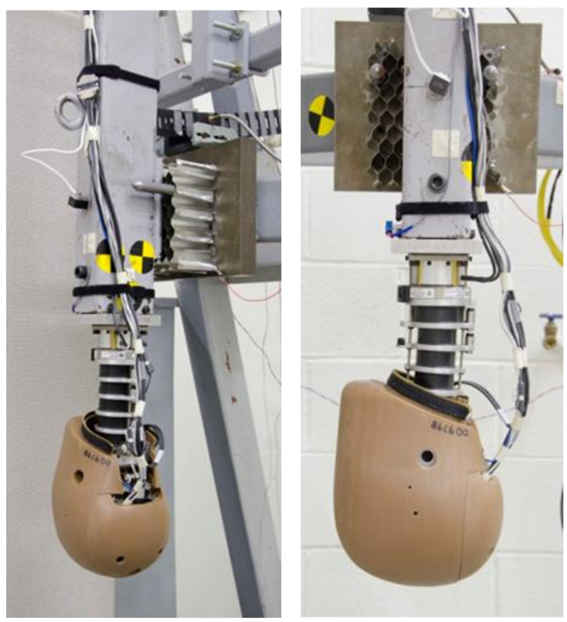

Figure 8-1. Neck lateral flexion test setup

8.2 Neck Lateral Flexion Repeatability Results

Sections 8.2.1 to 8.2.5 illustrate the results of the left neck lateral flexion repeatability tests. For this study, only the left side was tested since the neck is symmetrical and results between left and right sides should be similar. Each section contains a table providing the quantified test data, followed by plot overlays of the five repeat tests conducted at all three labs. Note that the data in the tables containing the results of each test series are listed sequentially, with the test at the top of the table beginning the test series.

8.2.1 THOR-50M Neck EB6007 Testing at VRTC

Repeatability results at VRTC for Neck EB6007 (left) in the lateral flexion qualification yielded CV values all below 5 percent (Table 8-1 and Table 8-2, Figure 8-2 to Figure 8-4).

Table 8-1. VRTC THOR-50M Neck EB6007 Left Lateral Flexion Pulse Repeatability Results

Test Number	Pendulum Velocity at 4 ms After T0 (m/s)	Pendulum Velocity at 8 ms After T0 (m/s)	Pendulum Velocity at 12 ms After T0 (m/s)
170328-15	1.24	2.43	3.55
170328-18	1.20	2.35	3.53
170328-20	1.20	2.36	3.54
170328-21	1.23	2.36	3.50
170328-22	1.18	2.29	3.48
Mean	**1.21**	**2.36**	**3.52**
Std. Dev.	**0.02**	**0.05**	**0.03**
CV	**2.0%**	**2.1%**	**0.9%**

Table 8-2. VRTC THOR-50M Neck EB6007 Left Lateral Flexion Repeatability Results

Test Number	Upper Neck Mx After 40.0 ms (N-m)	Peak Head Angular Velocity ω_x (relative to earth) (deg/s)	Peak Head Rotation (relative to pendulum) (deg)
170328-15	51.4	-1353	-40.9
170328-18	51.0	-1366	-42.4
170328-20	51.3	-1360	-42.1
170328-21	50.3	-1344	-42.5
170328-22	50.6	-1346	-42.6
Mean	**50.9**	**-1354**	**-42.1**
Std. Dev.	**0.5**	**9**	**0.7**
CV	**0.9%**	**0.7%**	**1.7%**

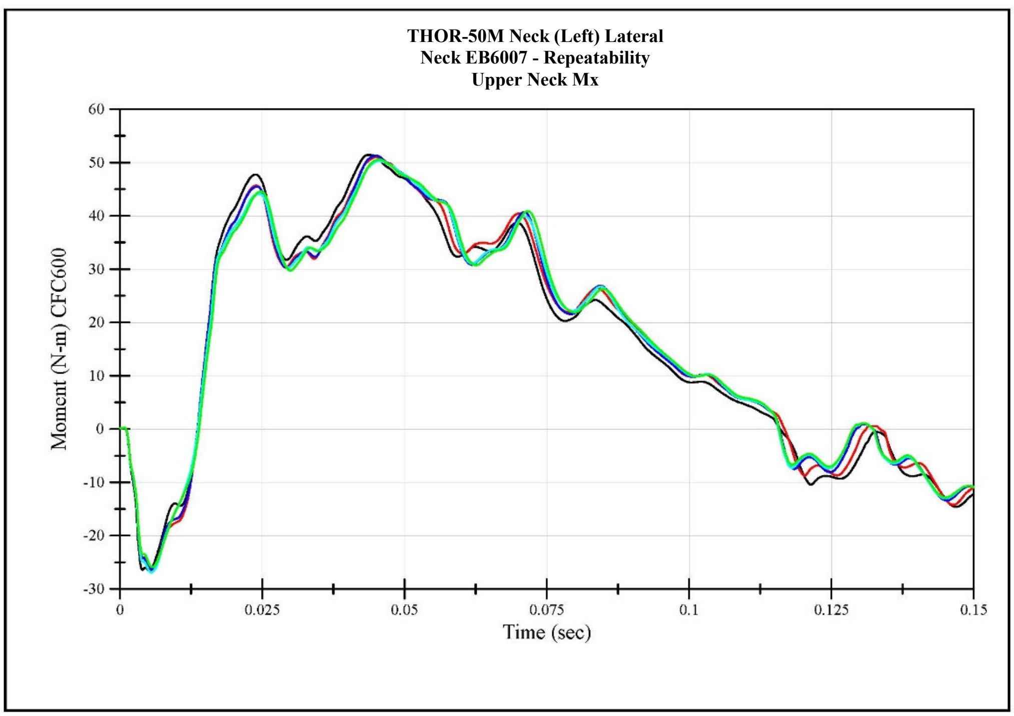

Figure 8-2. VRTC neck left lateral flexion upper neck X-moment repeatability for Neck EB6007

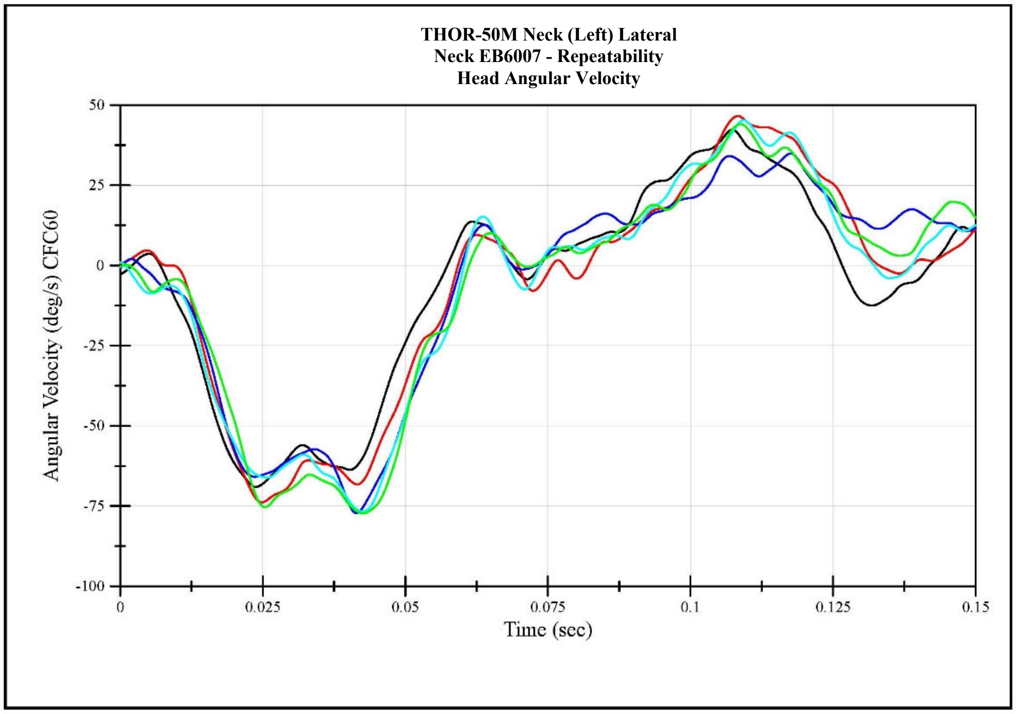

Figure 8-3. VRTC neck left lateral flexion head angular velocity repeatability for Neck EB6007

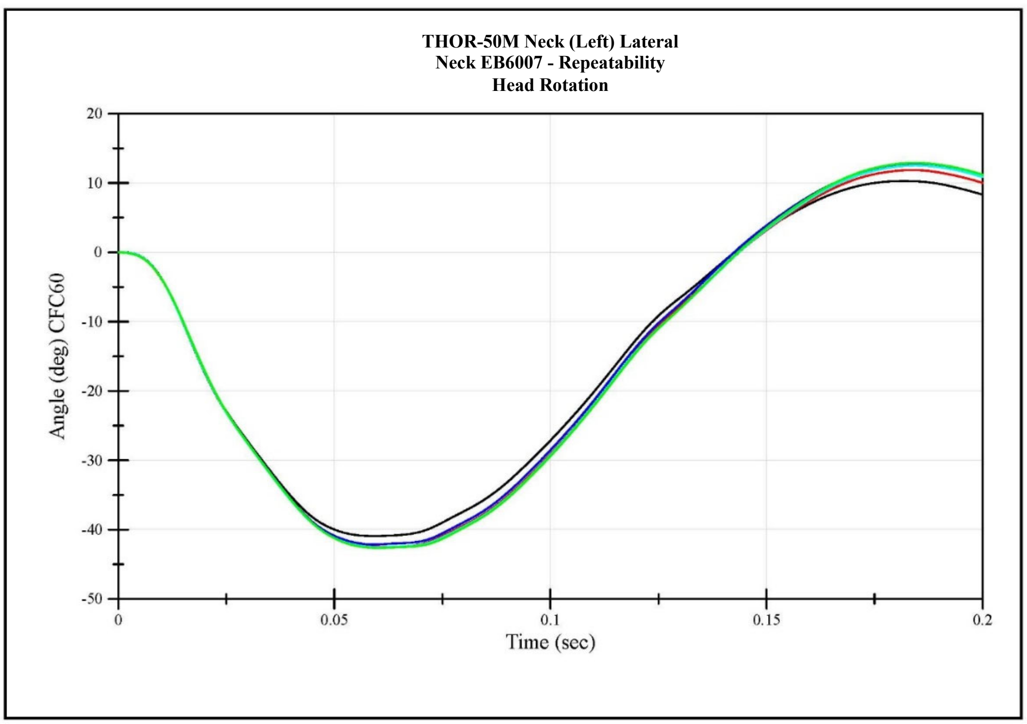

Figure 8-4. VRTC neck left lateral head rotation repeatability for Neck EB6007

8.2.2 THOR-50M Neck EB6006 Testing at VRTC

Repeatability results at VRTC for Neck EB6006 (left) in the lateral flexion qualification yielded CV values all below 5 percent (Table 8-3 and Table 8-4, Figure 8-5 to Figure 8-7).

Table 8-3. VRTC THOR-50M Neck EB6006 Left Lateral Flexion Pulse Repeatability Results

Test Number	Pendulum Velocity at 4 ms After T0 (m/s)	Pendulum Velocity at 8 ms After T0 (m/s)	Pendulum Velocity at 12 ms After T0 (m/s)
170315-8	1.26	2.46	3.54
170315-9	1.15	2.28	3.41
170315-10	1.18	2.28	3.46
170315-13	1.15	2.29	3.46
170316-2	1.15	2.23	3.44
Mean	**1.18**	**2.31**	**3.46**
Std. Dev.	**0.04**	**0.09**	**0.05**
CV	**3.8%**	**3.8%**	**1.4%**

Table 8-4. VRTC THOR-50M Neck EB6006 Left Lateral Flexion Repeatability Results

Test Number	Upper Neck Mx After 40.0 ms (N-m)	Peak Head Angular Velocity ω_x (relative to earth) (deg/s)	Peak Head Rotation (relative to pendulum) (deg)
170315-8	49.5	-1361	-41.9
170315-9	50.1	-1326	-42.4
170315-10	50.1	-1337	-43.0
170315-13	49.4	-1341	-43.2
170316-2	50.3	-1322	-42.9
Mean	**49.9**	**-1337**	**-42.7**
Std. Dev.	**0.4**	**15**	**0.5**
CV	**0.8%**	**1.1%**	**1.2%**

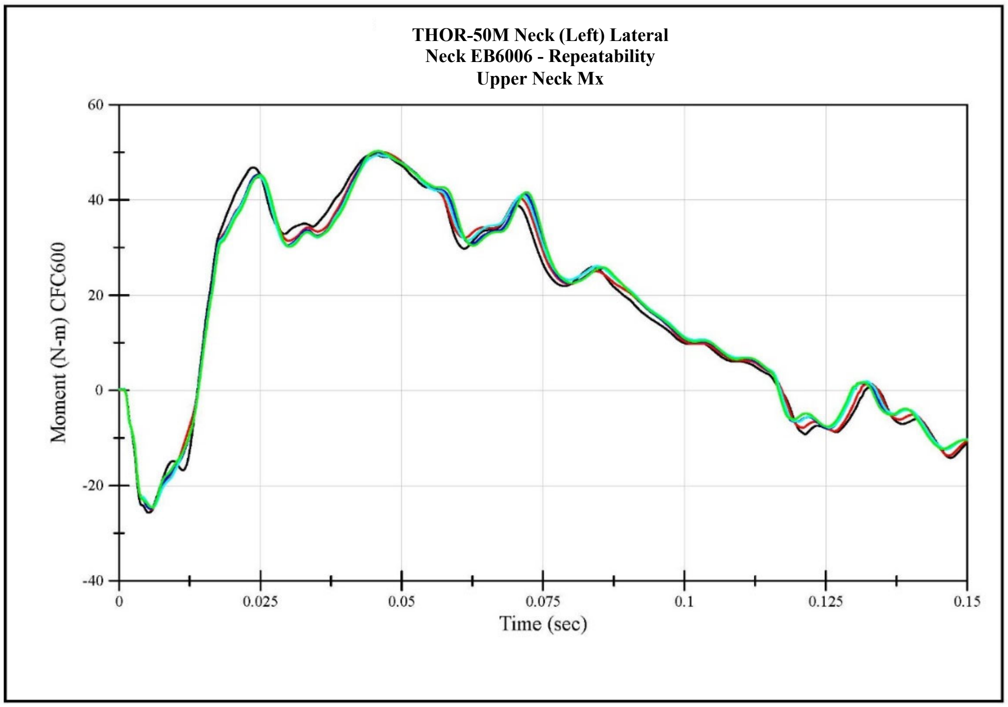

Figure 8-5. VRTC neck left lateral flexion upper neck X-moment repeatability for Neck EB6006

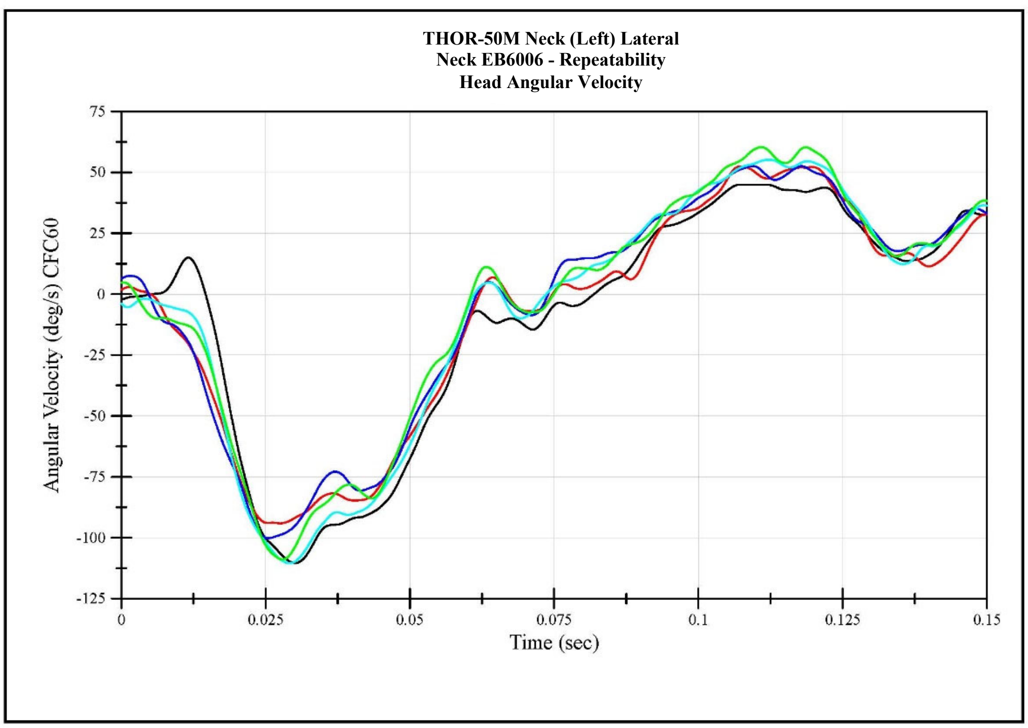

Figure 8-6. VRTC neck left lateral flexion head angular velocity repeatability for Neck EB6006

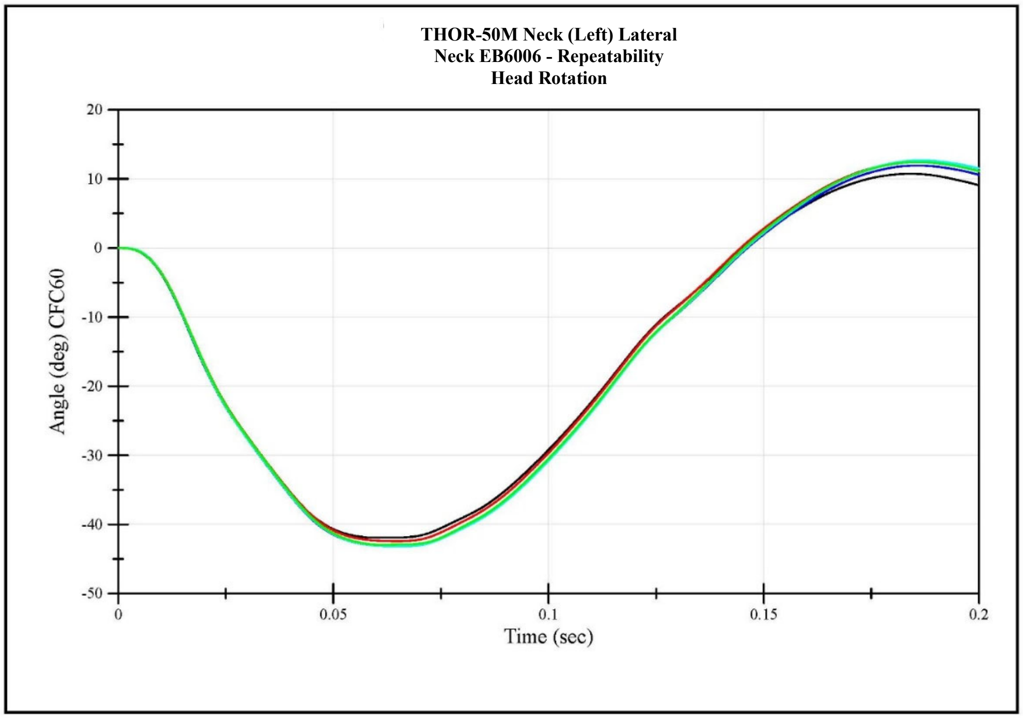

Figure 8-7. VRTC neck left lateral flexion head rotation repeatability for Neck EB6006

8.2.3 THOR-50M Neck EB6005 Testing at VRTC

Repeatability results at VRTC for Neck EB6005 (left) in the lateral flexion qualification yielded CV values all below 5 percent (Table 8-5 and Table 8-6, Figure 8-8 to Figure 8-10).

Table 8-5. VRTC THOR-50M Neck EB6005 Left Lateral Flexion Pulse Repeatability Results

Test Number	Pendulum Velocity at 4 ms After T0 (m/s)	Pendulum Velocity at 8 ms After T0 (m/s)	Pendulum Velocity at 12 ms After T0 (m/s)
170323-1	1.23	2.38	3.53
170323-3	1.27	2.32	3.46
170323-5	1.31	2.39	3.51
170323-9	1.18	2.22	3.41
170323-14	1.22	2.30	3.43
Mean	**1.24**	**2.32**	**3.47**
Std. Dev.	**0.05**	**0.07**	**0.05**
CV	**4.2%**	**2.9%**	**1.5%**

Table 8-6. VRTC THOR-50M Neck EB6005 Left Lateral Flexion Repeatability Results

Test Number	**Upper Neck Mx After 40.0 ms (N-m)**	**Peak Head Angular Velocity ω_x (relative to earth) (deg/s)**	**Peak Head Rotation (relative to pendulum) (deg)**
170323-1	48.8	-1338	-42.3
170323-3	49.5	-1422	-44.4
170323-5	49.9	-1439	-44.6
170323-9	48.5	-1353	-43.8
170323-14	48.2	-1433	-45.2
Mean	**49.0**	**-1397**	**-44.1**
Std. Dev.	**0.7**	**48**	**1.1**
CV	**1.4%**	**3.4%**	**2.5%**

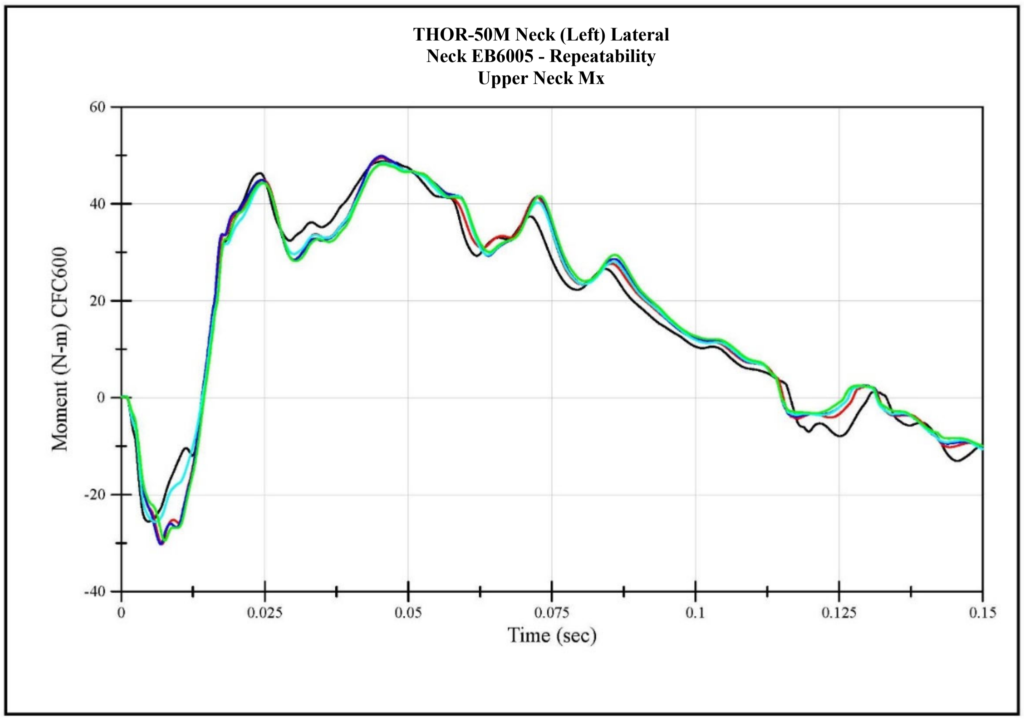

Figure 8-8. VRTC neck left lateral flexion upper neck X-moment repeatability for Neck EB6005

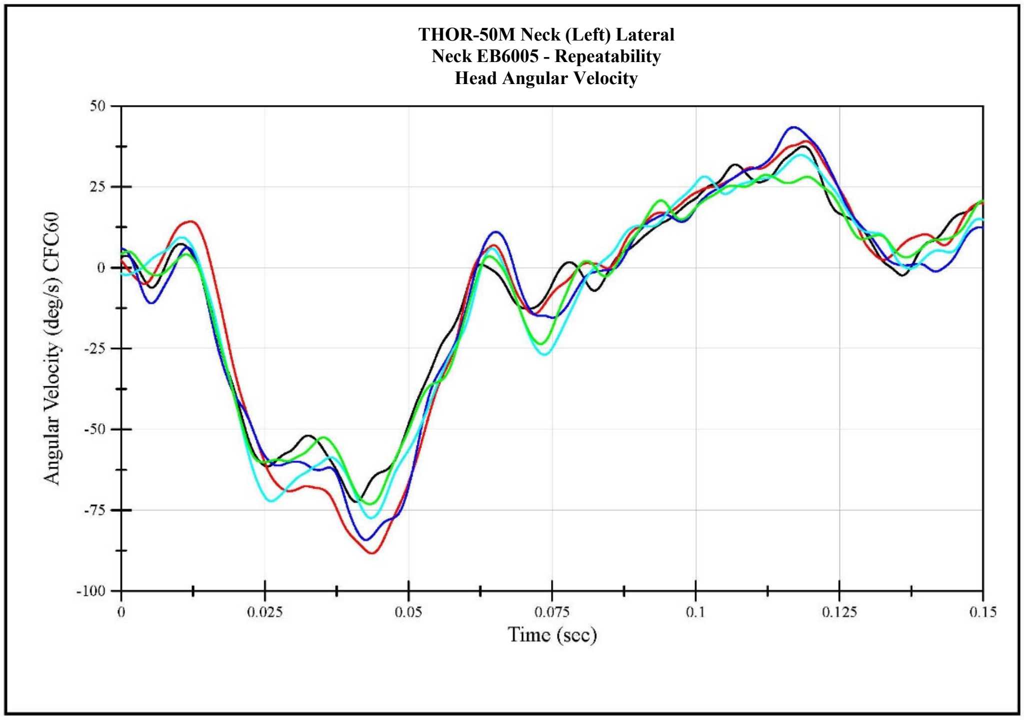

Figure 8-9. VRTC neck left lateral flexion head angular velocity repeatability for Neck EB6005

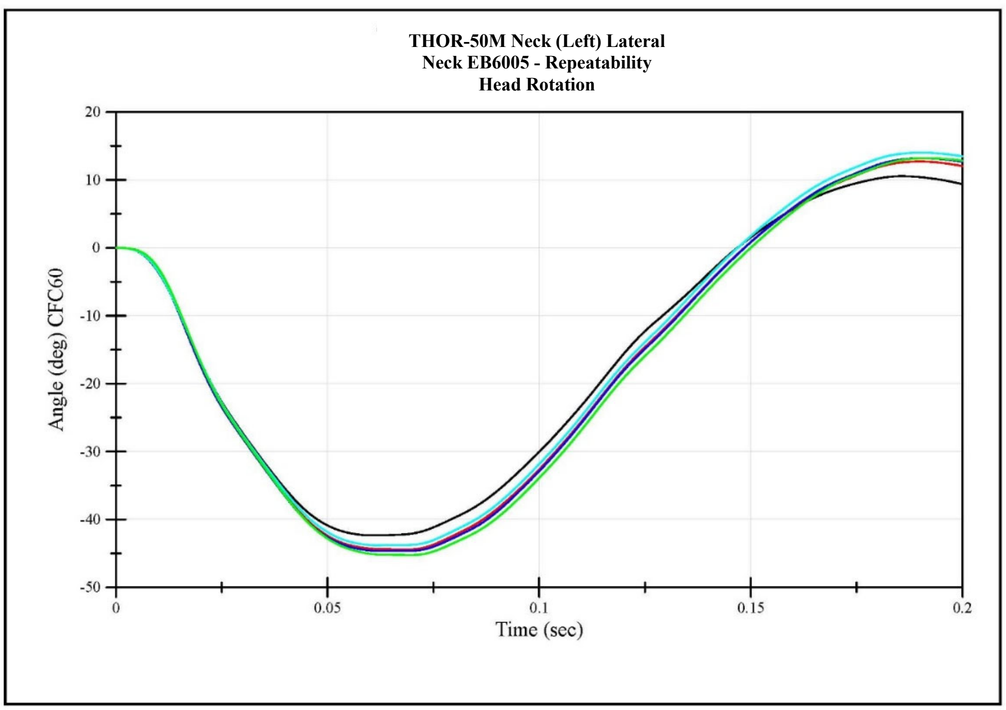

Figure 8-10. VRTC neck left lateral flexion head rotation repeatability for Neck EB6005

8.2.4 THOR-50M Neck EB6007 Testing at Humanetics

Repeatability results at Humanetics for Neck EB6007 (left) in the lateral flexion qualification yielded CV values all below 5 percent (Table 8-7 and Table 8-8, Figure 8-11 to Figure 8-13).

Table 8-7. Humanetics THOR-50M Neck EB6007 Left Lateral Flexion Pulse Repeatability Results

Test Number	Pendulum Velocity at 4 ms After T0 (m/s)	Pendulum Velocity at 8 ms After T0 (m/s)	Pendulum Velocity at 12 ms After T0 (m/s)
370515.01	1.16	2.32	3.62
370519	1.15	2.20	3.34
370521	1.15	2.35	3.60
370524	1.09	2.16	3.34
370526	1.12	2.27	3.56
Mean	**1.13**	**2.26**	**3.49**
Std. Dev.	**0.03**	**0.08**	**0.14**
CV	**2.5%**	**3.6%**	**4.0%**

Table 8-8. Humanetics THOR-50M Neck EB6007 Left Lateral Flexion Repeatability Results

Test Number	Upper Neck Mx After 40.0 ms (N-m)	Peak Head Angular Velocity ω_x (relative to earth) (deg/s)	Peak Head Rotation (relative to pendulum) (deg)
370515.01	50.5	-1375	-40.5
370519	50.4	-1313	-40.2
370521	51.0	-1377	-40.7
370524	51.0	-1323	-40.7
370526	51.9	-1364	-40.6
Mean	**51.0**	**-1350**	**-40.6**
Std. Dev.	**0.6**	**30**	**0.2**
CV	**1.2%**	**2.2%**	**0.5%**

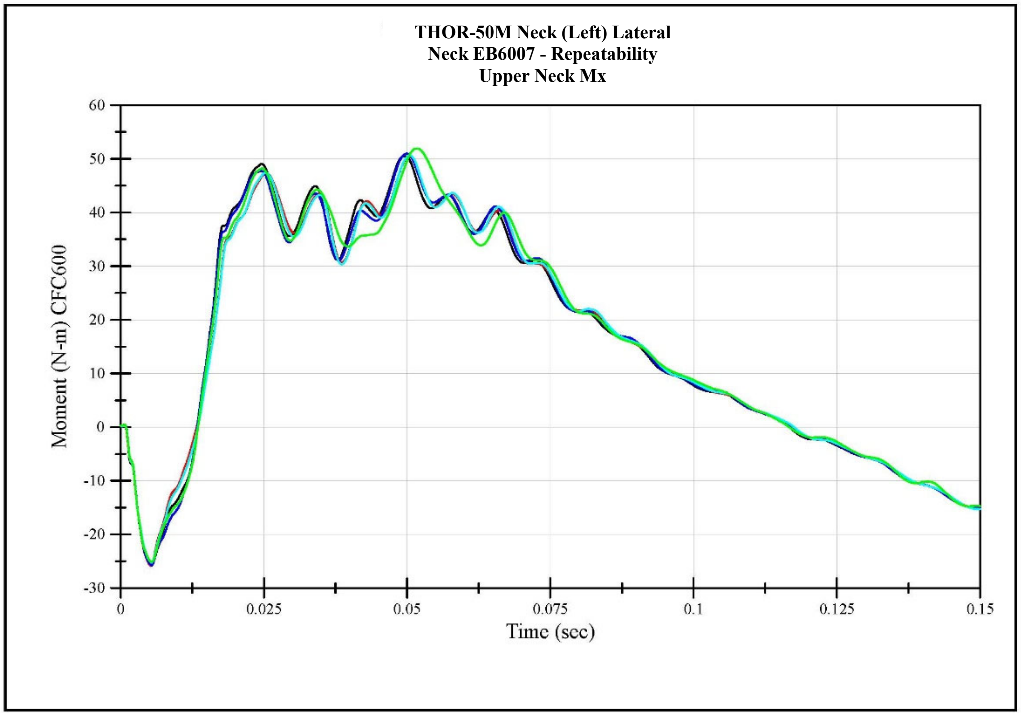

Figure 8-11. Humanetics neck left lateral flexion upper neck X-moment repeatability for Neck EB6007

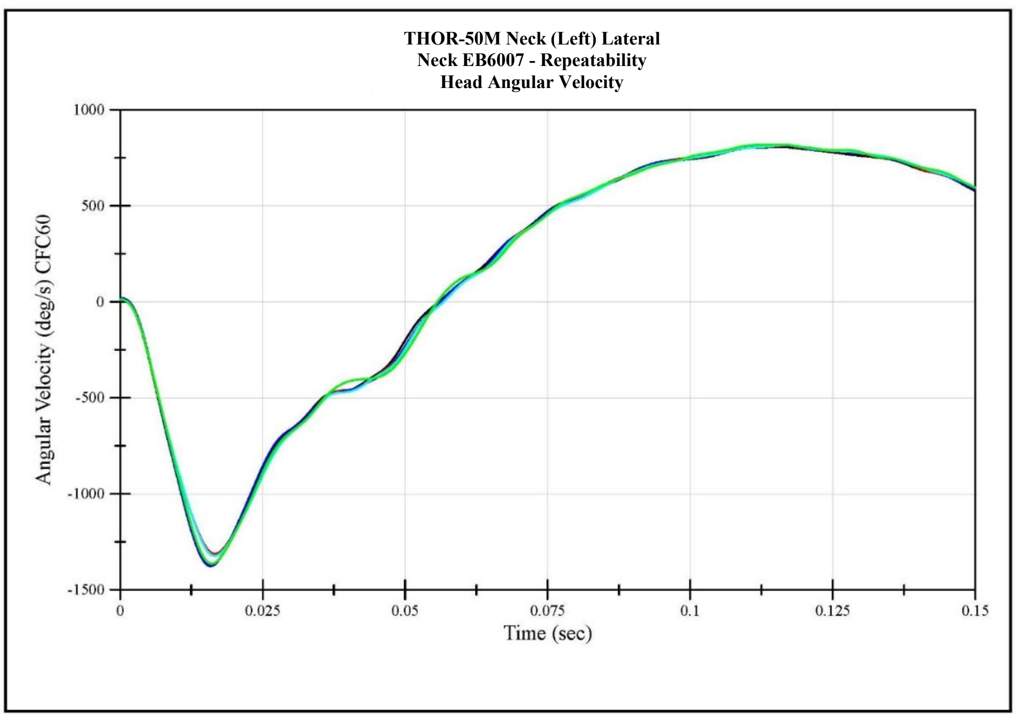

Figure 8-12. Humanetics neck left lateral flexion head angular velocity repeatability for Neck EB6007

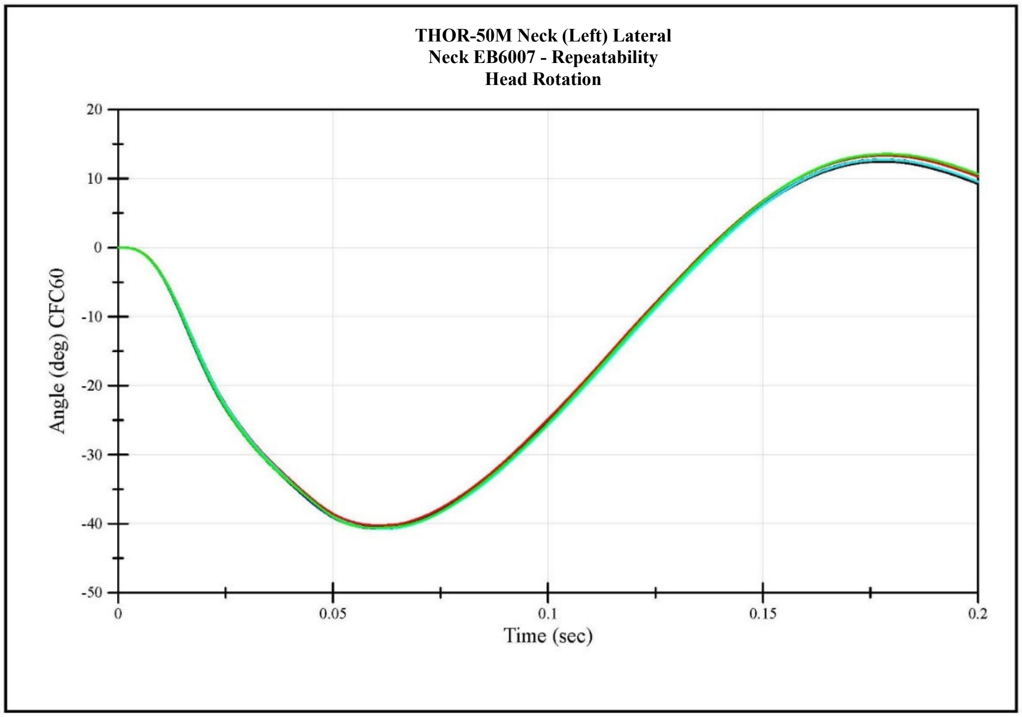

Figure 8-13. Humanetics neck left lateral head rotation repeatability for Neck EB6007

8.2.5 THOR-50M Neck EB6007 Testing at Calspan

Repeatability results at Calspan for Neck EB6007 (left) in the lateral flexion qualification yielded CV values all below 5 percent (Table 8-9 and Table 8-10, Figure 8-14 to Figure 8-16).

Table 8-9. Calspan THOR-50M Neck EB6007 Left Lateral Flexion Pulse Repeatability Results

Test Number	Pendulum Velocity at 4 ms After T0 (m/s)	Pendulum Velocity at 8 ms After T0 (m/s)	Pendulum Velocity at 12 ms After T0 (m/s)
20170524104134	1.10	2.28	3.53
20170524111308	1.15	2.36	3.60
20170523142255	1.12	2.35	3.64
20170524123323	1.11	2.33	3.66
20170524130455	1.14	2.38	3.65
Mean	**1.12**	**2.34**	**3.62**
Std. Dev.	**0.02**	**0.04**	**0.05**
CV	**1.6%**	**1.6%**	**1.4%**

Table 8-10. Calspan THOR-50M Neck EB6007 Left Lateral Flexion Repeatability Results

Test Number	Upper Neck Mx After 40.0 ms (N-m)	Peak Head Angular Velocity ω_x (relative to earth) (deg/s)	Peak Head Rotation (relative to pendulum) (deg)
20170524104134	48.5	-1358	-38.7
20170524111308	49.2	-1369	-39.1
20170523142255	44.6	-1383	-39.4
20170524123323	50.2	-1380	-39.5
20170524130455	47.4	-1371	-39.4
Mean	**48.0**	**-1372**	**-39.2**
Std. Dev.	**2.1**	**10**	**0.3**
CV	**4.4%**	**0.7%**	**0.8%**

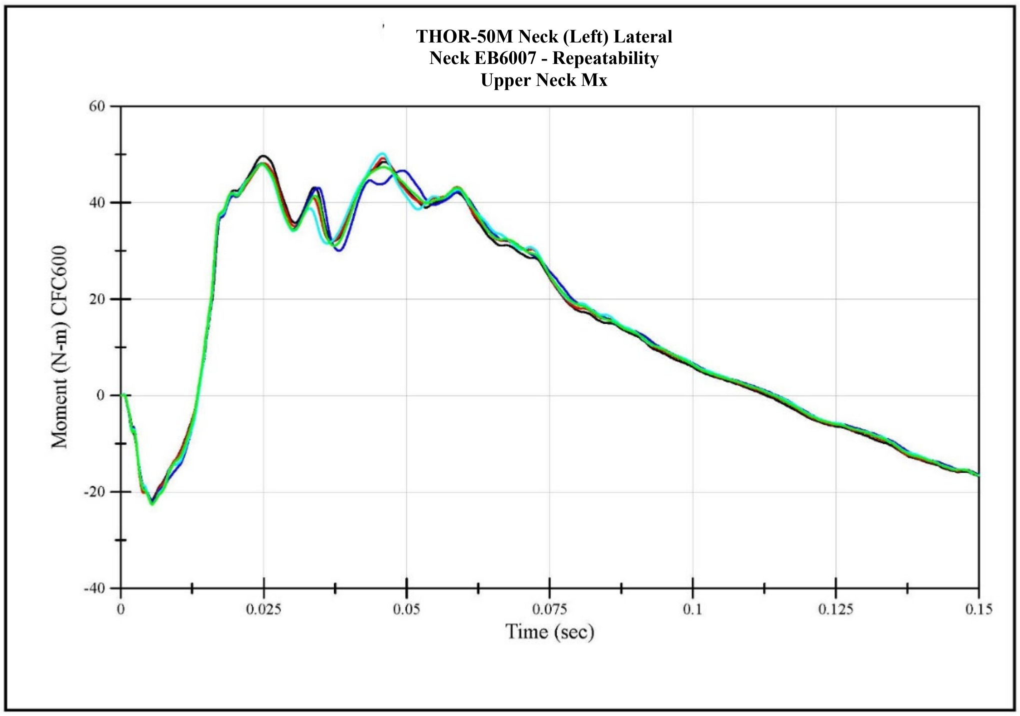

Figure 8-14. Calspan neck left lateral flexion upper neck X-moment repeatability for Neck EB6007

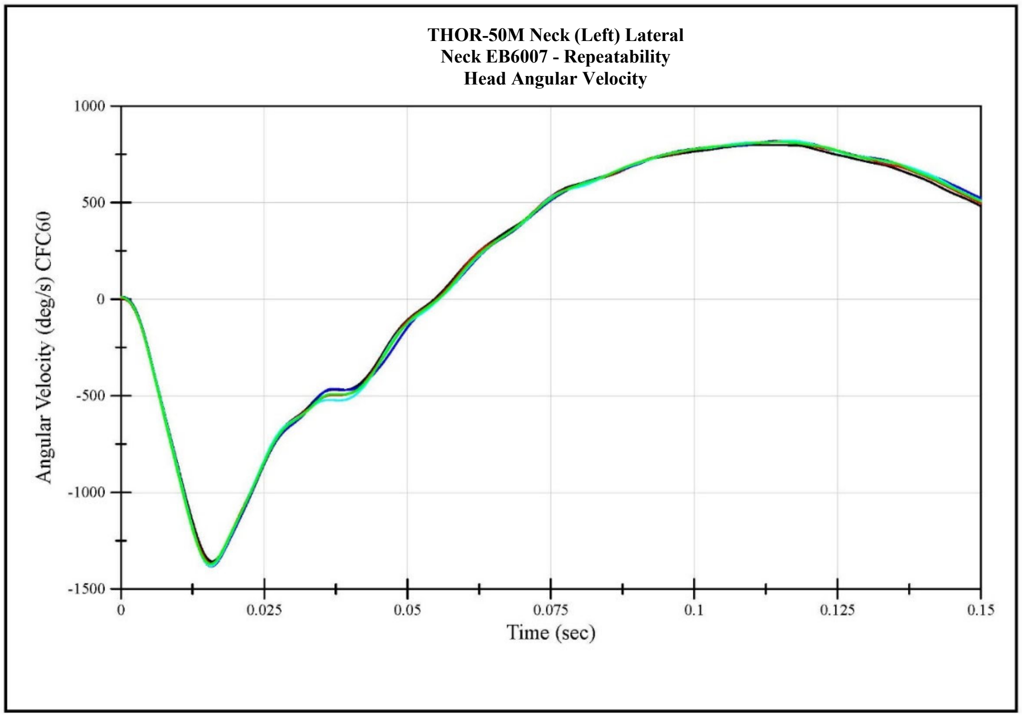

Figure 8-15. Calspan neck left lateral flexion head angular velocity repeatability for Neck EB6007

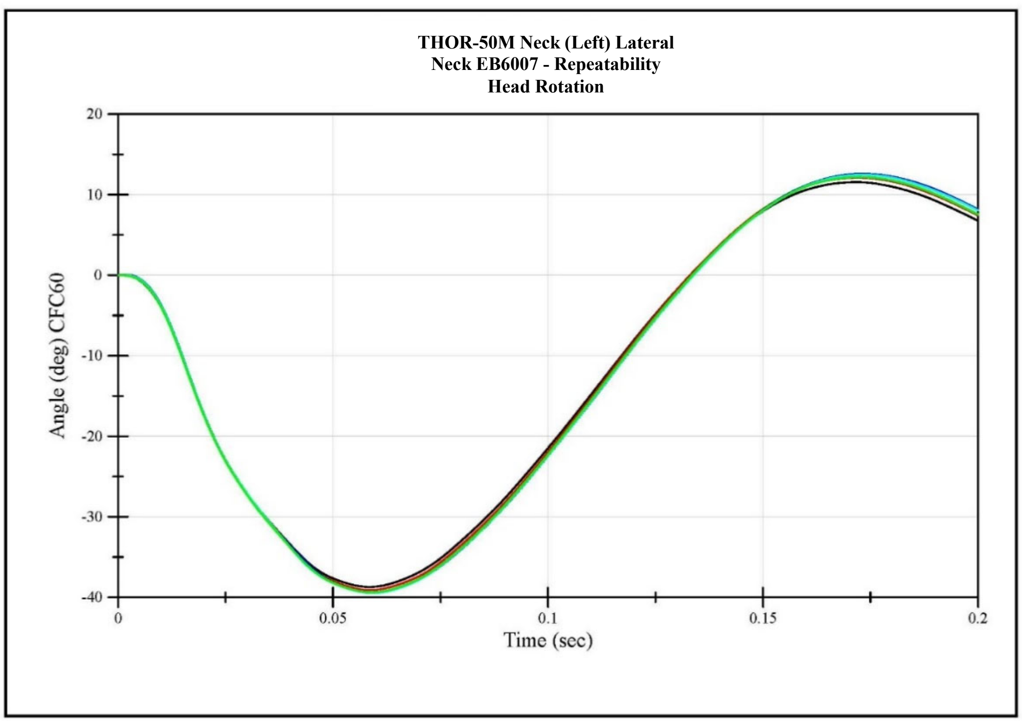

Figure 8-16. Calspan neck left lateral head rotation repeatability for Neck EB6007

8.3 Neck Lateral Flexion Dummy Reproducibility Results

Dummy Reproducibility results at VRTC for the three THOR-50M necks yielded CV values all below 5 percent (Table 8-11 and Table 8-12).

Table 8-11. THOR-50M Neck Left Lateral Flexion Pulse Dummy Reproducibility Results

Neck Number	Test Number	Pendulum Velocity at 4 ms After T0 (m/s)	Pendulum Velocity at 8 ms After T0 (m/s)	Pendulum Velocity at 12 ms After T0 (m/s)
VRTC Neck EB6007	170328-15	1.24	2.43	3.55
	170328-18	1.20	2.35	3.53
	170328-20	1.20	2.36	3.54
	170328-21	1.23	2.36	3.50
	170328-22	1.18	2.29	3.48
VRTC Neck EB6006	170315-8	1.26	2.46	3.54
	170315-9	1.15	2.28	3.41
	170315-10	1.18	2.28	3.46
	170315-13	1.15	2.29	3.46
	170316-2	1.15	2.23	3.44
VRTC Neck EB6005	170323-1	1.23	2.38	3.53
	170323-3	1.27	2.32	3.46
	170323-5	1.31	2.39	3.51
	170323-9	1.18	2.22	3.41
	170323-14	1.22	2.30	3.43
Mean		**1.21**	**2.33**	**3.48**
Std. Dev.		**0.05**	**0.07**	**0.05**
CV		**3.9%**	**2.9%**	**1.4%**

Table 8-12. THOR-50M Neck Left Lateral Flexion Reproducibility Results

Neck Number	Test Number	Upper Neck Mx After 40.0 ms (N-m)	Peak Head Angular Velocity ω_x (relative to earth) (deg/s)	Peak Head Rotation (relative to pendulum) (deg)
VRTC Neck EB6007	170328-15	51.4	-1353	-40.9
	170328-18	51.0	-1366	-42.4
	170328-20	51.3	-1360	-42.1
	170328-21	50.3	-1344	-42.5
	170328-22	50.6	-1346	-42.6
VRTC Neck EB6006	170315-8	49.5	-1361	-41.9
	170315-9	50.1	-1326	-42.4
	170315-10	50.1	-1337	-43.0
	170315-13	49.4	-1341	-43.2
	170316-2	50.3	-1322	-42.9
VRTC Neck EB6005	170323-1	48.8	-1338	-42.3
	170323-3	49.5	-1422	-44.4
	170323-5	49.9	-1439	-44.6
	170323-9	48.5	-1353	-43.8
	170323-14	48.2	-1433	-45.2
Mean		**49.9**	**-1363**	**-43.0**
Std. Dev.		**1.0**	**38**	**1.1**
CV		**1.9%**	**2.8%**	**2.6%**

8.4 THOR-50M Neck EB6007 Lab-to-Lab Variability Analysis

The results for neck lateral flexion qualification tests from each lab are presented in Table 8-13 and Table 8-14. The last four rows of each table show the *Test Reproducibility* results when data from all three labs are combined. The CV values for the pulses (Table 8-13) and dummy metrics (Table 8-14) are all below 5 percent.

Table 8-13. THOR-50M Neck Left Lateral Flexion Pulse Lab-to-Lab Variability Results

Neck Number	Pendulum Velocity at 4 ms After T0 (m/s)	Pendulum Velocity at 8 ms After T0 (m/s)	Pendulum Velocity at 12 ms After T0 (m/s)
VRTC Neck EB6007	1.24	2.43	3.55
	1.20	2.35	3.53
	1.20	2.36	3.54
	1.23	2.36	3.50
	1.18	2.29	3.48
Humanetics Neck EB6007	1.16	2.32	3.62
	1.15	2.20	3.34
	1.15	2.35	3.60
	1.09	2.16	3.34
	1.12	2.27	3.56
Calspan Neck EB6007	1.10	2.28	3.53
	1.15	2.36	3.60
	1.12	2.35	3.64
	1.11	2.33	3.66
	1.14	2.38	3.65
Test Reproducibility EB6007 ALL Labs			
Mean	**1.16**	**2.32**	**3.54**
Std. Dev.	**0.05**	**0.07**	**0.10**
CV	**4.1%**	**3.0%**	**2.8%**

Table 8-14. THOR-50M Neck Left Lateral Flexion Lab-to-Lab Variability Results

Test Number	**Upper Neck Mx After 40.0 ms (N-m)**	**Peak Head Angular Velocity ω_x (relative to earth) (deg/s)**	**Peak Head Rotation (relative to pendulum) (deg)**
VRTC Neck EB6007	51.4	-1353	-40.9
	51.0	-1366	-42.4
	51.3	-1360	-42.1
	50.3	-1344	-42.5
	50.6	-1346	-42.6
Humanetics Neck EB6007	50.5	-1375	-40.5
	50.4	-1313	-40.2
	51.0	-1377	-40.7
	51.0	-1323	-40.7
	51.9	-1364	-40.6
Calspan Neck EB6007	48.5	-1358	-38.7
	49.2	-1369	-39.1
	44.6	-1383	-39.4
	50.2	-1380	-39.5
	47.4	-1371	-39.4
Repeatability EB6007 ALL Labs			
Mean	**50.0**	**-1359**	**-40.6**
Std. Dev.	**1.9**	**20**	**1.3**
CV	**3.8%**	**1.5%**	**3.2%**

8.5 Corridor Development

All the data used to determine the neck lateral flexion qualification corridors is shown in Table 8-15 and Table 8-16. The qualification corridors were calculated using the mean plus or minus 10 percent of the peak for the specified measured or calculated channels (Table 8-17).

Table 8-15. THOR-50M Neck Left Lateral Flexion Pulse Qualification Corridor Results

Neck Number	Test Number	Pendulum Velocity at 4 ms After T0 (m/s)	Pendulum Velocity at 8 ms After T0 (m/s)	Pendulum Velocity at 12 ms After T0 (m/s)
VRTC Neck EB6007	**170328-15**	1.24	2.43	3.55
	170328-18	1.20	2.35	3.53
	170328-20	1.20	2.36	3.54
	170328-21	1.23	2.36	3.50
	170328-22	1.18	2.29	3.48
VRTC Neck EB6006	**170315-8**	1.26	2.46	3.54
	170315-9	1.15	2.28	3.41
	170315-10	1.18	2.28	3.46
	170315-13	1.15	2.29	3.46
	170316-2	1.15	2.23	3.44
VRTC Neck EB6005	**170323-1**	1.23	2.38	3.53
	170323-3	1.27	2.32	3.46
	170323-5	1.31	2.39	3.51
	170323-9	1.18	2.22	3.41
	170323-14	1.22	2.30	3.43
Humanetics Neck EB6007	**370515.01**	1.16	2.32	3.62
	370519	1.15	2.20	3.34
	370521	1.15	2.35	3.60
	370524	1.09	2.16	3.34
	370526	1.12	2.27	3.56
Calspan Neck EB6007	**20170524104134**	1.10	2.28	3.53
	20170524111308	1.15	2.36	3.60
	20170523142255	1.12	2.35	3.64
	20170524123323	1.11	2.33	3.66
	20170524130455	1.14	2.38	3.65
Mean		**1.18**	**2.32**	**3.51**
Std. Dev.		**0.06**	**0.07**	**0.09**
CV		**4.8%**	**3.0%**	**2.5%**

Table 8-16. THOR-50M Neck Left Lateral Flexion Qualification Corridor Results

Test Number	Test Number	Upper Neck Mx After 40.0 ms (N-m)	Peak Head Angular Velocity ω_x (relative to earth) (deg/s)	Peak Head Rotation (relative to pendulum) (deg)
VRTC Neck EB6007	**170328-15**	51.4	-1353	-40.9
	170328-18	51.0	-1366	-42.4
	170328-20	51.3	-1360	-42.1
	170328-21	50.3	-1344	-42.5
	170328-22	50.6	-1346	-42.6
VRTC Neck EB6006	**170315-8**	49.5	-1361	-41.9
	170315-9	50.1	-1326	-42.4
	170315-10	50.1	-1337	-43.0
	170315-13	49.4	-1341	-43.2
	170316-2	50.3	-1322	-42.9
VRTC Neck EB6005	**170323-1**	48.8	-1338	-42.3
	170323-3	49.5	-1422	-44.4
	170323-5	49.9	-1439	-44.6
	170323-9	48.5	-1353	-43.8
	170323-14	48.2	-1433	-45.2
Humanetics Neck EB6007	**370515.01**	50.5	-1375	-40.5
	370519	50.4	-1313	-40.2
	370521	51.0	-1377	-40.7
	370524	51.0	-1323	-40.7
	370526	51.9	-1364	-40.6
Calspan Neck EB6007	**20170524104134**	48.5	-1358	-38.7
	20170524111308	49.2	-1369	-39.1
	20170523142255	44.6	-1383	-39.4
	20170524123323	50.2	-1380	-39.5
	20170524130455	47.4	-1371	-39.4
Mean		**49.7**	**-1362**	**-41.7**
Std. Dev.		**1.5**	**32**	**1.8**
CV		**3.1%**	**2.4%**	**4.4%**

Table 8-17. Neck Lateral Flexion Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Pendulum Velocity at 4 ms after T0	**m/s**	1.06	1.30	1.18	10.0%
Pendulum Velocity at 8 ms after T0	**m/s**	2.09	2.55	2.32	10.0%
Pendulum Velocity at 12 ms after T0	**m/s**	3.16	3.86	3.51	10.0%
Impact Velocity	**m/s**	3.35	3.45	3.40	
Left Upper Neck X First Peak After 40.0 ms	**N-m**	44.8	54.7	49.7	10.0%
Left First Peak Head Angular Velocity ω_x (relative to earth)	**deg/s**	-1498	-1226	-1362	10.0%
Left Peak Head Rotation (relative to pendulum)	**deg**	-45.9	-37.6	-41.7	10.0%
Right Upper Neck Mx First Peak After 40.0 ms	**N-m**	-54.7	-44.8	-49.7	10.0%
Right First Peak Head Angular Velocity ω_x (relative to earth)	**deg/s**	1226	1498	1362	10.0%
Right Peak Head Rotation (relative to pendulum)	**deg**	37.6	45.9	41.7	10.0%

Discussion. There were no instances in which a test did not achieve the target response ± 10 percent. All CVs were below 5 percent. There are no indications that there are problems with repeatability or reproducibility for this test condition.

9 Neck Torsion

9.1 Methodology

Repeatability and reproducibility tests were performed using the neck torsion qualification procedures described in the *THOR-50M Qualification Procedures Manual*. These tests assess the response of the neck about the Z-axis. The neck pendulum is 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 9-1). The neck qualification in the torsion mode utilizes 152.4 mm (6") aluminum honeycomb for pendulum deceleration from an impact velocity of 5.00 ± 0.05 m/s. During these tests the upper neck Z-axis moment (Mz), head angular rate, and head rotation were measured.

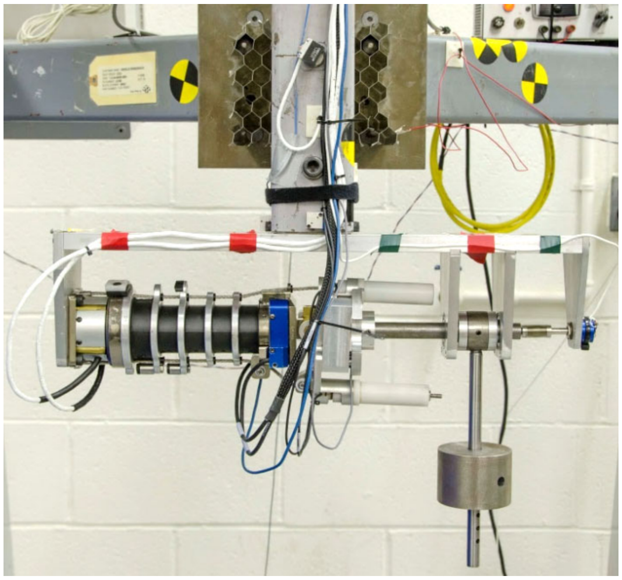

Figure 9-1. Neck torsion test setup

9.2 Neck Torsion Repeatability Results

Sections 9.2.1 to 9.2.5 illustrate the results of the neck torsion repeatability tests. For this study, only the left side was tested (i.e., simulates head turning about the Z-axis towards the left shoulder) since the neck is symmetrical and results between the left and right sides should be similar. Each section contains a table providing the quantified test data, followed by plot overlays of the five repeat tests conducted at all three labs. Note that the data in the tables containing the results of each test series are listed sequentially, with the test at the top of the table beginning the test series.

9.2.1 THOR-50M Neck EB6007 Testing at VRTC

Repeatability results at VRTC for Neck EB6007 (left) in the neck torsion qualification yielded CV values all below 5 percent (Table 9-1 and Table 9-2, Figure 9-2 to Figure 9-4).

Table 9-1. VRTC THOR-50M Neck EB6007 Left Torsion Pulse Repeatability Results

Test Number	Pendulum Velocity at 10 ms After T0 (m/s)	Pendulum Velocity at 15 ms After T0 (m/s)	Pendulum Velocity at 20 ms After T0 (m/s)	Pendulum Velocity at 25 ms After T0 (m/s)
170327-5	1.83	2.80	3.78	4.65
170327-6	1.90	2.86	3.87	4.76
170327-7	1.90	2.83	3.81	4.70
170327-8	1.91	2.90	3.91	4.84
170327-9	1.91	2.90	3.90	4.84
Mean	**1.89**	**2.86**	**3.85**	**4.76**
Std. Dev.	**0.04**	**0.04**	**0.06**	**0.08**
CV	**1.9%**	**1.5%**	**1.5%**	**1.7%**

Table 9-2. VRTC THOR-50M Neck EB6007 Left Torsion Repeatability Results

Test Number	Peak Upper Neck Mz (N-m)	First Peak Upper Neck Angular Velocity ω_z (relative to earth) (deg/s)	Peak Neck Fixture Rotation (deg)
170327-5	43.1	-1380	45.5
170327-6	42.8	-1386	46.4
170327-7	42.3	-1386	46.6
170327-8	42.2	-1408	47.3
170327-9	42.1	-1424	47.5
Mean	**42.5**	**-1397**	**46.7**
Std. Dev.	**0.45**	**18**	**0.8**
CV	**1.1%**	**1.3%**	**1.7%**

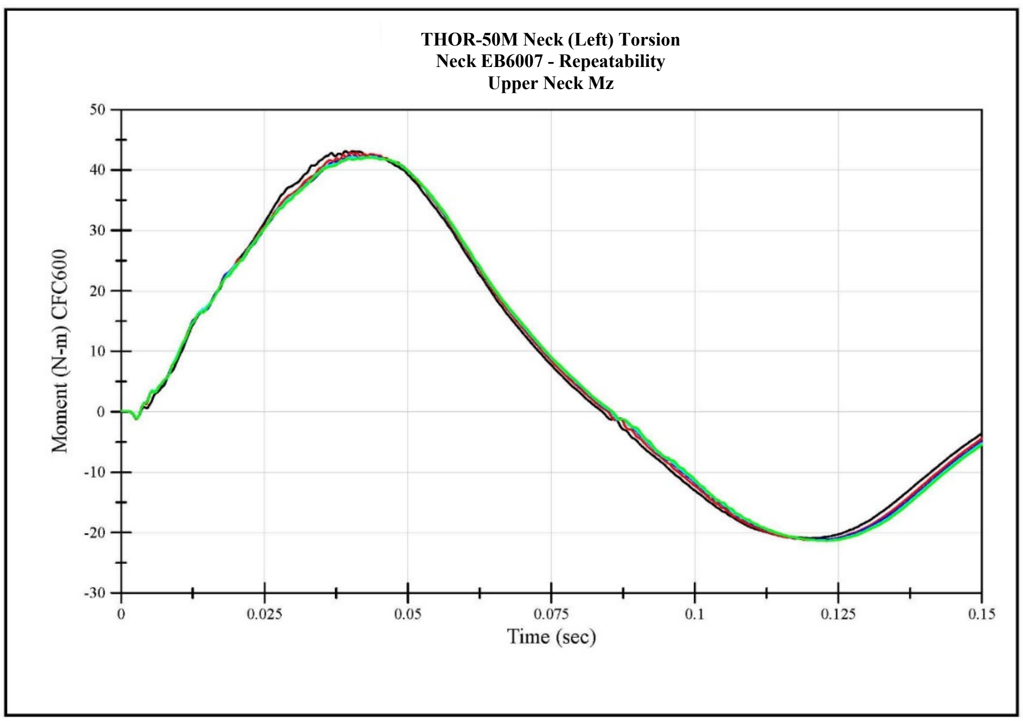

Figure 9-2. VRTC neck left torsion upper neck Z-moment repeatability for Neck EB6007

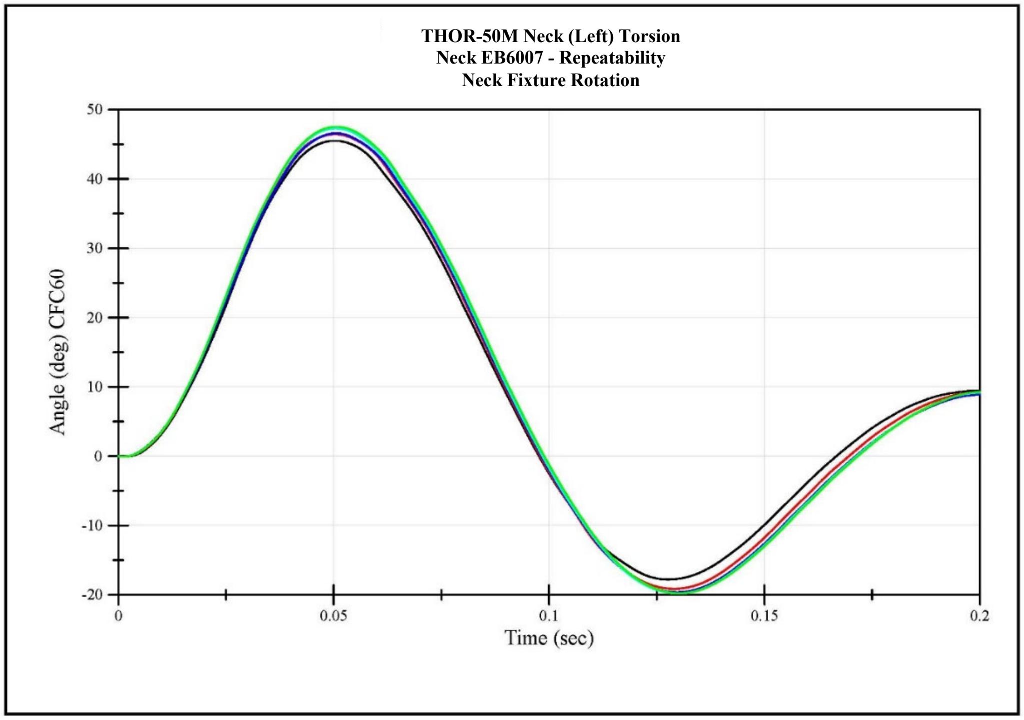

Figure 9-3. VRTC neck left torsion neck fixture rotation repeatability for Neck EB6007

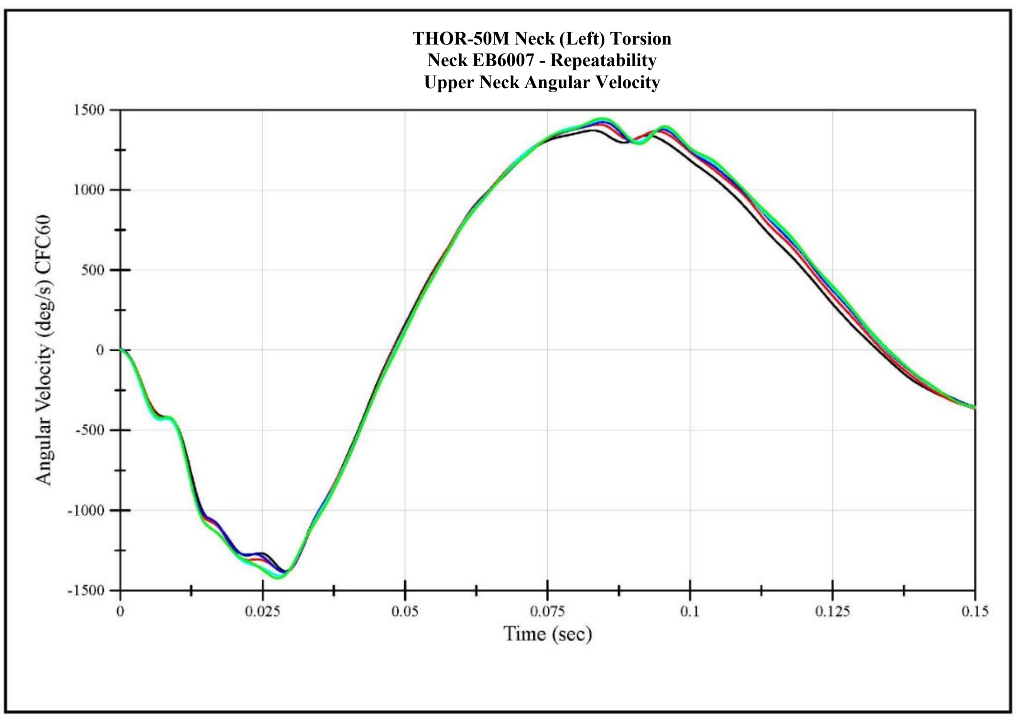

Figure 9-4. VRTC neck left torsion upper neck angular velocity repeatability for Neck EB6007

9.2.2 THOR-50M Neck EB6006 Testing at VRTC

Repeatability results at VRTC for Neck EB6006 (left) in the neck torsion qualification yielded CV values all below 5 percent (Table 9-3 and Table 9-4, Figure 9-5 to Figure 9-7).

Table 9-3. VRTC THOR-50M Neck EB6006 Left Torsion Pulse Repeatability Results

Test Number	Pendulum Velocity at 10 ms After T0 (m/s)	Pendulum Velocity at 15 ms After T0 (m/s)	Pendulum Velocity at 20 ms After T0 (m/s)	Pendulum Velocity at 25 ms After T0 (m/s)
170316-7	1.88	2.82	3.80	4.68
170316-8	1.92	2.85	3.79	4.67
170316-9	1.98	2.98	3.95	4.84
170316-10	1.88	2.83	3.76	4.63
170316-13	1.92	2.87	3.82	4.70
Mean	**1.91**	**2.87**	**3.82**	**4.70**
Std. Dev.	**0.04**	**0.06**	**0.07**	**0.08**
CV	**2.1%**	**2.2%**	**1.9%**	**1.7%**

Table 9-4. VRTC THOR-50M Neck EB6006 Left Torsion Repeatability Results

Test Number	Peak Upper Neck Mz (N-m)	First Peak Upper Neck Angular Velocity ω_z (relative to earth) (deg/s)	Peak Neck Fixture Rotation (deg)
170316-7	40.8	-1355	47.2
170316-8	40.5	-1372	47.8
170316-9	40.6	-1409	48.6
170316-10	40.2	-1384	48.2
170316-13	40.2	-1395	48.3
Mean	**40.5**	**-1383**	**48.0**
Std. Dev.	**0.2**	**21**	**0.6**
CV	**0.6%**	**1.5%**	**1.2%**

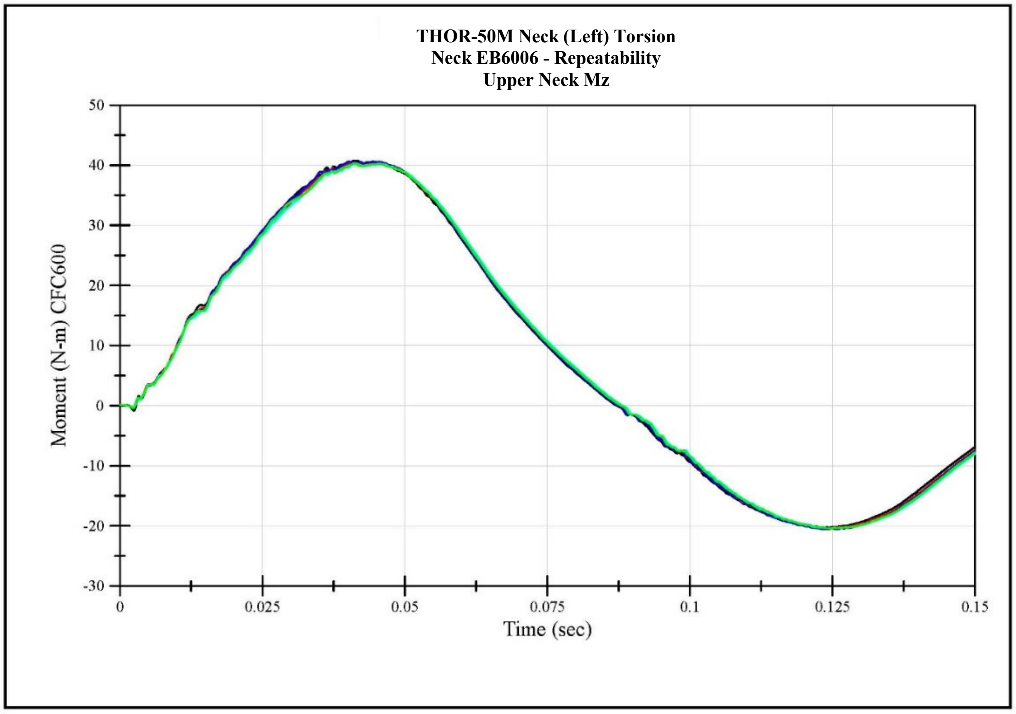

Figure 9-5. VRTC neck left torsion upper neck Z-moment repeatability for Neck EB6006

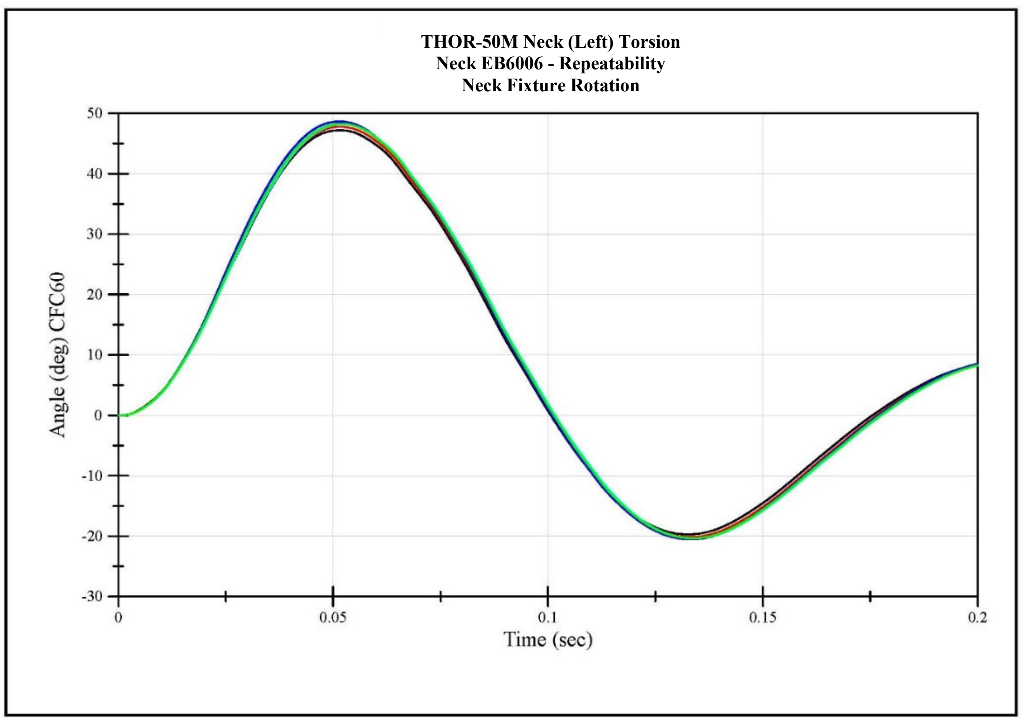

Figure 9-6. VRTC neck left torsion neck fixture rotation repeatability for Neck EB6006

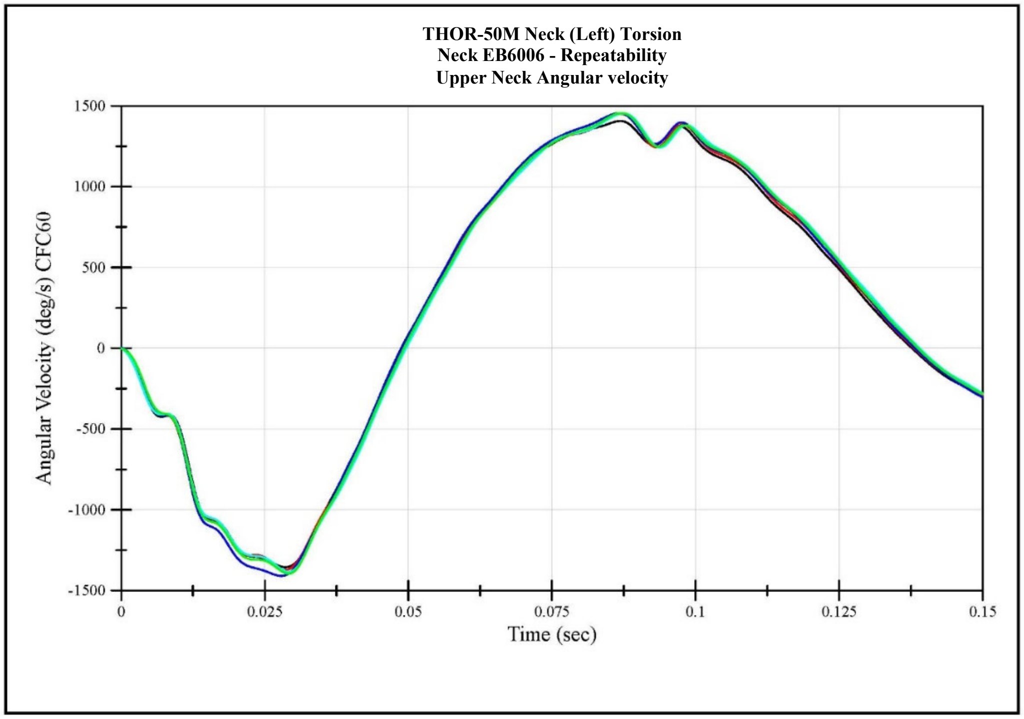

Figure 9-7. VRTC neck left torsion upper neck angular velocity repeatability for Neck EB6006

9.2.3 THOR-50M Neck EB6005 Testing at VRTC

Repeatability results at VRTC for Neck EB6005 (left) in the neck torsion qualification yielded CV values all below 5 percent (Table 9-5 and Table 9-6, Figure 9-8 to Figure 9-10).

Table 9-5. VRTC THOR-50M Neck EB6005 Left Torsion Pulse Repeatability Results

Test Number	**Pendulum Velocity at 10 ms After T0 (m/s)**	**Pendulum Velocity at 15 ms After T0 (m/s)**	**Pendulum Velocity at 20 ms After T0 (m/s)**	**Pendulum Velocity at 25 ms After T0 (m/s)**
170321-2	1.90	2.86	3.87	4.75
170321-3	1.88	2.86	3.89	4.82
170321-4	1.91	2.89	3.89	4.78
170321-5	1.91	2.87	3.91	4.84
170321-7	1.94	2.90	3.93	4.81
Mean	**1.91**	**2.88**	**3.90**	**4.80**
Std. Dev.	**0.02**	**0.02**	**0.02**	**0.03**
CV	**1.2%**	**0.6%**	**0.6%**	**0.7%**

Table 9-6. VRTC THOR-50M Neck EB6005 Left Torsion Repeatability Results

Test Number	Peak Upper Neck Mz (N-m)	First Peak Upper Neck Angular Velocity ω_z (relative to earth) (deg/s)	Peak Neck Fixture Rotation (deg)
170321-2	41.8	-1398	47.7
170321-3	40.9	-1448	52.0
170321-4	40.6	-1456	49.6
170321-5	40.4	-1467	49.8
170321-7	40.4	-1466	50.1
Mean	**40.8**	**-1447**	**49.9**
Std. Dev.	**0.6**	**28**	**1.5**
CV	**1.4%**	**2.0%**	**3.1%**

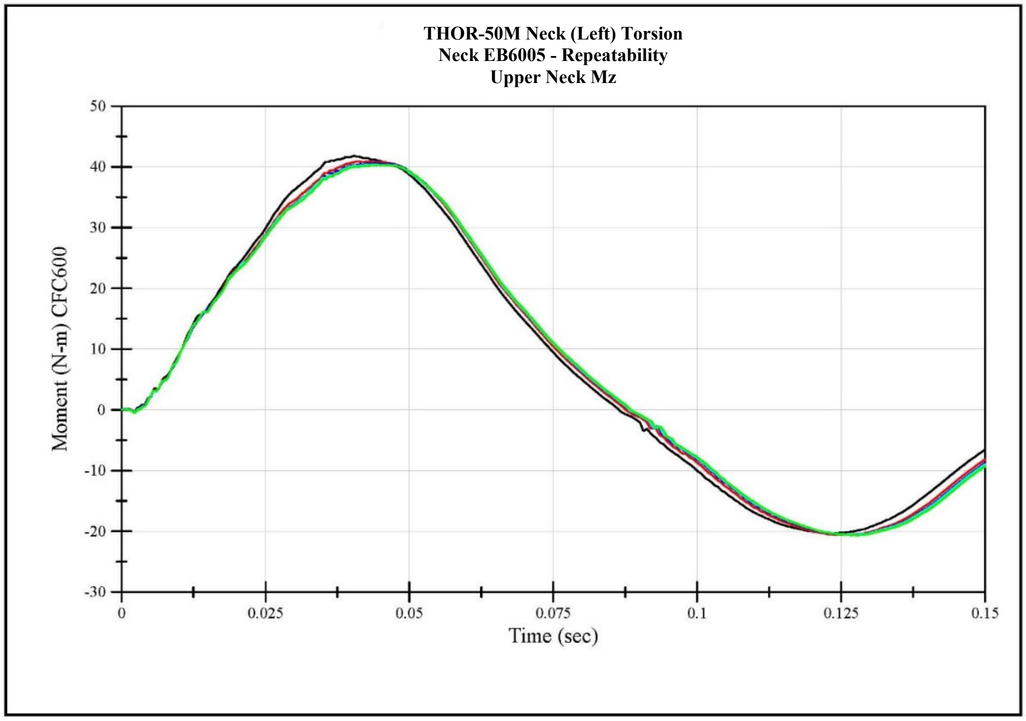

Figure 9-8. VRTC neck left torsion upper neck Z-moment repeatability for Neck EB6005

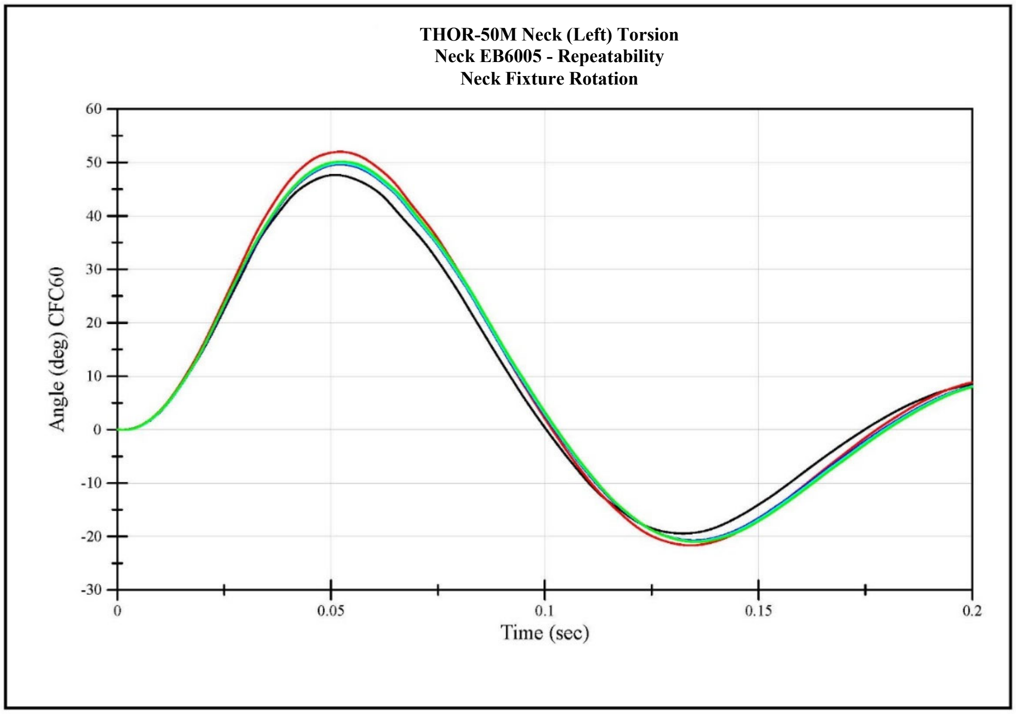

Figure 9-9. VRTC neck left torsion neck fixture rotation repeatability for Neck EB6005

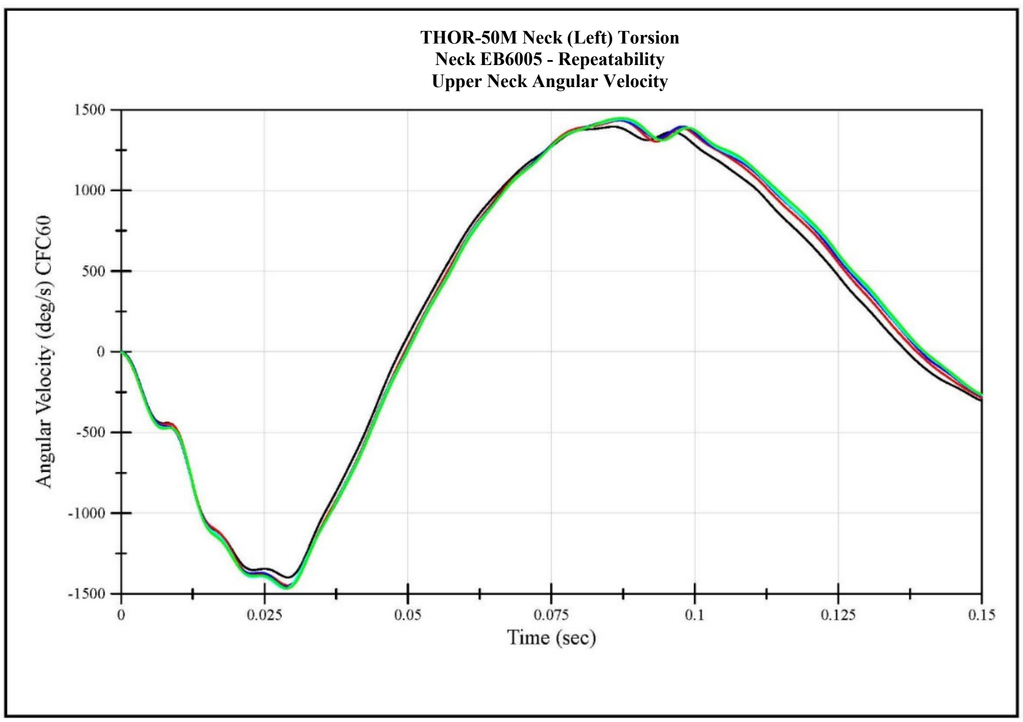

Figure 9-10. VRTC neck left torsion upper neck angular velocity repeatability for Neck EB6005

9.2.4 THOR-50M Neck EB6007 Testing at Humanetics

Repeatability results at Humanetics for Neck EB6007 (left) in the neck torsion qualification yielded CV values all below 5 percent (Table 9-7 and Table 9-8, Figure 9-11 to Figure 9-13)

Table 9-7. Humanetics THOR-50M Neck EB6007 Left Torsion Pulse Repeatability Results

Test Number	Pendulum Velocity at 10 ms After T0 (m/s)	Pendulum Velocity at 15 ms After T0 (m/s)	Pendulum Velocity at 20 ms After T0 (m/s)	Pendulum Velocity at 25 ms After T0 (m/s)
370553	1.86	2.77	3.78	4.68
370564	1.91	2.87	3.89	4.75
370580	1.86	2.74	3.70	4.55
370586	1.87	2.79	3.79	4.67
370594	1.88	2.80	3.74	4.60
Mean	**1.87**	**2.79**	**3.78**	**4.65**
Std. Dev.	**0.02**	**0.05**	**0.07**	**0.07**
CV	**1.2%**	**1.8%**	**1.9%**	**1.6%**

Table 9-8. Humanetics THOR-50M Neck EB6007 Left Torsion Repeatability Results

Test Number	Peak Upper Neck Mz (N-m)	First Peak Upper Neck Angular Velocity ω_z (relative to earth) (deg/s)	Peak Neck Fixture Rotation (deg)
370553	41.6	-1425	47.2
370564	41.4	-1401	46.8
370580	41.0	-1397	46.9
370586	41.2	-1425	47.0
370594	41.0	-1402	46.8
Mean	**41.2**	**-1410**	**46.9**
Std. Dev.	**0.3**	**14**	**0.2**
CV	**0.7%**	**1.0%**	**0.4%**

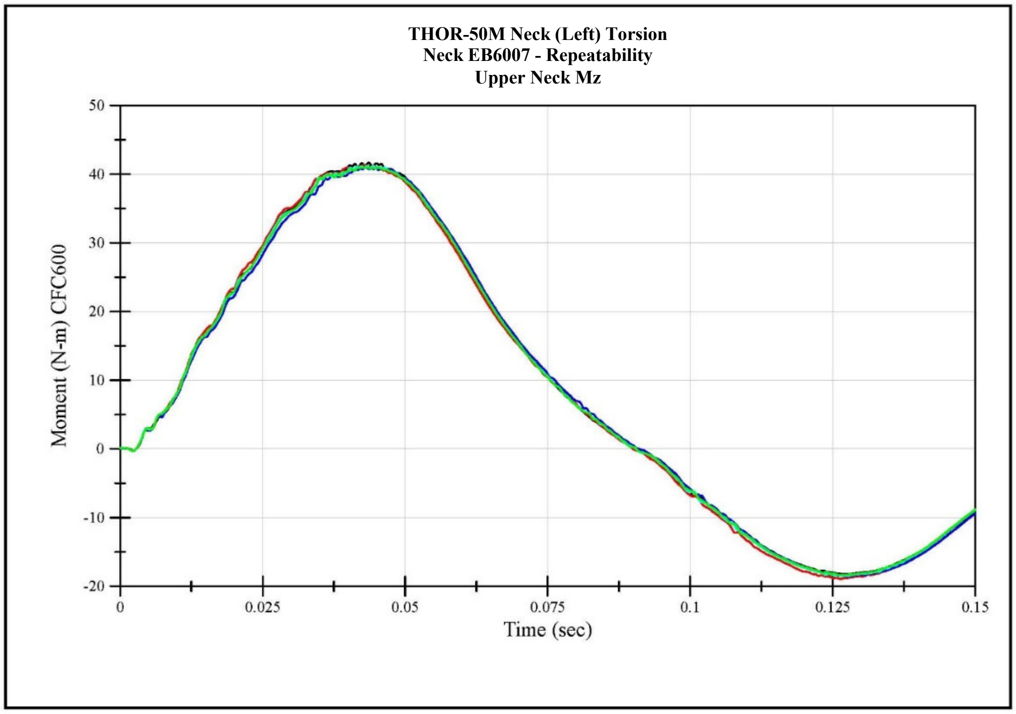

Figure 9-11. Humanetics neck left torsion upper neck Z-moment repeatability for Neck EB6007

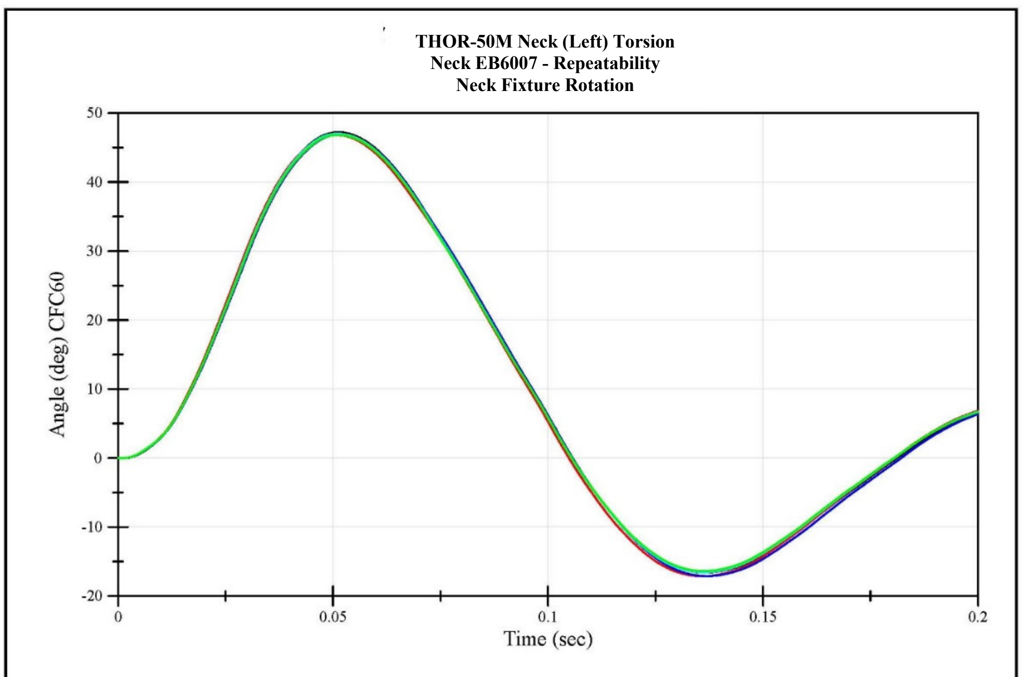

Figure 9-12. Humanetics neck left torsion neck fixture rotation repeatability for Neck EB6007

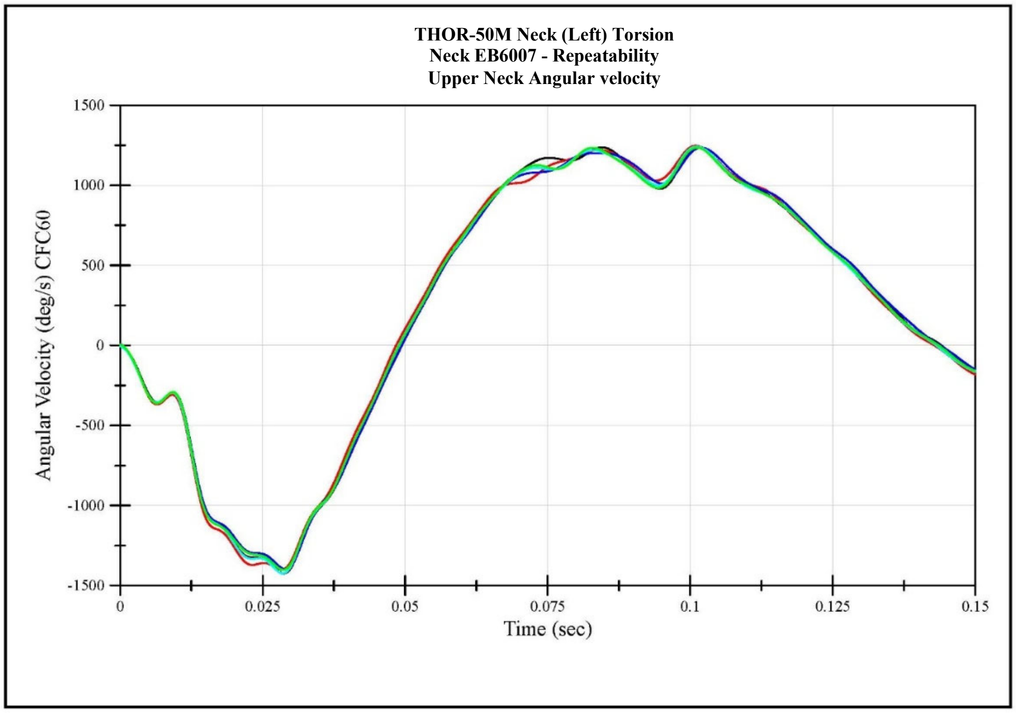

Figure 9-13. Humanetics neck left torsion upper neck angular velocity repeatability for Neck EB6007

9.2.5 THOR-50M Neck EB6007 Testing at Calspan

Repeatability results at Calspan for Neck EB6007 (left) in the neck torsion qualification yielded CV values all below 5 percent with the exception of the peak upper neck angular velocity which was above 5 percent but less than 10 percent (Table 9-9 and Table 9-10, Figure 9-14 and Figure 9-15). Instrumentation issues precluded collecting data for the neck fixture rotation.

Table 9-9. Calspan THOR-50M Neck EB6007 Left Torsion Pulse Repeatability Results

Test Number	Pendulum Velocity at 10 ms After T0 (m/s)	Pendulum Velocity at 15 ms After T0 (m/s)	Pendulum Velocity at 20 ms After T0 (m/s)	Pendulum Velocity at 25 ms After T0 (m/s)
20170525085334	1.90	2.91	3.94	4.86
20170525092720	1.86	2.83	3.79	4.70
20170525095849	1.89	2.83	3.80	4.71
20170525113452	2.01	3.03	4.05	4.97
20170525135110	1.93	2.89	3.88	4.81
Mean	**1.92**	**2.90**	**3.89**	**4.81**
Std. Dev.	**0.06**	**0.08**	**0.11**	**0.11**
CV	**3.0%**	**2.8%**	**2.7%**	**2.3%**

Table 9-10. Calspan THOR-50M Neck EB6007 Left Torsion Repeatability Results

Test Number	Peak Upper Neck Mz (N-m)	First Peak Upper Neck Angular Velocity ω_z (relative to earth) (deg/s)	Peak Neck Fixture Rotation (deg)
20170525085334	42.4	-1358	N/A
20170525092720	41.9	-1335	N/A
20170525095849	41.8	-1333	N/A
20170525113452	42.5	-1369	N/A
20170525135110	42.4	-1180	N/A
Mean	**42.2**	**-1315**	**N/A**
Std. Dev.	**0.3**	**77**	**N/A**
CV	**0.8%**	**5.9%**	**N/A**

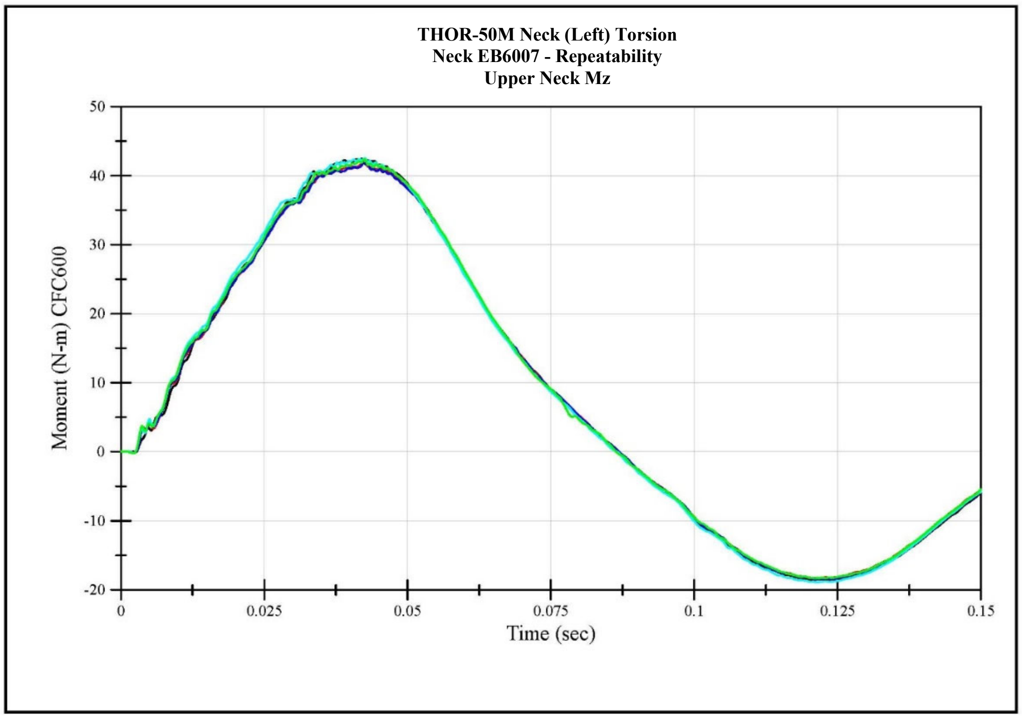

Figure 9-14. Calspan neck left torsion upper neck Z-moment repeatability for Neck EB6007

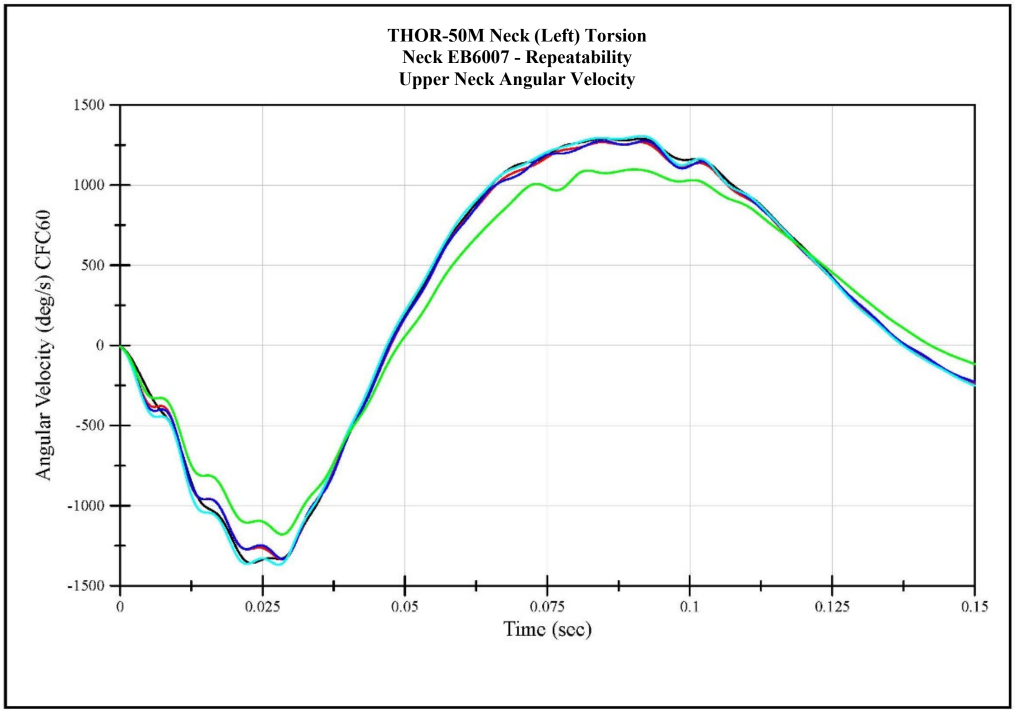

Figure 9-15. Calspan neck left torsion upper neck angular velocity repeatability for Neck EB6007

9.3 Neck Torsion Dummy Reproducibility Results

Dummy Reproducibility results at VRTC for the three THOR-50M necks yielded CV values all below 5 percent (Table 9-11 and Table 9-12).

Table 9-11. THOR-50M Neck Left Torsion Pulse Dummy Reproducibility Results

Neck Number	Test Number	Pendulum Velocity at 10 ms After T0 (m/s)	Pendulum Velocity at 15 ms After T0 (m/s)	Pendulum Velocity at 20 ms After T0 (m/s)	Pendulum Velocity at 25 ms After T0 (m/s)
VRTC Neck EB6007	**170327-5**	1.83	2.80	3.78	4.65
	170327-6	1.90	2.86	3.87	4.76
	170327-7	1.90	2.83	3.81	4.70
	170327-8	1.91	2.90	3.91	4.84
	170327-9	1.91	2.90	3.90	4.84
VRTC Neck EB6006	**170316-7**	1.88	2.82	3.80	4.68
	170316-8	1.92	2.85	3.79	4.67
	170316-9	1.98	2.98	3.95	4.84
	170316-10	1.88	2.83	3.76	4.63
	170316-13	1.92	2.87	3.82	4.70
VRTC Neck EB6005	**170321-2**	1.90	2.86	3.87	4.75
	170321-3	1.88	2.86	3.89	4.82
	170321-4	1.91	2.89	3.89	4.78
	170321-5	1.91	2.87	3.91	4.84
	170321-7	1.94	2.90	3.93	4.81
Mean		**1.90**	**2.87**	**3.86**	**4.75**
Std. Dev.		**0.03**	**0.04**	**0.06**	**0.08**
CV		**1.7%**	**1.5%**	**1.5%**	**1.6%**

Table 9-12. THOR-50M Neck Left Torsion Reproducibility Results

Neck Number	Test Number	Peak Upper Neck Mz (N-m)	First Peak Upper Neck Angular Velocity ω_z (relative to earth) (deg/s)	Peak Neck Fixture Rotation (deg)
VRTC Neck EB6007	**170327-5**	43.1	-1380	45.5
	170327-6	42.8	-1386	46.4
	170327-7	42.3	-1386	46.6
	170327-8	42.2	-1408	47.3
	170327-9	42.1	-1424	47.5
VRTC Neck EB6006	**170316-7**	40.8	-1355	47.2
	170316-8	40.5	-1372	47.8
	170316-9	40.6	-1409	48.6
	170316-10	40.2	-1384	48.2
	170316-13	40.2	-1395	48.3
VRTC Neck EB6005	**170321-2**	41.8	-1398	47.7
	170321-3	40.9	-1448	52.0
	170321-4	40.6	-1456	49.6
	170321-5	40.4	-1467	49.8
	170321-7	40.4	-1466	50.1
Mean		**41.3**	**-1409**	**48.2**
Std. Dev.		**1.0**	**35**	**1.7**
CV		**2.5%**	**2.5%**	**3.5%**

9.4 THOR-50M Neck EB6007 Lab-to-Lab Variability Analysis

The results for the neck torsion qualification tests from each lab are presented in Table 9-13 and Table 9-14. The last four rows of each table show the *Test Reproducibility* results when data from all three labs are combined. The CV values for the pulses (Table 9-13) and dummy metrics (Table 9-14) are all below 5 percent. The Calspan data for the peak head rotation was unavailable due to a potentiometer malfunction.

Table 9-13. THOR-50M Neck Left Torsion Pulse Lab-to-Lab Variability Results

Neck Number	Pendulum Velocity at 10 ms After T0 (m/s)	Pendulum Velocity at 15 ms After T0 (m/s)	Pendulum Velocity at 20 ms After T0 (m/s)	Pendulum Velocity at 25 ms After T0 (m/s)
VRTC Neck EB6007	1.83	2.80	3.78	4.65
	1.90	2.86	3.87	4.76
	1.90	2.83	3.81	4.70
	1.91	2.90	3.91	4.84
	1.91	2.90	3.90	4.84
Humanetics Neck EB6007	1.86	2.77	3.78	4.68
	1.91	2.87	3.89	4.75
	1.86	2.74	3.70	4.55
	1.87	2.79	3.79	4.67
	1.88	2.80	3.74	4.60
Calspan Neck EB6007	1.90	2.91	3.94	4.86
	1.86	2.83	3.79	4.70
	1.89	2.83	3.80	4.71
	2.01	3.03	4.05	4.97
	1.93	2.89	3.88	4.81
Test Reproducibility EB6007 ALL Labs				
Mean	**1.89**	**2.85**	**3.84**	**4.74**
Std. Dev.	**0.04**	**0.07**	**0.09**	**0.11**
CV	**2.2%**	**2.5%**	**2.3%**	**2.3%**

Table 9-14. THOR-50M Neck Left Torsion Lab-to-Lab Variability Results

Neck Number	Peak Upper Neck Mz (N-m)	First Peak Upper Neck Angular Velocity ω_z (relative to earth) (deg/s)	Peak Neck Fixture Rotation (deg)
VRTC Neck EB6007	43.1	-1380	45.5
	42.8	-1386	46.4
	42.3	-1386	46.6
	42.2	-1408	47.3
	42.1	-1424	47.5
Humanetics Neck EB6007	41.6	-1425	47.2
	41.4	-1401	46.8
	41.0	-1397	46.9
	41.2	-1425	47.0
	41.0	-1402	46.8
Calspan Neck EB6007	42.4	-1358	N/A
	41.9	-1335	N/A
	41.8	-1333	N/A
	42.5	-1369	N/A
	42.4	-1180	N/A
Repeatability EB6007 ALL Labs			
Mean	**42.0**	**-1374**	**46.8**
Std. Dev.	**0.7**	**61**	**0.6**
CV	**1.5%**	**4.5%**	**1.2%**

9.5 Corridor Development

All the data used to determine the neck torsion qualification corridors are shown in Table 9-15 and Table 9-16. The qualification corridors were calculated using the mean plus or minus 10 percent of the peak for the specified measured or calculated channels (Table 9-17).

Table 9-15. THOR-50M Neck Left Torsion Pulse Qualification Corridor Results

Neck Number	Test Number	Pendulum Velocity at 10 ms After T0 (m/s)	Pendulum Velocity at 15 ms After T0 (m/s)	Pendulum Velocity at 20 ms After T0 (m/s)	Pendulum Velocity at 25 ms After T0 (m/s)
VRTC Neck EB6007	170327-5	1.83	2.80	3.78	4.65
	170327-6	1.90	2.86	3.87	4.76
	170327-7	1.90	2.83	3.81	4.70
	170327-8	1.91	2.90	3.91	4.84
	170327-9	1.91	2.90	3.90	4.84
VRTC Neck EB6006	170316-7	1.88	2.82	3.80	4.68
	170316-8	1.92	2.85	3.79	4.67
	170316-9	1.98	2.98	3.95	4.84
	170316-10	1.88	2.83	3.76	4.63
	170316-13	1.92	2.87	3.82	4.70
VRTC Neck EB6005	170321-2	1.90	2.86	3.87	4.75
	170321-3	1.88	2.86	3.89	4.82
	170321-4	1.91	2.89	3.89	4.78
	170321-5	1.91	2.87	3.91	4.84
	170321-7	1.94	2.90	3.93	4.81
Humanetics Neck EB6007	370553	1.86	2.77	3.78	4.68
	370564	1.91	2.87	3.89	4.75
	370580	1.86	2.74	3.70	4.55
	370586	1.87	2.79	3.79	4.67
	370594	1.88	2.80	3.74	4.60
Calspan Neck EB6007	20170525085334	1.90	2.91	3.94	4.86
	20170525092720	1.86	2.83	3.79	4.70
	20170525095849	1.89	2.83	3.80	4.71
	20170525113452	2.01	3.03	4.05	4.97
	20170525135110	1.93	2.89	3.88	4.81
Mean		**1.90**	**2.86**	**3.85**	**4.74**
Std. Dev.		**0.04**	**0.06**	**0.08**	**0.10**
CV		**2.0%**	**2.1%**	**2.1%**	**2.0%**

Table 9-16. THOR-50M Neck Left Torsion Qualification Corridor Results

Neck Number	Test Number	Peak Upper Neck Mz (N-m)	First Peak Upper Neck Angular Velocity ω_z (relative to earth) (deg/s)	Peak Neck Fixture Rotation (deg)
VRTC Neck EB6007	**170327-5**	43.1	-1380	45.5
	170327-6	42.8	-1386	46.4
	170327-7	42.3	-1386	46.6
	170327-8	42.2	-1408	47.3
	170327-9	42.1	-1424	47.5
VRTC Neck EB6006	**170316-7**	40.8	-1355	47.2
	170316-8	40.5	-1372	47.8
	170316-9	40.6	-1409	48.6
	170316-10	40.2	-1384	48.2
	170316-13	40.2	-1395	48.3
VRTC Neck EB6005	**170321-2**	41.8	-1398	47.7
	170321-3	40.9	-1448	52.0
	170321-4	40.6	-1456	49.6
	170321-5	40.4	-1467	49.8
	170321-7	40.4	-1466	50.1
Humanetics Neck EB6007	**370553**	41.6	-1425	47.2
	370564	41.4	-1401	46.8
	370580	41.0	-1397	46.9
	370586	41.2	-1425	47.0
	370594	41.0	-1402	46.8
Calspan Neck EB6007	**20170525085334**	42.4	-1358	N/A
	20170525092720	41.9	-1335	N/A
	20170525095849	41.8	-1333	N/A
	20170525113452	42.5	-1369	N/A
	20170525135110	42.4	-1180	N/A
Mean		**41.4**	**-1390**	**47.9**
Std. Dev.		**0.9**	**57**	**1.5**
CV		**2.1%**	**4.1%**	**3.2%**

Table 9-17. Neck Torsion Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Pendulum Velocity at 10 ms after T0	**m/s**	1.71	2.09	1.90	10.0%
Pendulum Velocity at 15 ms after T0	**m/s**	2.57	3.14	2.86	10.0%
Pendulum Velocity at 20 ms after T0	**m/s**	3.46	4.23	3.85	10.0%
Pendulum Velocity at 25 ms after T0	**m/s**	4.27	5.22	4.75	10.0%
Impact Velocity	**m/s**	4.95	5.05	5.00	
Left Peak Upper Neck Mz	**N-m**	37.3	45.6	41.4	10.0%
Left Peak Neck Fixture Rotation	**deg**	-52.7	-43.1	-47.9	10.0%
Left First Peak Upper Neck Angular Velocity ω_z (relative to earth)	**deg/s**	-1529	-1251	-1390	10.0%
Right Peak Upper Neck Mz	**N-m**	-45.6	-37.3	-41.4	10.0%
Right Peak Neck Fixture Rotation	**deg**	43.1	52.7	47.9	10.0%
Right First Peak Upper Neck Angular Velocity ω_z (relative to earth)	**deg/s**	1251	1529	1390	10.0%

Discussion. There were no instances in which a test did not achieve the target response ± 10 percent. Aside from one repeatability test at Calspan (the peak upper neck angular velocity signal appears to be an anomaly) all CVs were below 5 percent. Otherwise, there are no indications that there are problems with repeatability or reproducibility for this test condition.

10 Upper Thorax

10.1 Methodology

Repeatability and reproducibility tests were performed using the upper thorax qualification procedures described in the *THOR-50M Qualification Procedures Manual*. These tests require 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 10-1). The upper ribcage central impact test uses the same impactor as the Hybrid III 50th percentile male ATD. In this test, an impactor with a mass of 23.36 kg and a 152.40 mm diameter contacts the ATD at mid-sternum level. During these tests, the resultant deflections of the left and right upper ribs and probe force at the time of peak resultant deflection were measured. The deflections were calculated *in the local spine coordinate system* to examine the force-deflection response of the upper thorax.

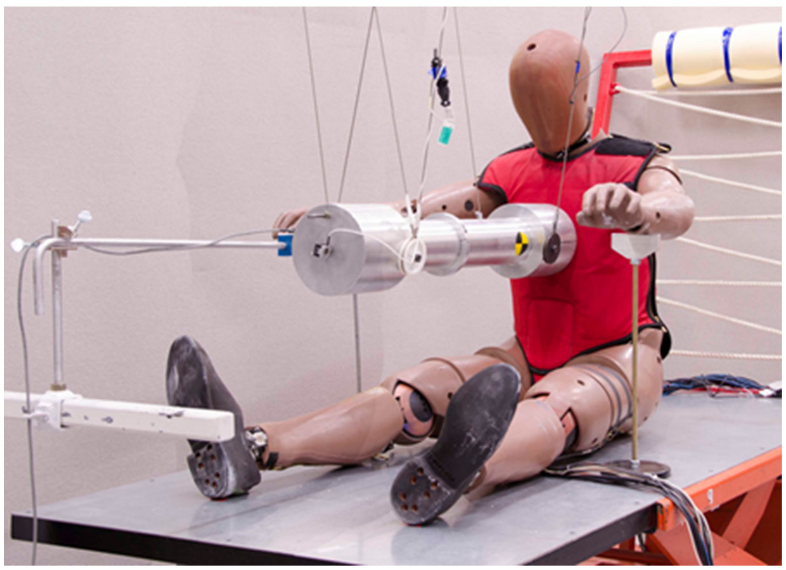

Figure 10-1. Upper thorax impact test setup

10.2 Upper Thorax Repeatability Results

Sections 10.2.1 to 10.2.5 illustrate the results of the upper thorax impact repeatability tests. Each section contains a table providing the test data, followed by plot overlays of the five repeat tests conducted at all three labs. Note that the data in the tables containing the results of each test series are listed sequentially, with the test at the top of the table beginning the test series.

10.2.1 THOR-50M DL9207 Testing at VRTC

Repeatability results at VRTC for the upper thorax qualification of DL9207 yielded CV values all below 5 percent (Table 10-1, Figure 10-2 to Figure 10-6).

Table 10-1. VRTC THOR-50M DL9207 Upper Thorax Repeatability Results

Test Number	Peak Probe Force (N)	Peak Upper Left Resultant Deflection (mm)	Peak Upper Right Resultant Deflection (mm)	Difference Between Peak Left & Right Resultant Deflections (mm)	Force at Left Peak Resultant Deflection (N)	Force at Right Peak Resultant Deflection (N)
180410-1	2752	51.9	50.6	1.3	2567	2588
180410-2	2732	52.0	49.6	2.4	2602	2584
180410-5	2751	51.6	50.9	0.7	2660	2657
180410-6	2780	52.6	52.0	0.6	2660	2637
180410-7	2682	51.9	51.8	0.2	2631	2619
Mean	**2739**	**51.5**		**N/A**	**2620**	
Std. Dev.	**36**	**0.9**		**N/A**	**34**	
CV	**1.3%**	**1.7%**		**N/A**	**1.3%**	

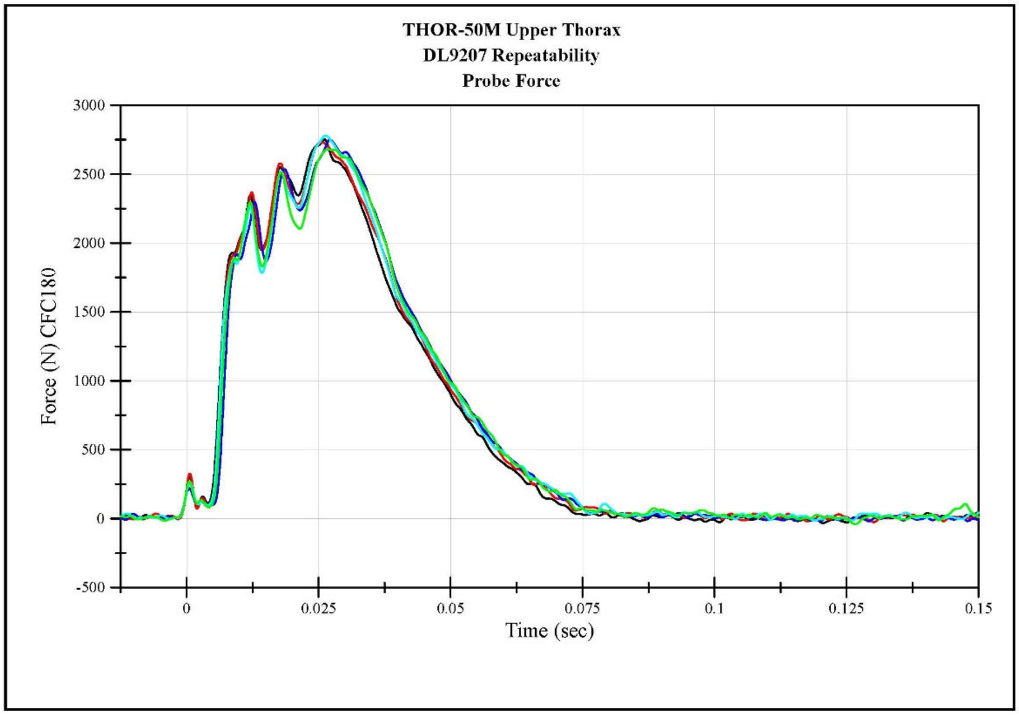

Figure 10-2. VRTC upper thorax probe force repeatability for DL9207

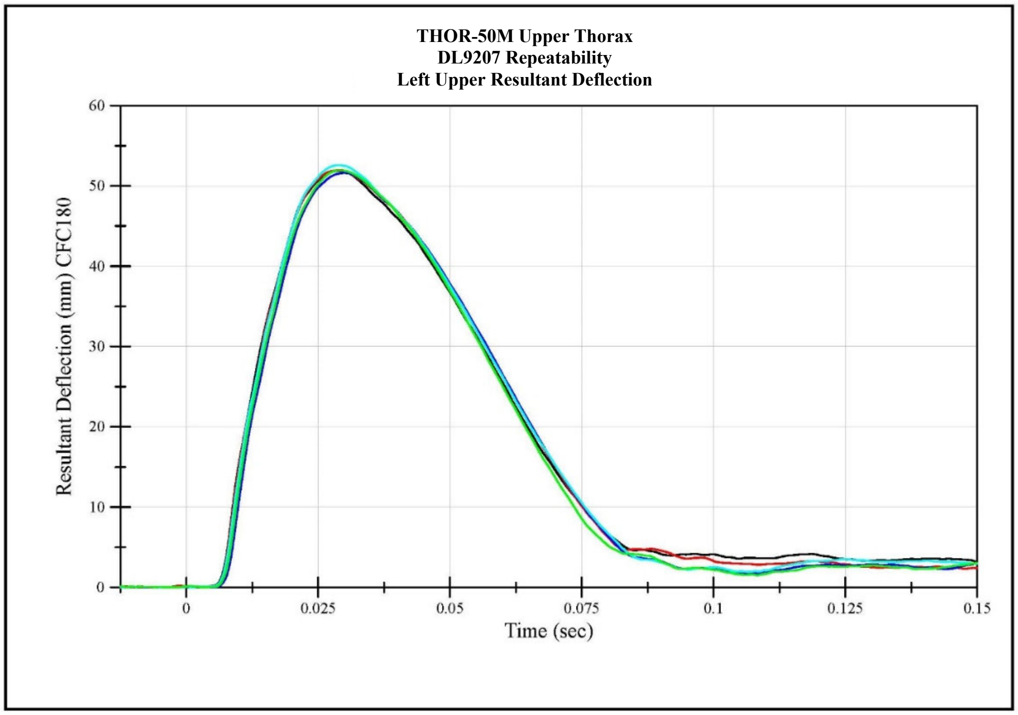

Figure 10-3. VRTC upper thorax upper left resultant deflection repeatability for DL9207

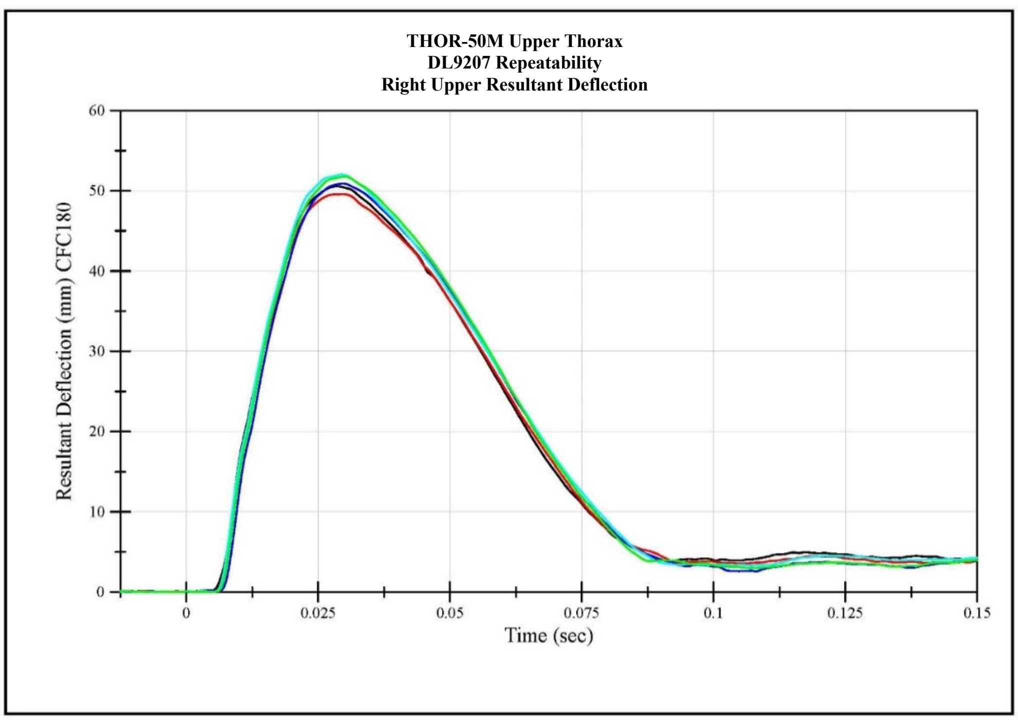

Figure 10-4. VRTC upper thorax upper right resultant deflection repeatability for DL9207

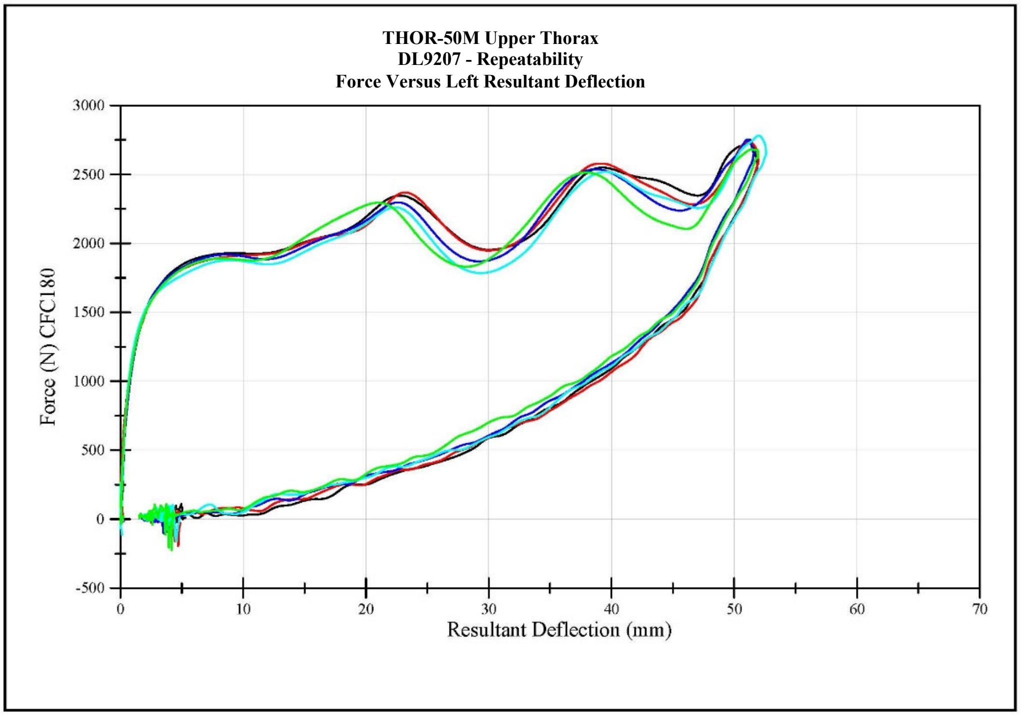

Figure 10-5. VRTC upper thorax force vs. left resultant deflection repeatability for DL9207

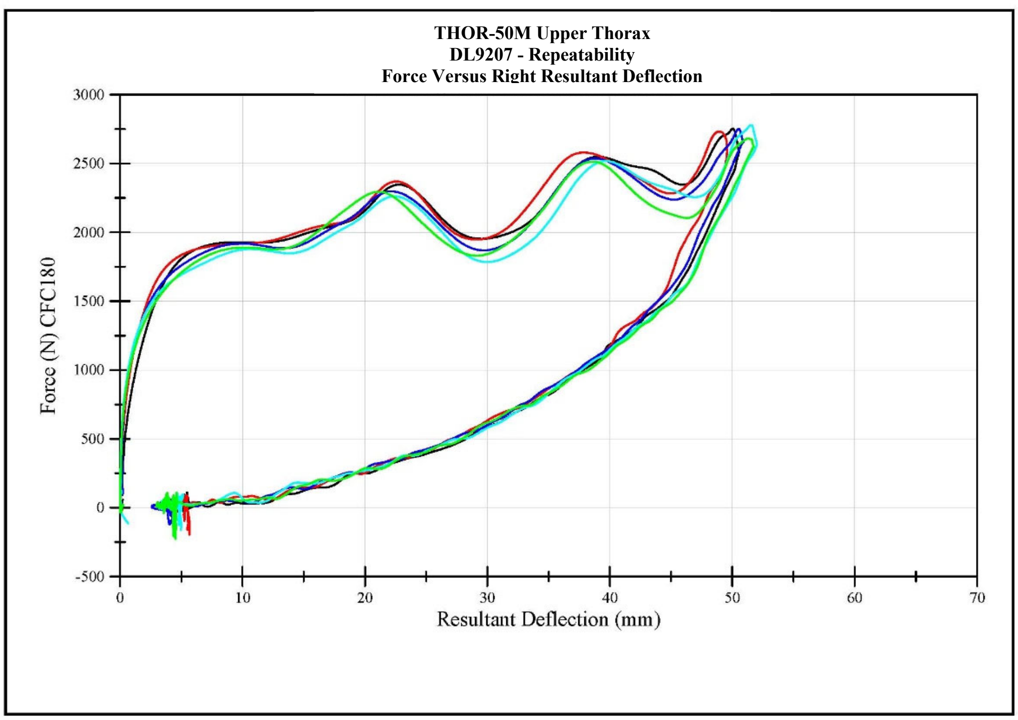

Figure 10-6. VRTC upper thorax force vs. right resultant deflection repeatability for DL9207

10.2.2 THOR-50M DO9798 Testing at VRTC

Repeatability results at VRTC for the upper thorax qualification of DO9798 yielded CV values all below 5 percent (Table 10-2, Figure 10-7 to Figure 10-11).

Table 10-2. VRTC THOR-50M DO9798 Upper Thorax Repeatability Results

Test Number	Peak Probe Force (N)	Peak Upper Left Resultant Deflection (mm)	Peak Upper Right Resultant Deflection (mm)	Difference Between Peak Left & Right Resultant Deflections (mm)	Force at Left Peak Resultant Deflection (N)	Force at Right Peak Resultant Deflection (N)
180517-1	2724	55.1	57.0	-1.8	2720	2675
180517-5	2617	54.7	55.8	-1.1	2605	2614
180517-6	2672	56.4	56.7	-0.3	2647	2662
180517-7	2672	56.0	56.6	-0.6	2671	2664
180517-9	2725	55.6	55.7	-0.2	2712	2719
Mean	**2682**	**56.0**		**N/A**	**2669**	
Std. Dev.	**45**	**0.7**		**N/A**	**40**	
CV	**1.7%**	**1.3%**		**N/A**	**1.5%**	

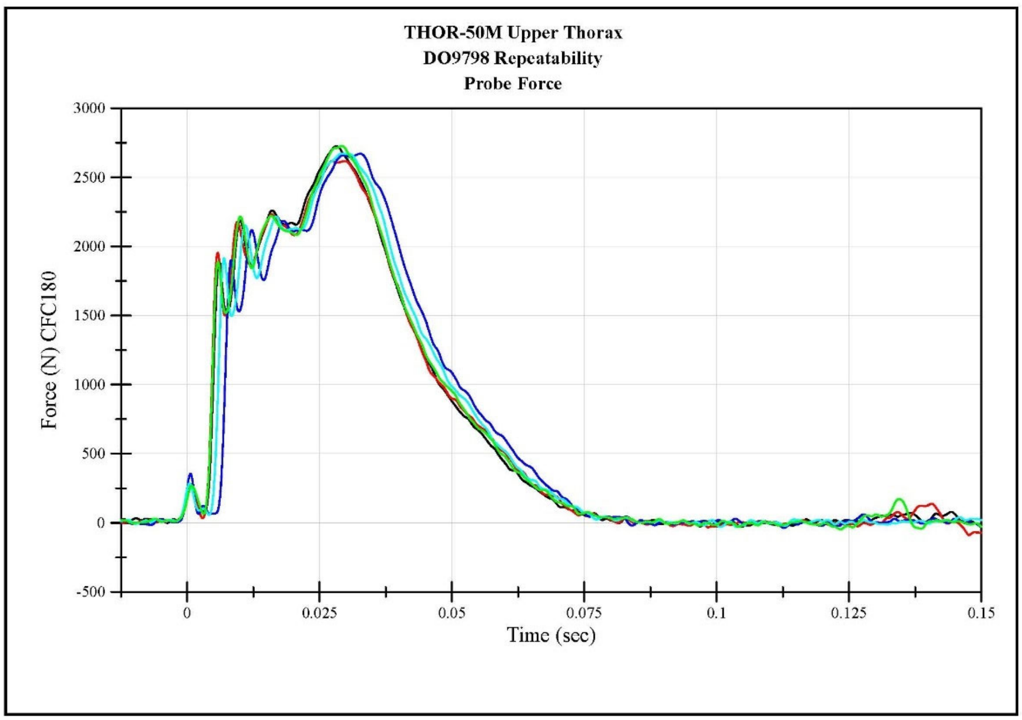

Figure 10-7. VRTC upper thorax probe force repeatability for DO9798

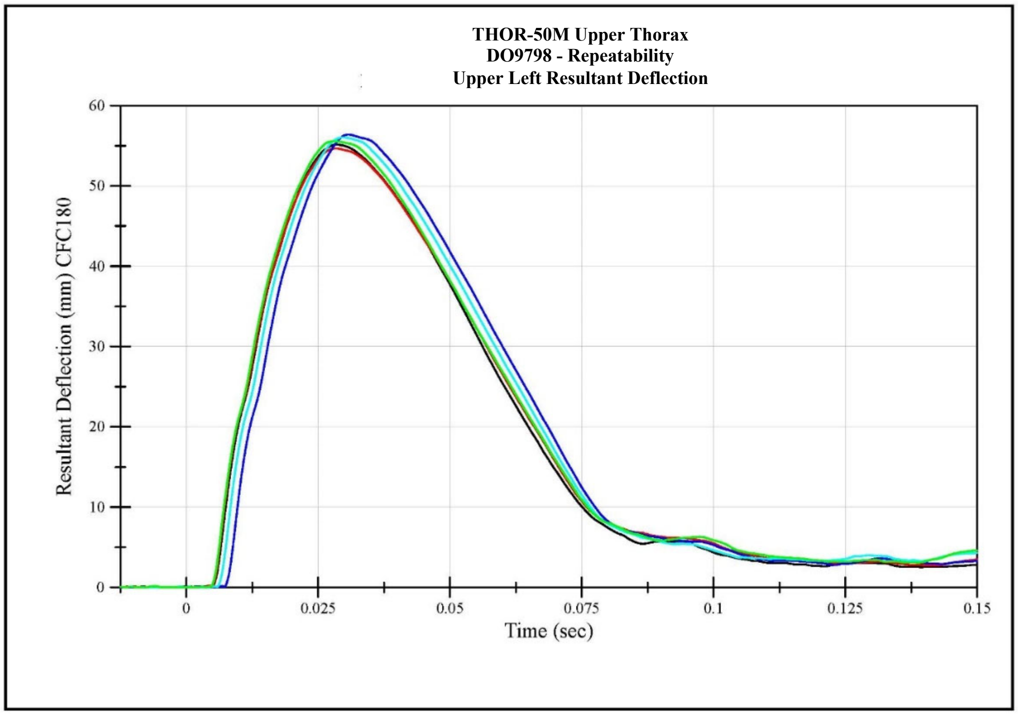

Figure 10-8. VRTC upper thorax upper left resultant deflection repeatability for DO9798

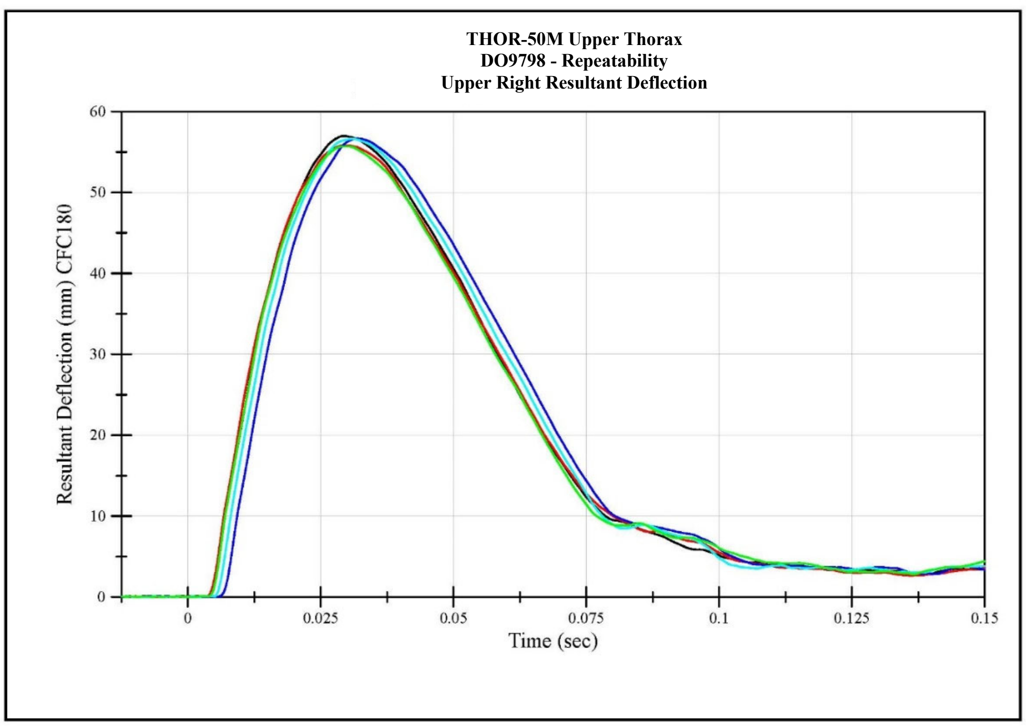

Figure 10-9. VRTC upper thorax upper right resultant deflection repeatability for DO9798

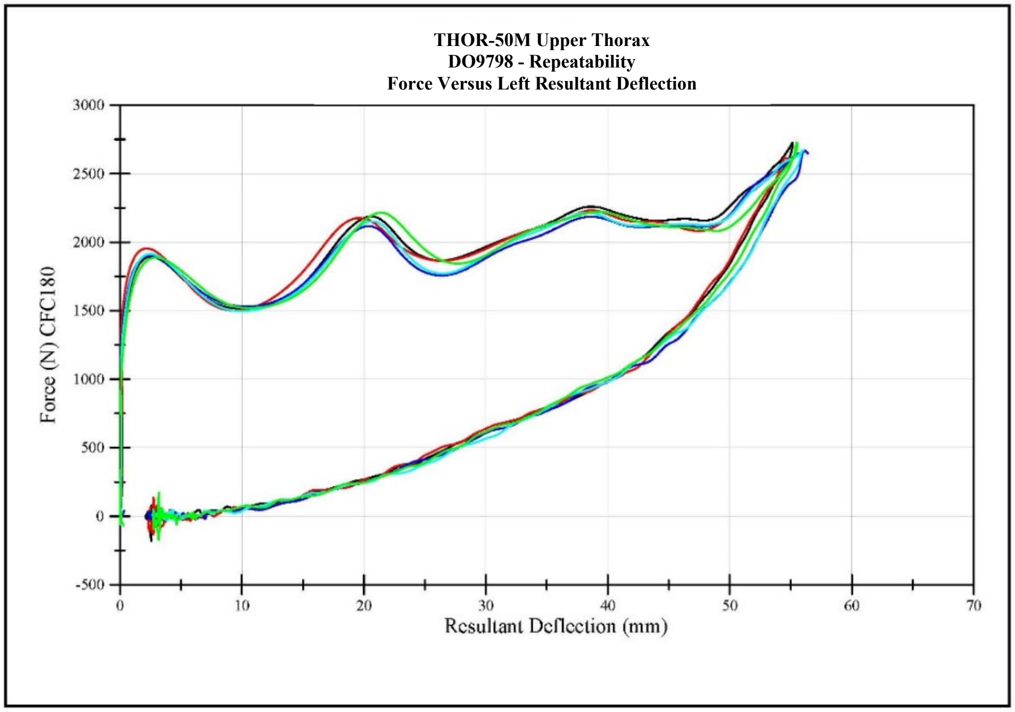

Figure 10-10. VRTC upper thorax force vs. left resultant deflection repeatability for DO9798

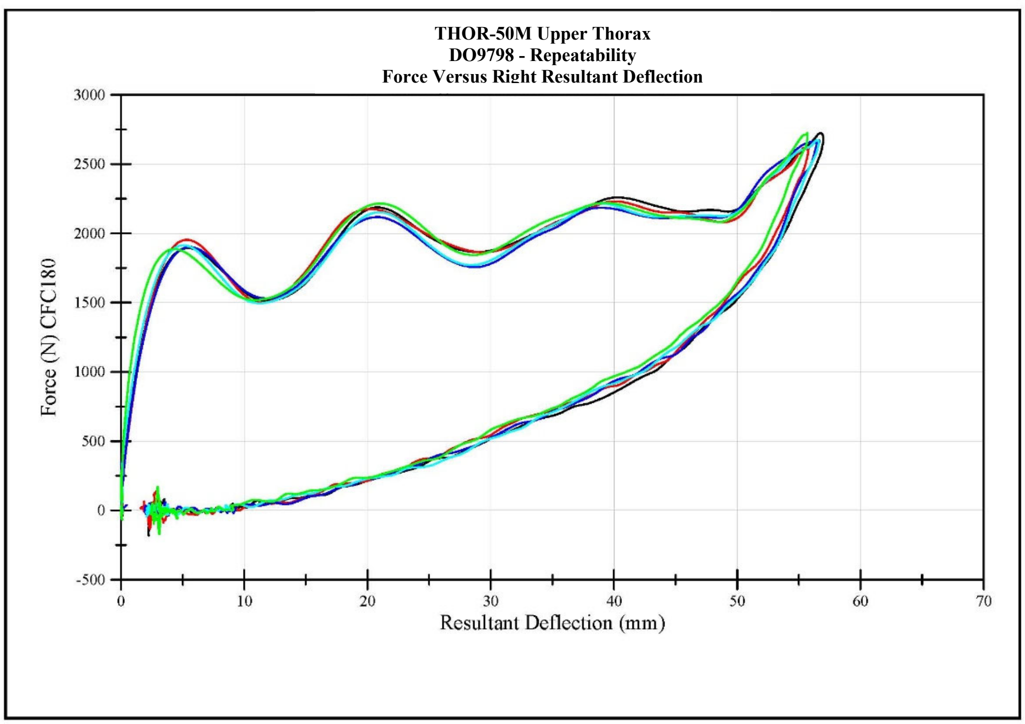

Figure 10-11. VRTC upper thorax force vs. right resultant deflection repeatability for DO9798

10.2.3 THOR-50M DO9799 Testing at VRTC

Repeatability results at VRTC for the upper thorax qualification of DO9799 yielded CV values all below 5 percent (Table 10-3, Figure 10-12 to Figure 10-16).

Table 10-3. VRTC THOR-50M DO9799 Upper Thorax Repeatability Results

Test Number	Peak Probe Force (N)	Peak Upper Left Resultant Deflection (mm)	Peak Upper Right Resultant Deflection (mm)	Difference Between Peak Left & Right Resultant Deflections (mm)	Force at Left Peak Resultant Deflection (N)	Force at Right Peak Resultant Deflection (N)
180328-1	2825	50.9	51.6	-0.8	2741	2694
180328-2	2812	51.7	52.1	-0.4	2661	2769
180328-3	2641	50.4	52.9	-2.5	2520	2585
180328-4	2750	52.7	53.3	-0.5	2667	2735
180328-5	2789	52.6	53.1	-0.5	2665	2739
Mean	**2763**	**52.1**		**N/A**	**2678**	
Std. Dev.	**74**	**1.0**		**N/A**	**77**	
CV	**2.7%**	**1.8%**		**N/A**	**2.9%**	

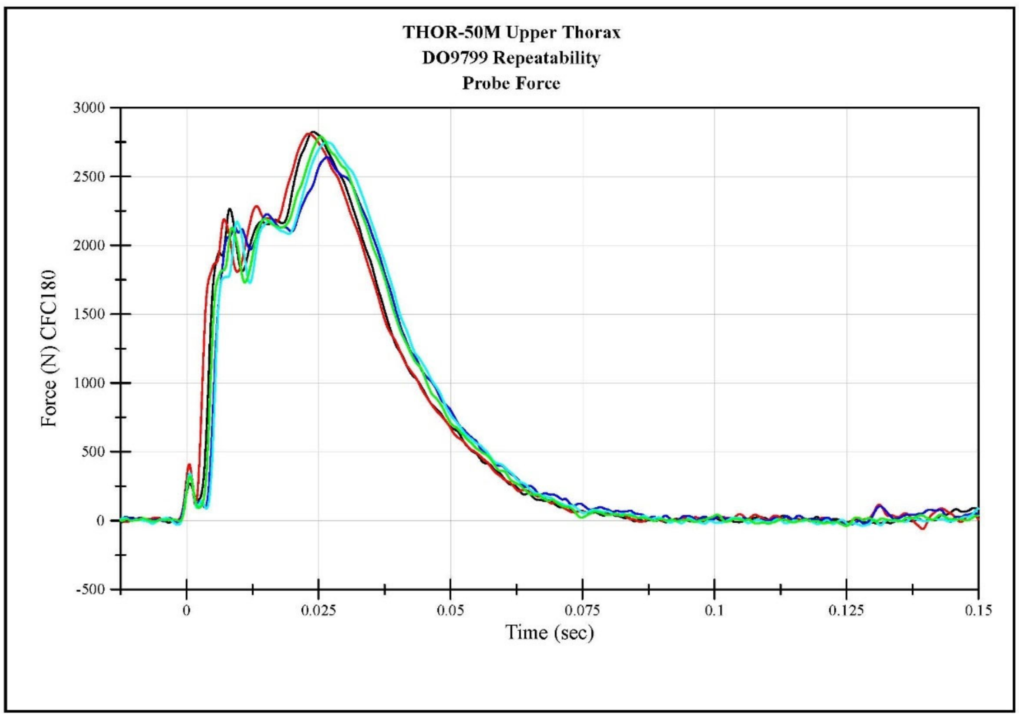

Figure 10-12. VRTC upper thorax probe force repeatability for DO9799

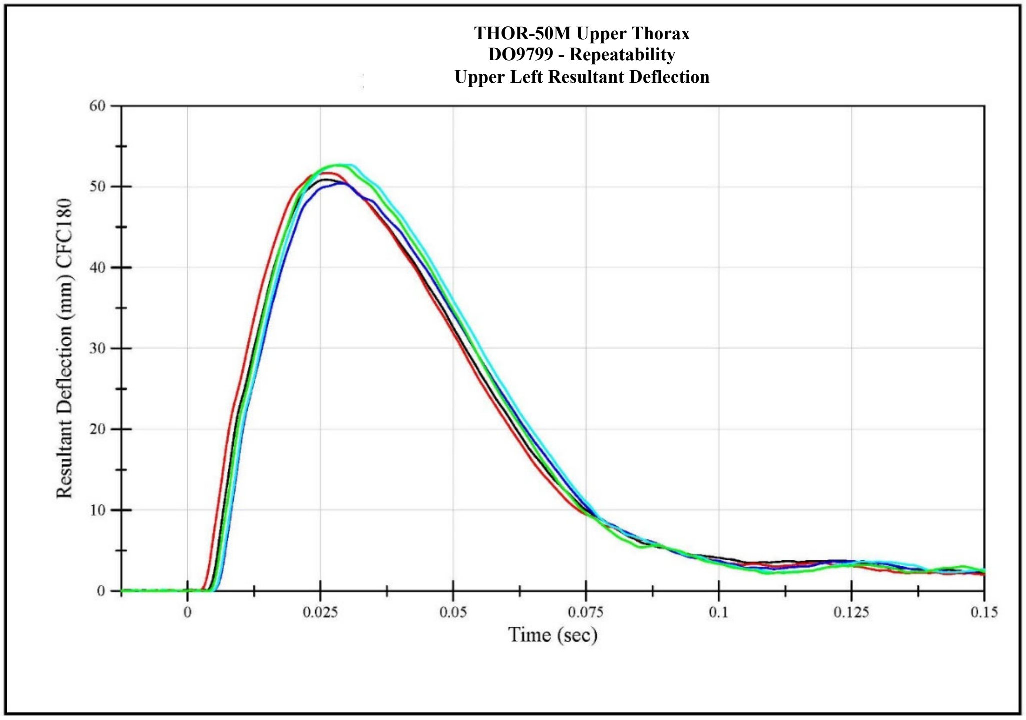

Figure 10-13. VRTC upper thorax upper left resultant deflection repeatability for DO9799

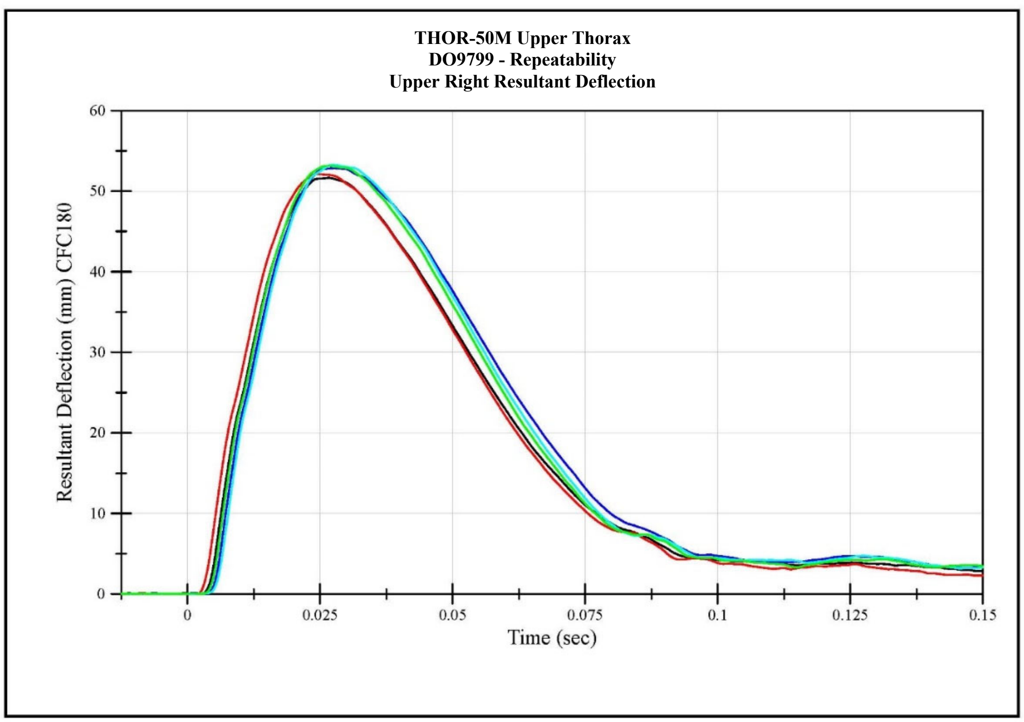

Figure 10-14. VRTC upper thorax upper right resultant deflection repeatability for DO9799

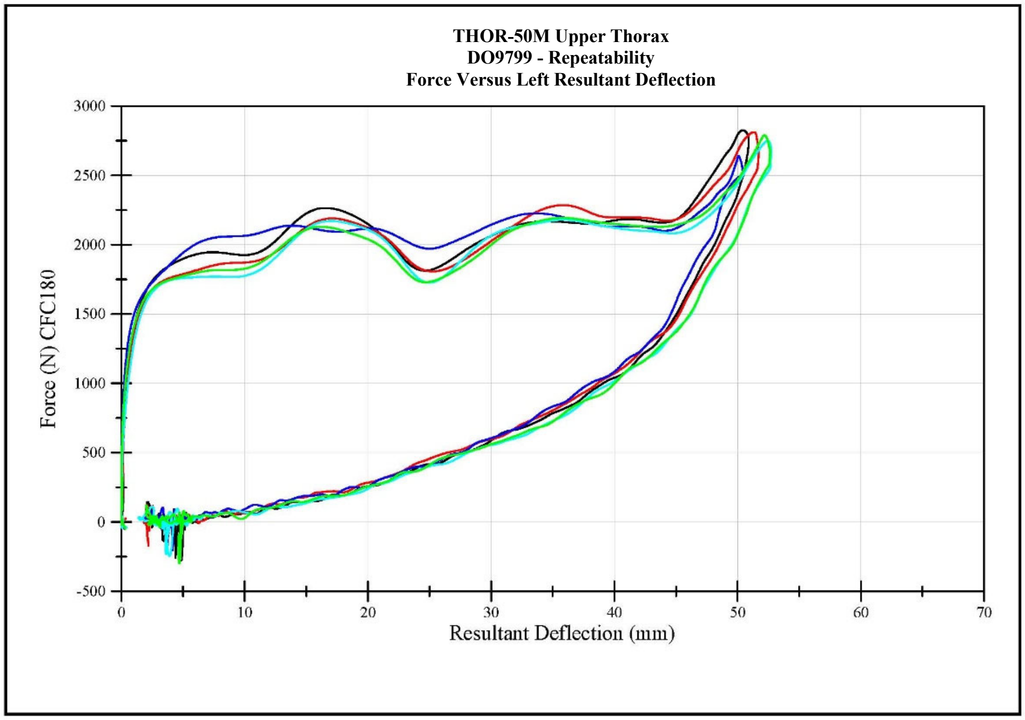

Figure 10-15. VRTC upper thorax force vs. left resultant deflection repeatability for DO9799

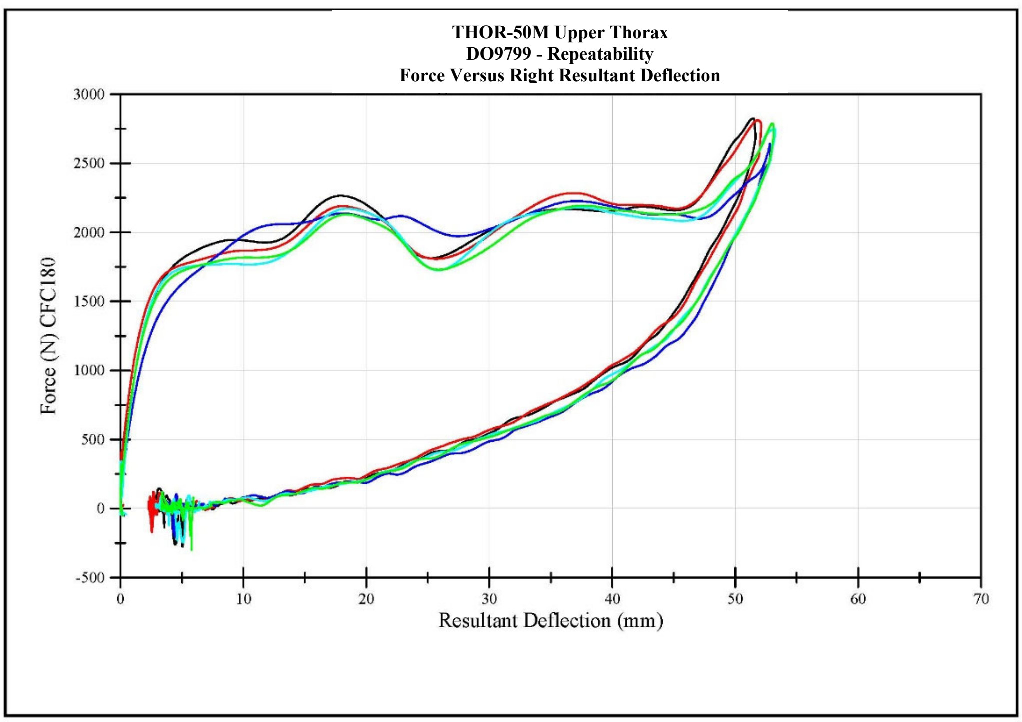

Figure 10-16. VRTC upper thorax force vs. right resultant deflection repeatability for DO9799

10.2.4 THOR-50M DO9799 Testing at Humanetics

Repeatability results at Humanetics for the upper thorax qualification of DO9799 yielded CV values all below 5 percent (Table 10-4, Figure 10-17 to Figure 10-21).

Table 10-4. Humanetics THOR-50M DO9799 Upper Thorax Repeatability Results

Test Number	Peak Probe Force (N)	Peak Upper Left Resultant Deflection (mm)	Peak Upper Right Resultant Deflection (mm)	Difference Between Peak Left & Right Resultant Deflections (mm)	Force at Left Peak Resultant Deflection (N)	Force at Right Peak Resultant Deflection (N)
423558	2930	52.1	54.3	-2.3	2706	2819
423559	2884	52.2	53.6	-1.3	2703	2753
423560	2838	53.1	54.9	-1.9	2754	2764
423562	2833	53.6	54.0	-0.4	2669	2734
423568	2888	52.6	55.4	-2.8	2748	2770
Mean	**2875**	**53.6**		**N/A**	**2742**	
Std. Dev.	**40**	**1.1**		**N/A**	**42**	
CV	**1.4%**	**2.1%**		**N/A**	**1.5%**	

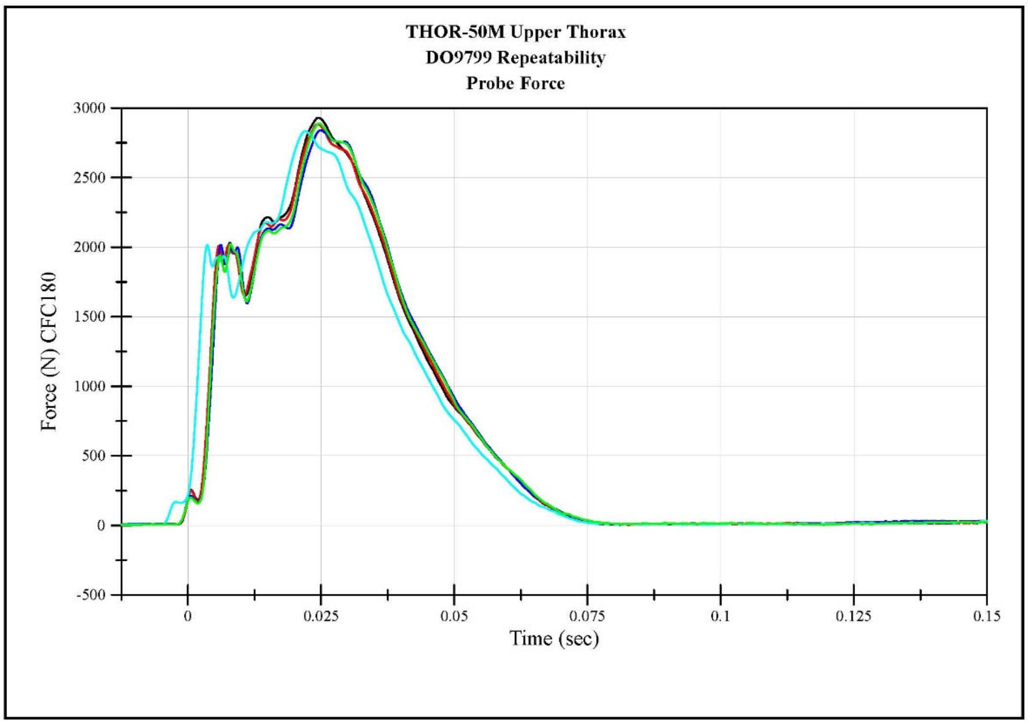

Figure 10-17. Humanetics upper thorax probe force repeatability for DO9799

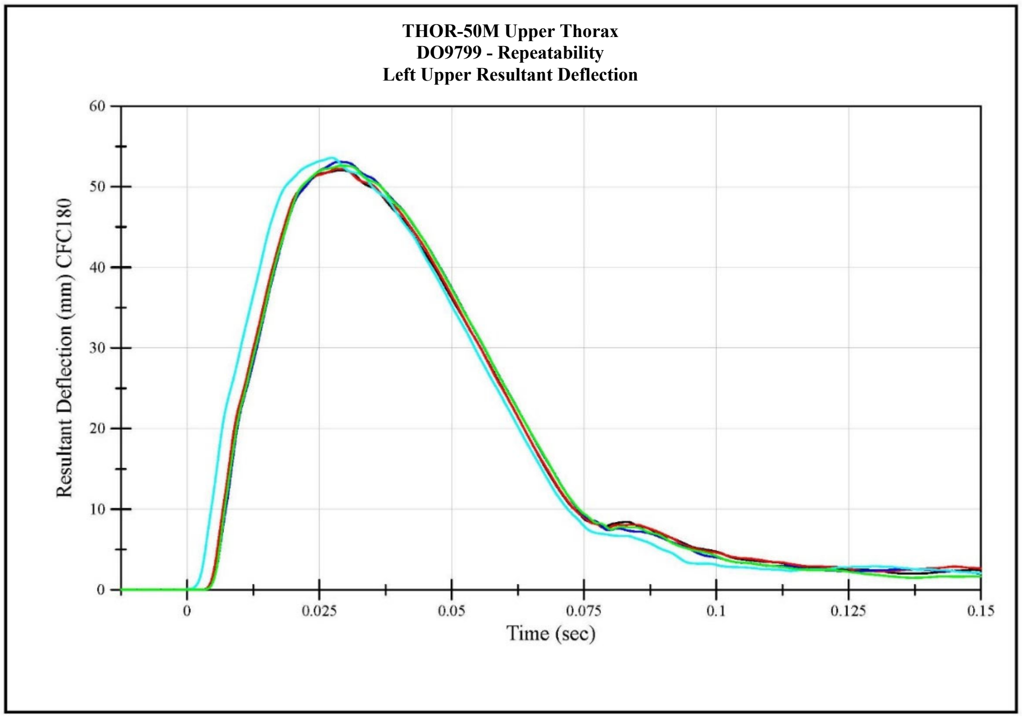

Figure 10-18. Humanetics upper thorax upper left resultant deflection repeatability for DO9799

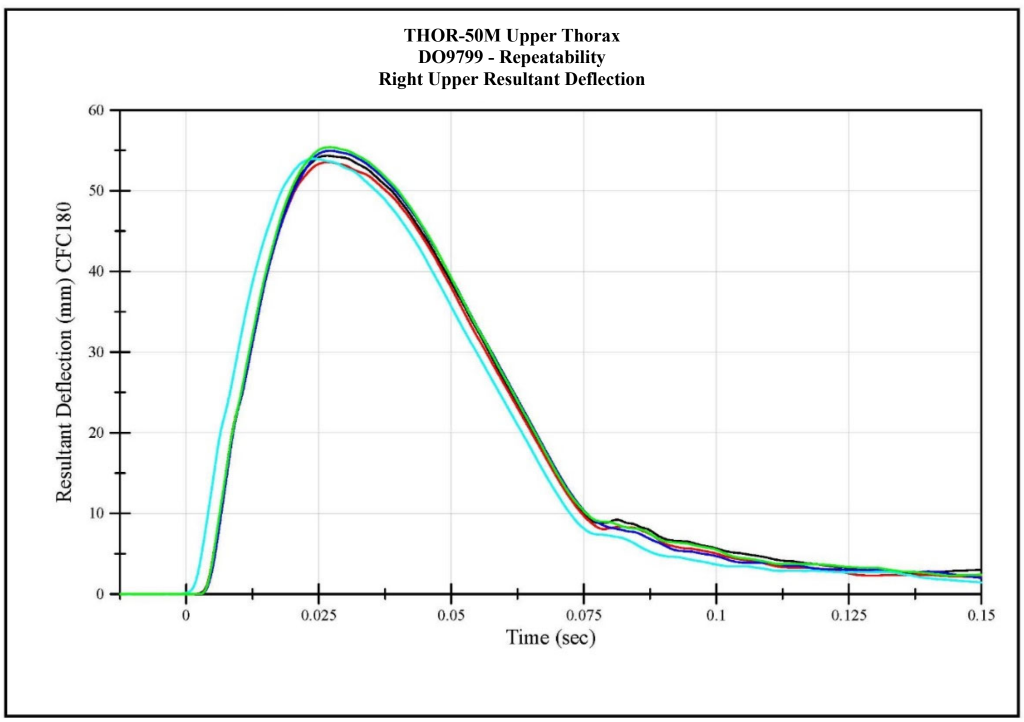

Figure 10-19. Humanetics upper thorax upper right resultant deflection repeatability for DO9799

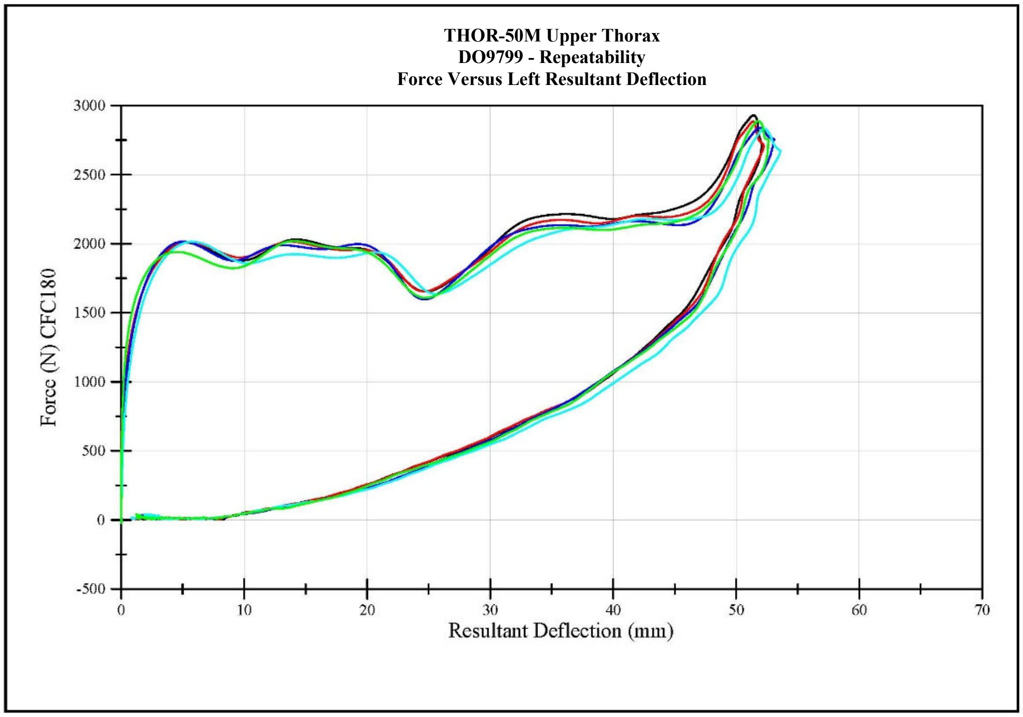

Figure 10-20. Humanetics upper thorax force vs. left resultant deflection repeatability for DO9799

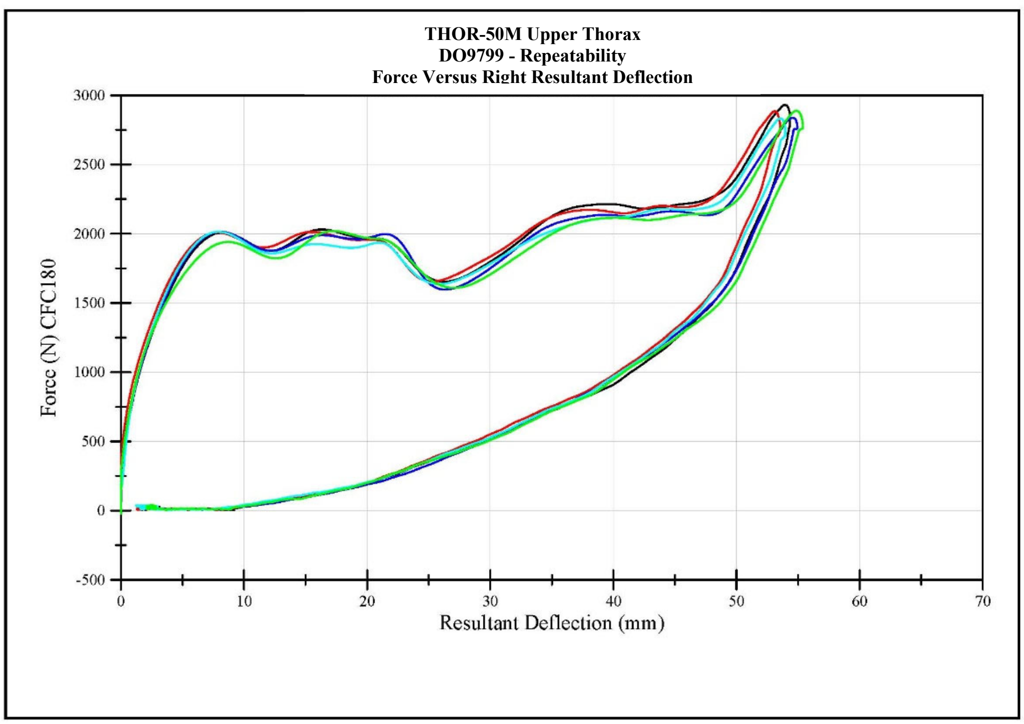

Figure 10-21. Humanetics upper thorax force vs. right resultant deflection repeatability for DO9799

10.2.5 THOR-50M DO9799 Testing at Calspan

Repeatability results at Calspan for the upper thorax qualification of DO9799 yielded CV values all below 5 percent (Table 10-5, Figure 10-22 to Figure 10-26).

Table 10-5. Calspan THOR-50M Upper Thorax Repeatability Results for DO9799

Test Number	Peak Probe Force (N)	Peak Upper Left Resultant Deflection (mm)	Peak Upper Right Resultant Deflection (mm)	Difference Between Peak Left & Right Resultant Deflections (mm)	Force at Left Peak Resultant Deflection (N)	Force at Right Peak Resultant Deflection (N)
20180529190201	2703	53.0	54.6	-1.6	2636	2593
20180529194345	2746	54.7	53.6	1.1	2685	2672
20180530082032	2808	55.2	55.5	-0.3	2679	2686
20180530104859	2820	56.2	55.7	0.5	2716	2743
20180530113116	2707	55.9	55.8	0.1	2661	2667
Mean	**2757**	**55.0**		**N/A**	**2674**	
Std. Dev.	**55**	**1.1**		**N/A**	**41**	
CV	**2.0%**	**2.0%**		**N/A**	**1.5%**	

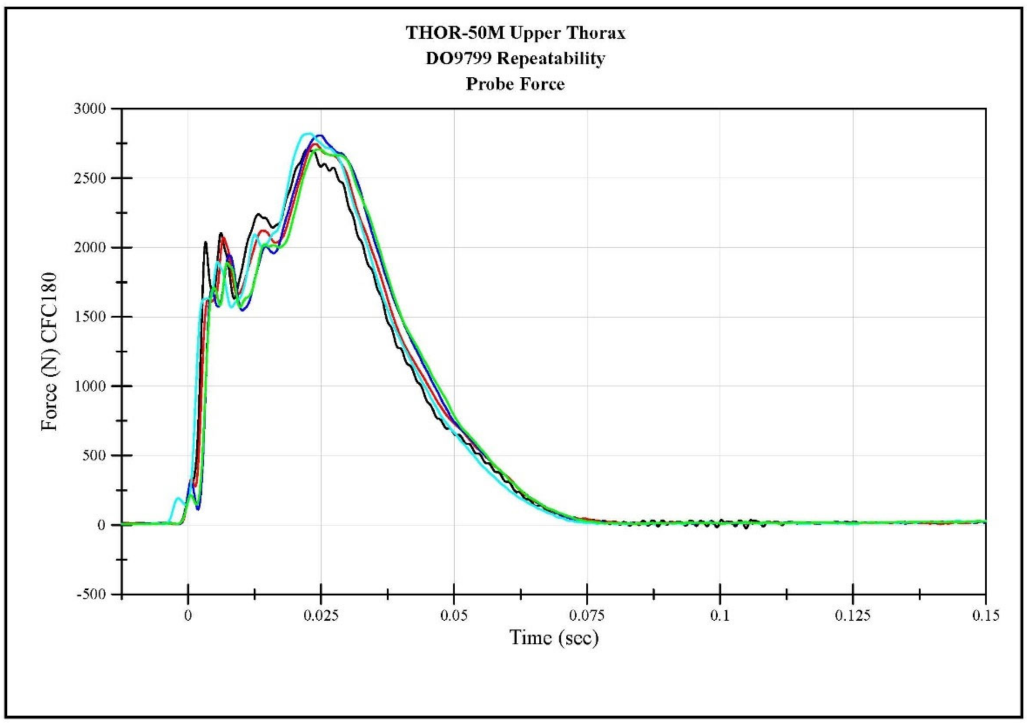

Figure 10-22. Calspan upper thorax probe force repeatability for DO9799

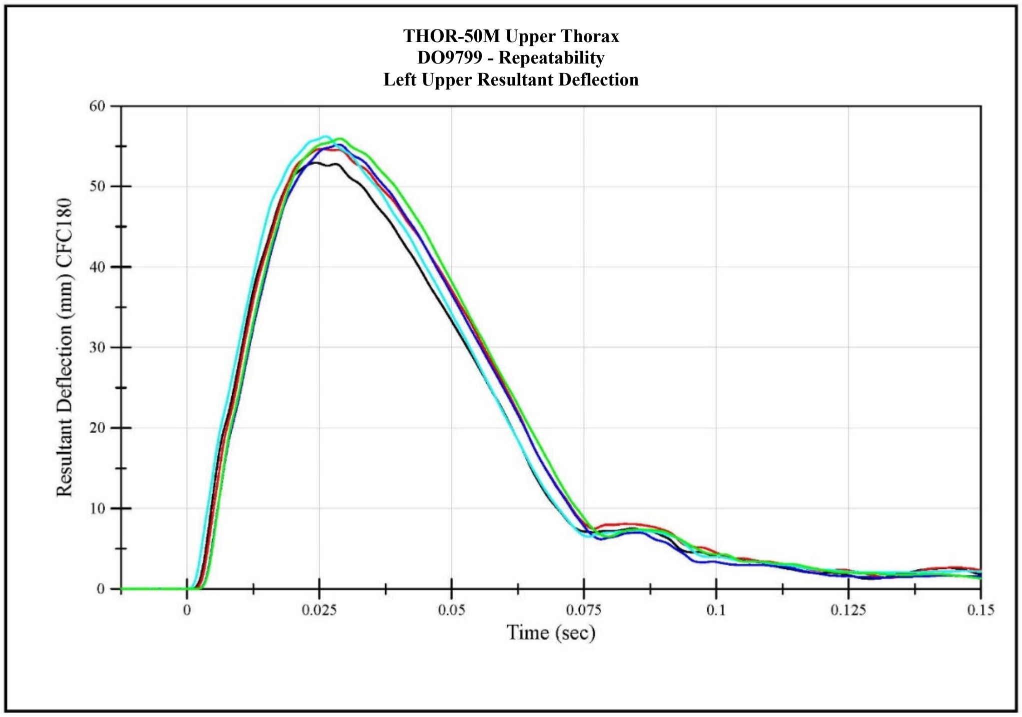

Figure 10-23. Calspan upper thorax upper left resultant deflection repeatability for DO9799

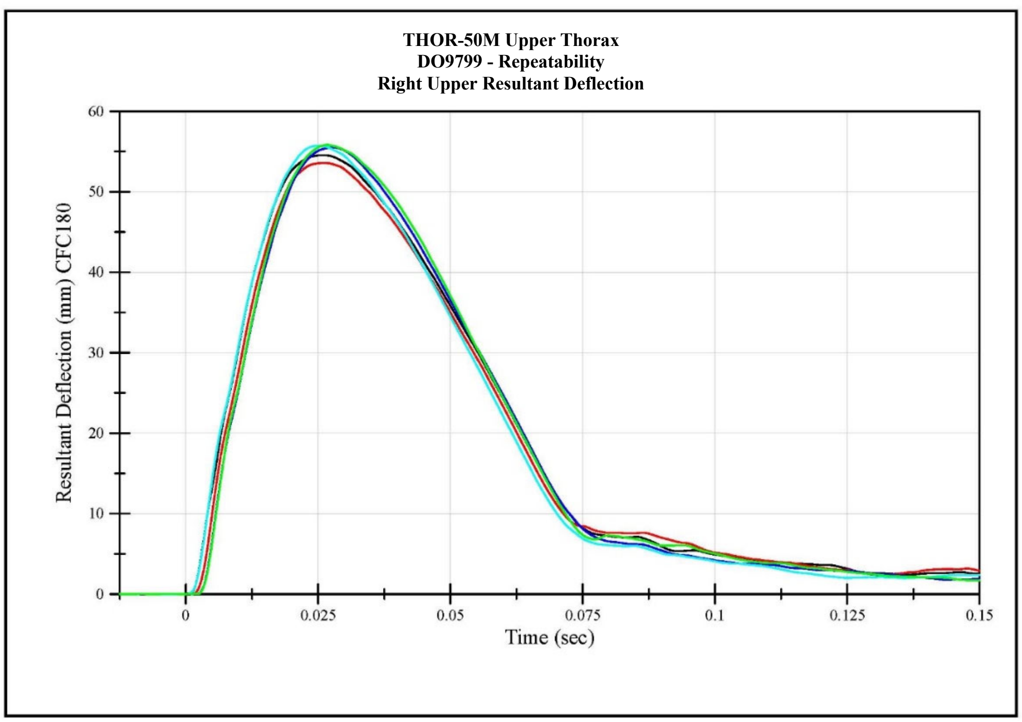

Figure 10-24. Calspan upper thorax upper right resultant deflection repeatability for DO9799

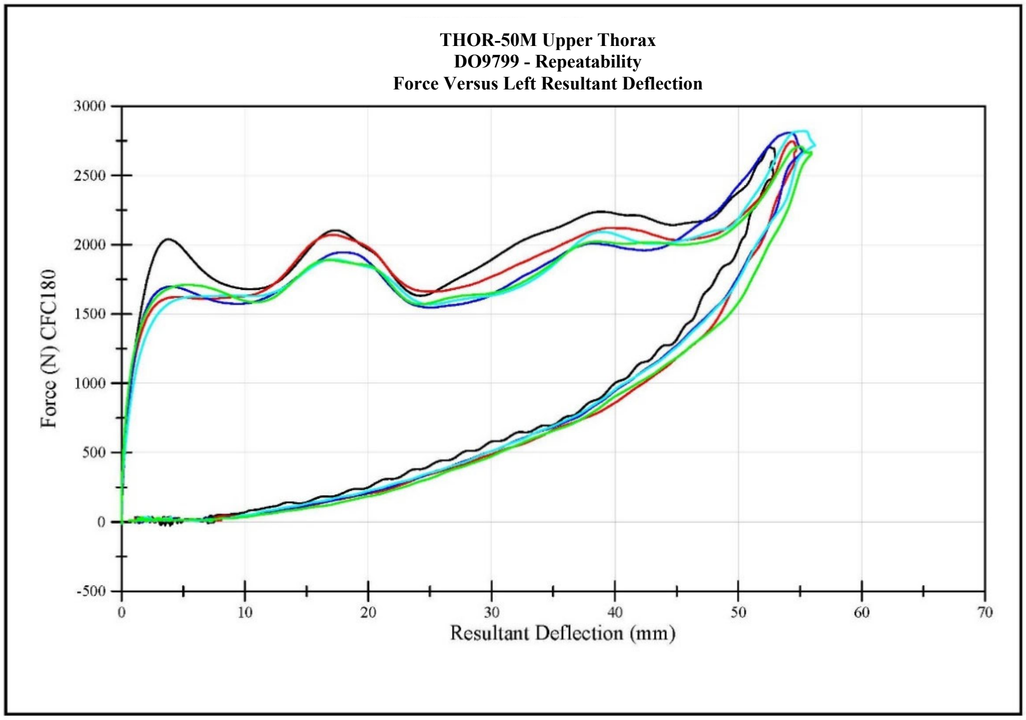

Figure 10-25. Calspan upper thorax force vs. left resultant deflection repeatability for DO9799

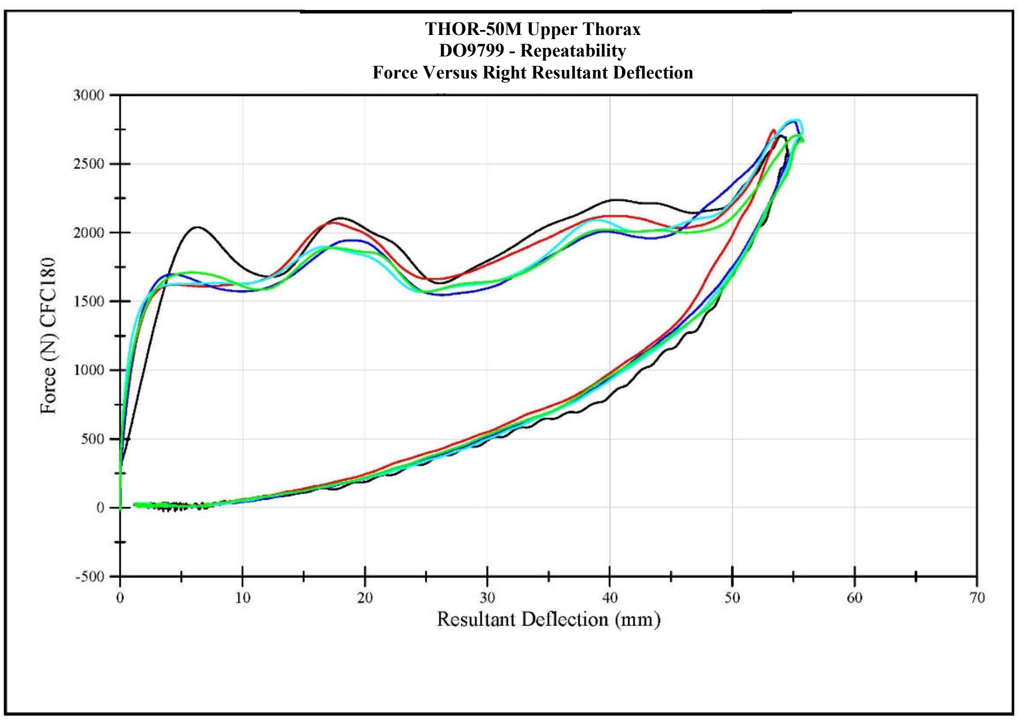

Figure 10-26. Calspan upper thorax force vs. right resultant deflection repeatability for DO9799

10.3 Upper Thorax Dummy Reproducibility Results

Dummy Reproducibility results at VRTC for the upper thorax qualification tests yielded CV values all below 5 percent (Table 10-6).

Table 10-6. THOR-50M Upper Thorax Dummy Reproducibility Results

Dummy Number	Test Number	Peak Probe Force (N)	Peak Upper Left Resultant Deflection (mm)	Peak Upper Right Resultant Deflection (mm)	Difference Between Peak Left & Right Resultant Deflections (mm)	Force at Left Peak Resultant Deflection (N)	Force at Right Peak Resultant Deflection (N)
VRTC DL9207	**180410-1**	2752	51.9	50.6	1.3	2567	2588
	180410-2	2732	52.0	49.6	2.4	2602	2584
	180410-5	2751	51.6	50.9	0.7	2660	2657
	180410-6	2780	52.6	52.0	0.6	2660	2637
	180410-7	2682	51.9	51.8	0.2	2631	2619
VRTC DO9798	**180517-1**	2724	55.1	57.0	-1.8	2720	2675
	180517-5	2617	54.7	55.8	-1.1	2605	2614
	180517-6	2672	56.4	56.7	-0.3	2647	2662
	180517-7	2672	56.0	56.6	-0.6	2671	2664
	180517-9	2725	55.6	55.7	-0.2	2712	2719
VRTC DO9799	**180328-1**	2825	50.9	51.6	-0.8	2741	2694
	180328-2	2812	51.7	52.1	-0.4	2661	2769
	180328-3	2641	50.4	52.9	-2.5	2520	2585
	180328-4	2750	52.7	53.3	-0.5	2667	2735
	180328-5	2789	52.6	53.1	-0.5	2665	2739
Mean		**2728**	**53**		**N/A**	**2656**	
Std. Dev.		**61**	**2**		**N/A**	**58**	
CV		**2.3%**	**3.7%**		**N/A**	**2.2%**	

10.4 Lab-to-Lab Variability Analysis

The results of the upper thorax qualification tests from each lab are presented in Table 10-7. The repeatability within each lab is indicated by CV values below 5 percent. The last four rows of the table show the *Test Reproducibility* results when data from all three labs are combined.

The difference between the left and right X deflections was also calculated to assure an even impact to the upper thorax. Ideally, the difference should be zero in a symmetrical impact scenario. Any differences would likely be attributed to setup variations which allowed a non-symmetrical impact, or could indicate a problem with the instrumentation. Both the within lab and between lab differences are small, since the mean differences are all lower than 1.2 mm (Table 10-6) and (Table 10-7).

Table 10-7. THOR-50M Upper Thorax Lab-to-Lab Variability Results

<table>
<tr><th>Dummy Number</th><th>Peak Probe Force (N)</th><th>Peak Upper Left Resultant Deflection (mm)</th><th>Peak Upper Right Resultant Deflection (mm)</th><th>Difference Between Peak Left & Right Resultant Deflections (mm)</th><th>Force at Left Peak Resultant Deflection (N)</th><th>Force at Right Peak Resultant Deflection (N)</th></tr>
<tr><td rowspan="5">VRTC DO9799</td><td>2825</td><td>50.9</td><td>51.6</td><td>-0.8</td><td>2741</td><td>2694</td></tr>
<tr><td>2812</td><td>51.7</td><td>52.1</td><td>-0.4</td><td>2661</td><td>2769</td></tr>
<tr><td>2641</td><td>50.4</td><td>52.9</td><td>-2.5</td><td>2520</td><td>2585</td></tr>
<tr><td>2750</td><td>52.7</td><td>53.3</td><td>-0.5</td><td>2667</td><td>2735</td></tr>
<tr><td>2789</td><td>52.6</td><td>53.1</td><td>-0.5</td><td>2665</td><td>2739</td></tr>
<tr><td rowspan="5">Humanetics DO9799</td><td>2930</td><td>52.1</td><td>54.3</td><td>-2.3</td><td>2706</td><td>2819</td></tr>
<tr><td>2884</td><td>52.2</td><td>53.6</td><td>-1.3</td><td>2703</td><td>2753</td></tr>
<tr><td>2838</td><td>53.1</td><td>54.9</td><td>-1.9</td><td>2754</td><td>2764</td></tr>
<tr><td>2833</td><td>53.6</td><td>54.0</td><td>-0.4</td><td>2669</td><td>2734</td></tr>
<tr><td>2888</td><td>52.6</td><td>55.4</td><td>-2.8</td><td>2748</td><td>2770</td></tr>
<tr><td rowspan="5">Calspan DO9799</td><td>2703</td><td>53.0</td><td>54.6</td><td>-1.6</td><td>2636</td><td>2593</td></tr>
<tr><td>2746</td><td>54.7</td><td>53.6</td><td>1.1</td><td>2685</td><td>2672</td></tr>
<tr><td>2808</td><td>55.2</td><td>55.5</td><td>-0.3</td><td>2679</td><td>2686</td></tr>
<tr><td>2820</td><td>56.2</td><td>55.7</td><td>0.5</td><td>2716</td><td>2743</td></tr>
<tr><td>2707</td><td>55.9</td><td>55.8</td><td>0.1</td><td>2661</td><td>2667</td></tr>
<tr><td>Test Reproducibility DO9799</td><td colspan="6"></td></tr>
<tr><td>Mean</td><td>2798</td><td colspan="2">53.1</td><td>N/A</td><td colspan="2">2698</td></tr>
<tr><td>Std. Dev.</td><td>78</td><td colspan="2">1.7</td><td>N/A</td><td colspan="2">63</td></tr>
<tr><td>CV</td><td>2.8%</td><td colspan="2">3.2%</td><td>N/A</td><td colspan="2">2.3%</td></tr>
</table>

10.5 Corridor Development

All the data used to determine the upper thorax qualification corridors is shown in Table 10-8. The qualification corridors were calculated using the mean plus or minus 10 percent of the peak for the specified measured or calculated channels (Table 10-9), with the exception of the difference between the left and right thorax resultant deflections which was ±10% (±5 mm) of the mean of the peak upper left and right resultant deflections.

Table 10-8. THOR-50M Upper Thorax Qualification Corridor Results

Dummy Number	Test Number	Peak Probe Force (N)	Peak Upper Left Resultant Deflection (mm)	Peak Upper Right Resultant Deflection (mm)	Difference Between Peak Left & Right Resultant Deflections (mm)	Force at Left Peak Resultant Deflection (N)	Force at Right Peak Resultant Deflection (N)
VRTC DL9207	**180410-1**	2752	51.9	50.6	1.3	2567	2588
	180410-2	2732	52.0	49.6	2.4	2602	2584
	180410-5	2751	51.6	50.9	0.7	2660	2657
	180410-6	2780	52.6	52.0	0.6	2660	2637
	180410-7	2682	51.9	51.8	0.2	2631	2619
VRTC DO9798	**180517-1**	2724	55.1	57.0	-1.8	2720	2675
	180517-5	2617	54.7	55.8	-1.1	2605	2614
	180517-6	2672	56.4	56.7	-0.3	2647	2662
	180517-7	2672	56.0	56.6	-0.6	2671	2664
	180517-9	2725	55.6	55.7	-0.2	2712	2719
VRTC DO9799 (Cont.)	**180328-1**	2825	50.9	51.6	-0.8	2741	2694
	180328-2	2812	51.7	52.1	-0.4	2661	2769
	180328-3	2641	50.4	52.9	-2.5	2520	2585
	180328-4	2750	52.7	53.3	-0.5	2667	2735
	180328-5	2789	52.6	53.1	-0.5	2665	2739
Humanetics DO9799	**423558**	2930	52.1	54.3	-2.3	2706	2819
	423559	2884	52.2	53.6	-1.3	2703	2753
	423560	2838	53.1	54.9	-1.9	2754	2764
	423562	2833	53.6	54.0	-0.4	2669	2734
	423568	2888	52.6	55.4	-2.8	2748	2770
Calspan DO9799	**20180529190201**	2703	53.0	54.6	-1.6	2636	2593
	20180529194345	2746	54.7	53.6	1.1	2685	2672
	20180530082032	2808	55.2	55.5	-0.3	2679	2686
	20180530104859	2820	56.2	55.7	0.5	2716	2743
	20180530113116	2707	55.9	55.8	0.1	2661	2667
Mean		**2763**	**53.6**		**N/A**	**2677**	
Std. Dev.		**80**	**1.9**		**N/A**	**61**	
CV		**2.9%**	**3.6%**		**N/A**	**2.3%**	

Table 10-9. Upper Thorax Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Impact Velocity	**m/s**	4.25	4.35	4.30	
Peak Probe Force	**N**	0	3039	3039	N/A
Peak Upper Left Resultant Deflection	**mm**	48.3	59.0	53.6	10%
Peak Upper Right Resultant Deflection	**mm**				
Difference Between Peak Left & Right Resultant Deflections	**mm**	-5	5	0	± 10% of the mean of resultant deflection
Force at Left & Right Peak Resultant Deflection	**N**	2409	2944	2677	10%

Discussion. There were no instances in which a test did not achieve the target response ± 10%. All CV values were below 5 percent. There are no indications that there are problems with repeatability or reproducibility for this test condition.

11 Lower Thorax

11.1 Methodology

Repeatability and reproducibility tests were performed using the lower thorax qualification procedures described in the *THOR-50M Qualification Procedures Manual*. This test mode requires blunt impacts to the lower ribcage on either the right or left sides of the thorax (Figure 11-1). The lower ribcage impact qualification tests use the same impactor as the upper ribcage central impact 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. Both left and right sides of the dummy were tested since they are not tests on the same components; this will allow a comparison of differences between the two sides. During these tests, the resultant deflection and probe force were measured. The deflections of the lower thorax (on the impacted side) were calculated *in the local spine coordinate system* to examine the force-deflection response of the lower ribcage.

Figure 11-1. Lower thorax impact test setup

11.2 Lower Thorax Repeatability Results

Sections 11.2.1 to 11.2.5 illustrate the results of the lower thorax impact repeatability tests. Each section contains a table providing the test data, followed by plot overlays of the five repeat tests conducted at all three labs. Note that the data in the tables containing the results of each test series are listed sequentially, with the test at the top of the table beginning the test series.

11.2.1 THOR-50M DL9207 Testing at VRTC

Repeatability results at VRTC for the lower thorax qualification of DL9207 yielded CV values all below 5 percent (Table 11-1, Figure 11-2 to Figure 11-5).

Table 11-1. VRTC THOR-50M DL9207 Lower Thorax Repeatability Results

Test Number	Impact Side	Left or Right Resultant Deflection at Peak Force (mm)	Peak Probe Force (N)
020315_01L	**Left Side**	47.3	3539
020315_02L		48.7	3444
020315_03L		50.5	3430
020315_04L		48.0	3523
020315_05		47.9	3541
Mean		**48.5**	**3496**
Std. Dev.		**1.2**	**54**
CV		**2.5%**	**1.5%**
020315_01R	**Right Side**	49.3	3443
020315_02R		49.0	3319
020315_03R		48.9	3360
020315_04R		50.5	3360
020415_05		48.6	3318
Mean		**49.3**	**3360**
Std. Dev.		**0.8**	**51**
CV		**1.5%**	**1.5%**

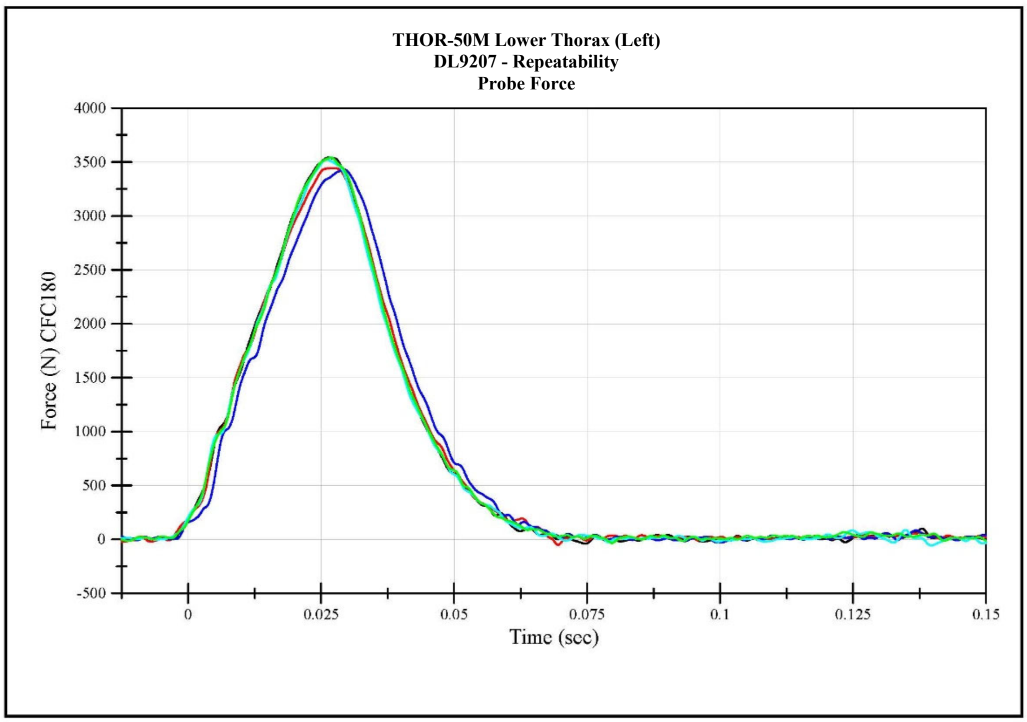

Figure 11-2. VRTC lower left thorax probe force repeatability for DL9207

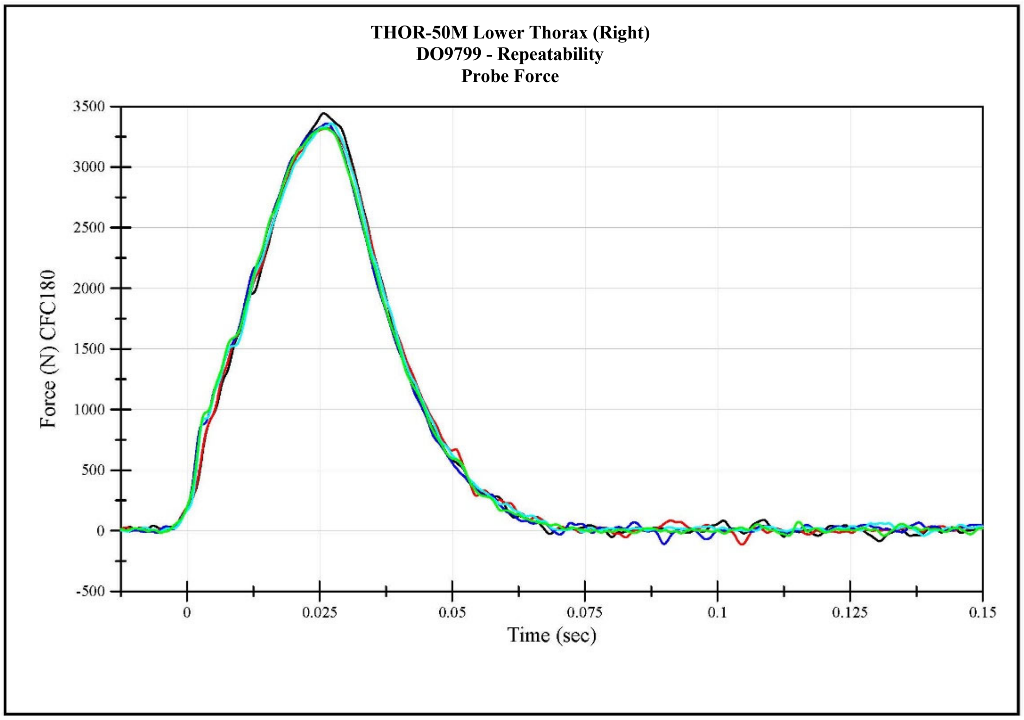

Figure 11-3. VRTC lower right thorax probe force repeatability for DL9207

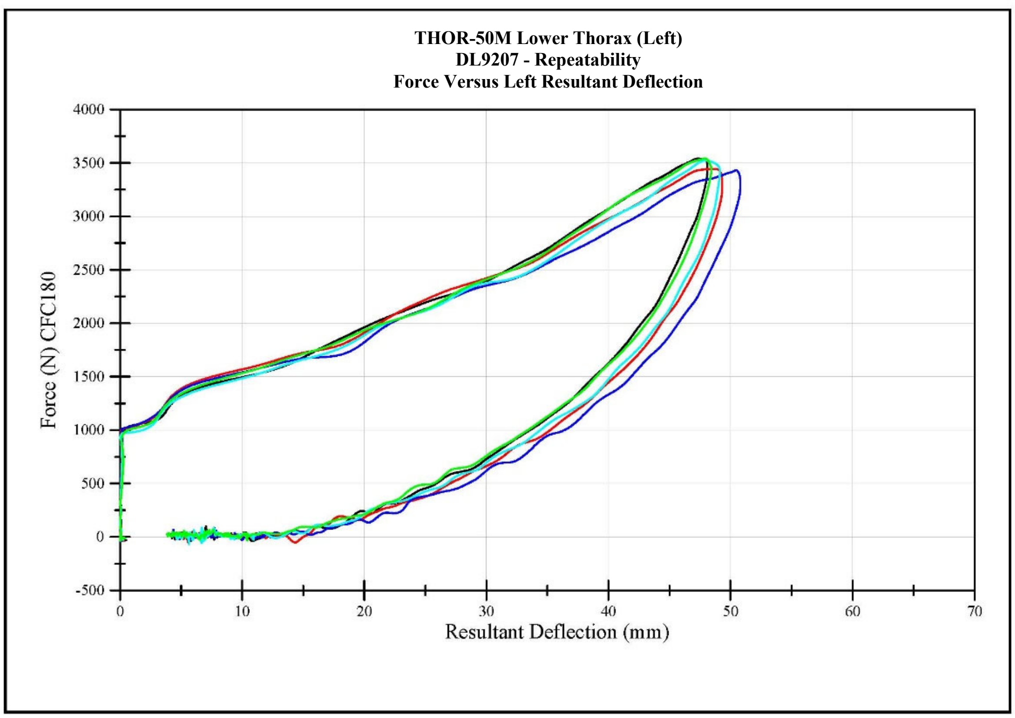

Figure 11-4. VRTC left lower thorax probe force vs. left resultant deflection repeatability for DL9207

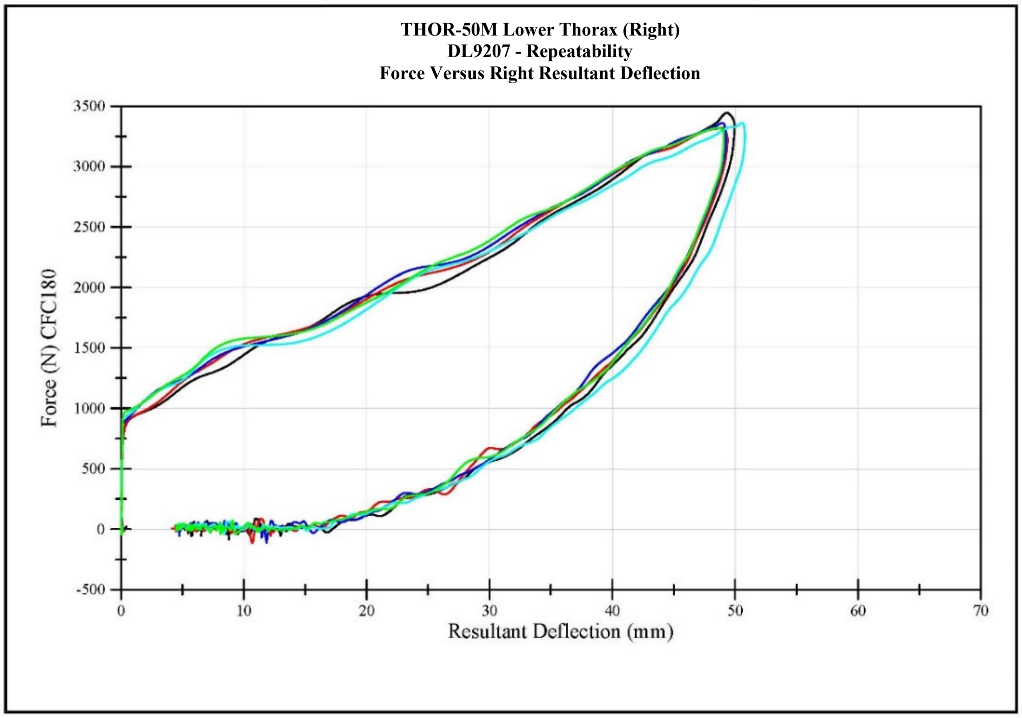

Figure 11-5. VRTC right lower thorax probe force vs. right resultant deflection repeatability for DL9207

11.2.2 THOR-50M DO9798 Testing at VRTC

Repeatability results at VRTC for the lower thorax qualification of DO9798 yielded CV values all below 5 percent (Table 11-2, Figure 11-6 to Figure 11-9).

Table 11-2. VRTC THOR-50M DO9798 Lower Thorax Repeatability Results

Test Number	Impact Side	Left or Right Resultant Deflection at Peak Force (mm)	Peak Probe Force (N)
080515_01L	**Left Side**	47.1	3353
080515_02		47.6	3529
080515_03		46.8	3544
080515_04		48.0	3547
080515_05		48.8	3521
Mean		**47.6**	**3499**
Std. Dev.		**0.8**	**82**
CV		**1.6%**	**2.4%**
080515_01R	**Right Side**	54.0	3478
080615_02		49.6	3577
080615_03		52.5	3551
080615_04		52.5	3611
080615_05		52.9	3584
Mean		**52.3**	**3560**
Std. Dev.		**1.6**	**51**
CV		**3.1%**	**1.4%**

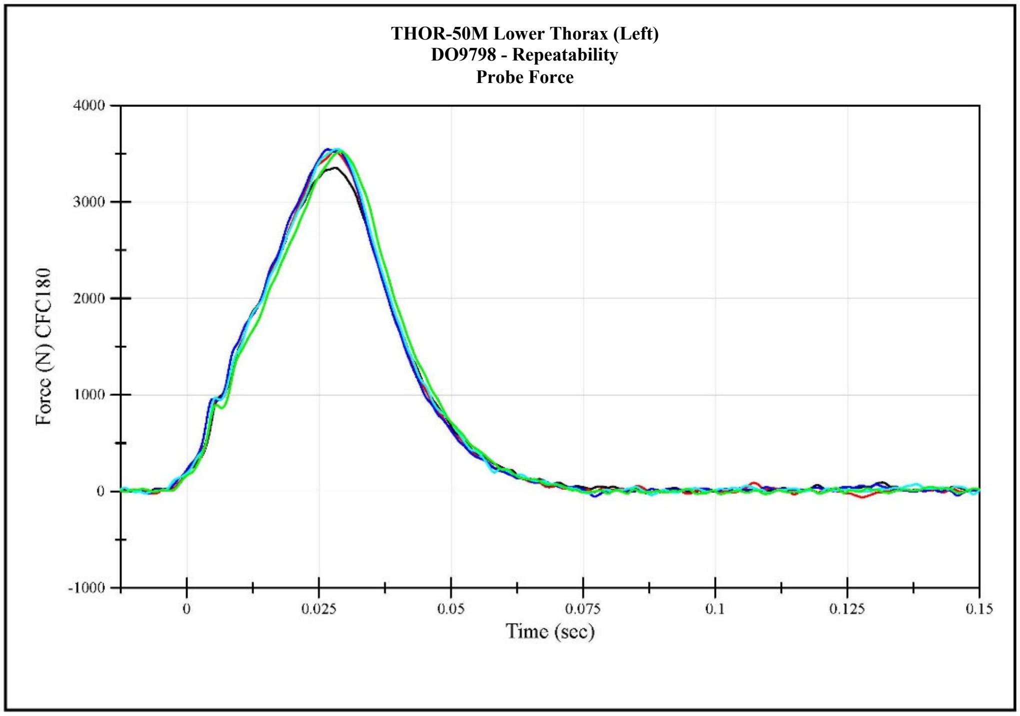

Figure 11-6. VRTC lower left thorax probe force repeatability for DO9798

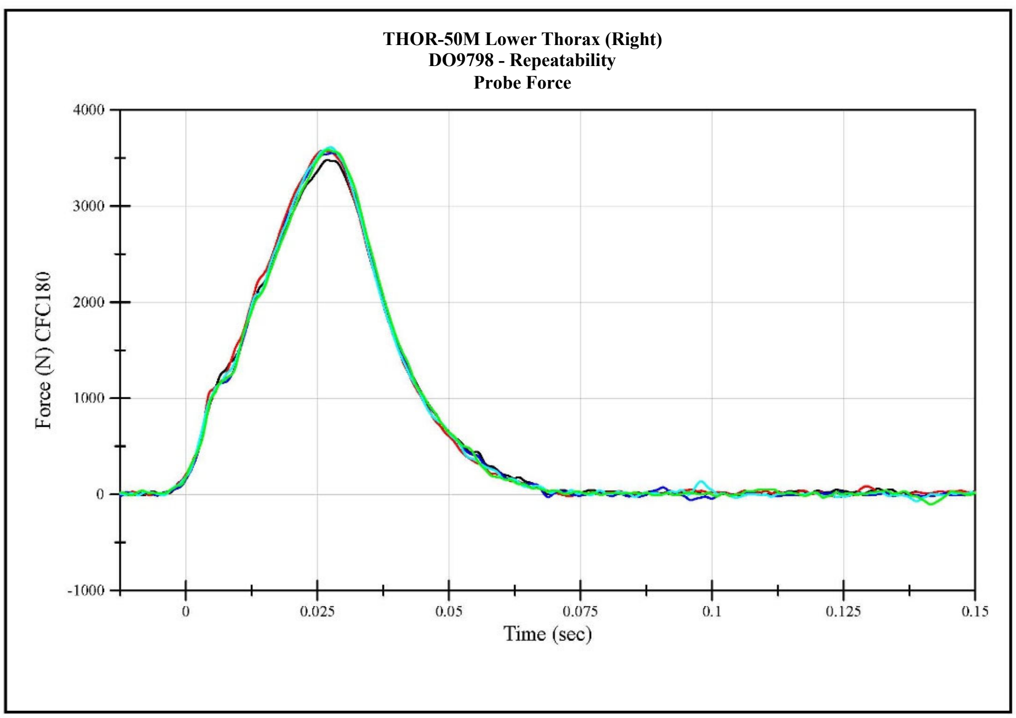

Figure 11-7. VRTC lower right thorax probe force repeatability for DO9798

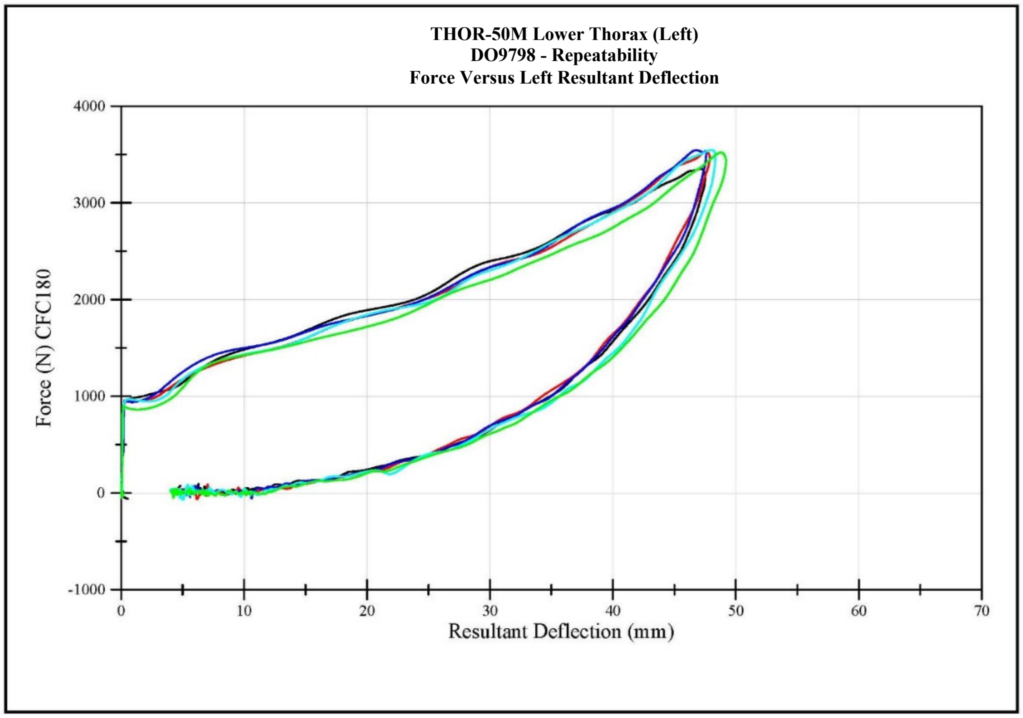

Figure 11-8. VRTC left lower thorax probe force vs. left resultant deflection repeatability for DO9798

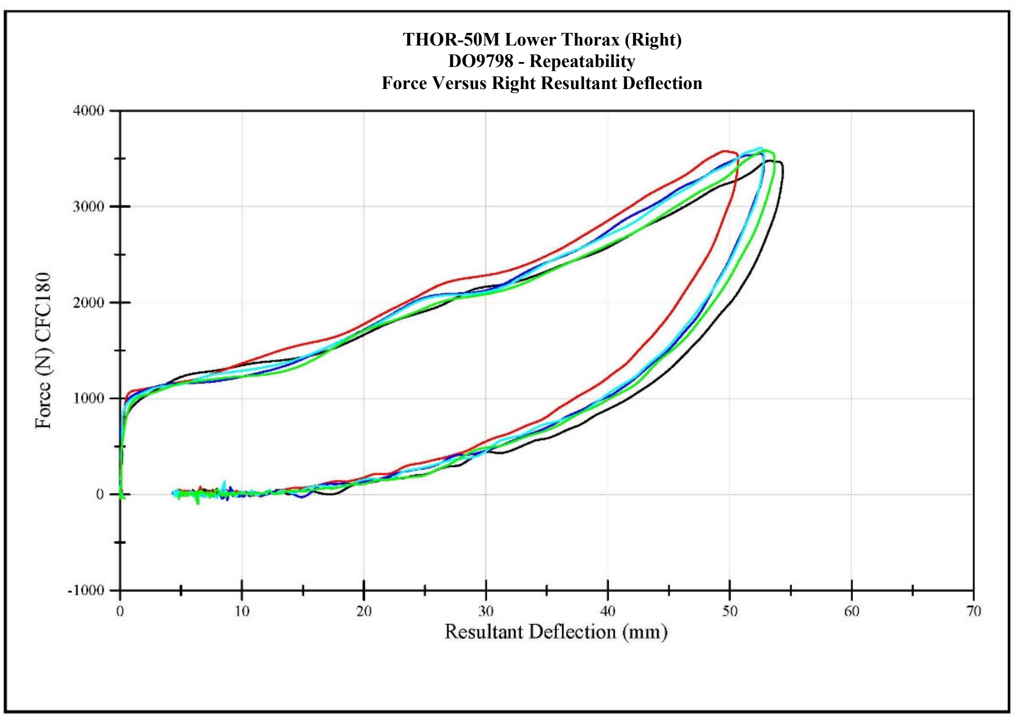

Figure 11-9. VRTC right lower thorax probe force vs. right resultant deflection repeatability for DO9798

11.2.3 THOR-50M DO9799 Testing at VRTC

Repeatability results at VRTC for the lower thorax qualification of DO9799 yielded CV values all below 5 percent (Table 11-3, Figure 11-10 to Figure 11-13).

Table 11-3. VRTC THOR-50M DO9799 Lower Thorax Repeatability Results

Test Number	Impact Side	Left or Right Resultant Deflection at Peak Force (mm)	Peak Probe Force (N)
062315_01L	**Left Side**	52.1	3287
062315_02L		52.0	3283
062415_03		51.6	3243
062415_05		50.9	3378
062415_06		51.1	3269
Mean		**3292**	**51.5**
Std. Dev.		**51**	**0.5**
CV		**1.6%**	**1.0%**
062315_01R	**Right Side**	54.0	3209
062315_02R		52.7	3316
062315_03		52.7	3311
062315_04		52.2	3435
062315_05		53.4	3366
Mean		**3327**	**53.0**
Std. Dev.		**83**	**0.7**
CV		**2.5%**	**1.3%**

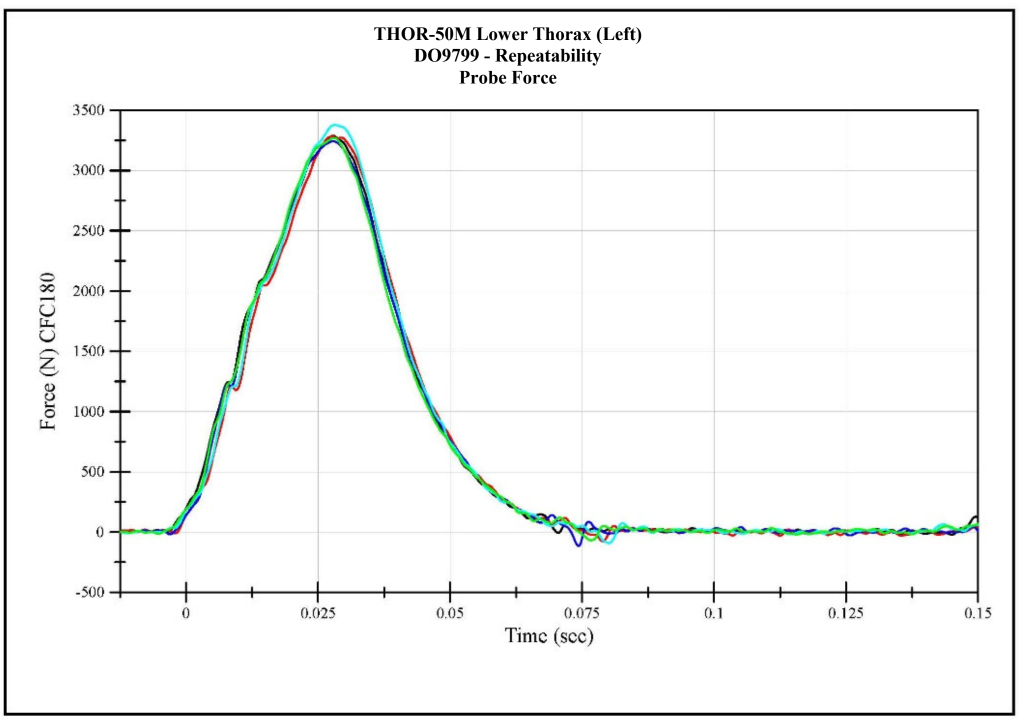

Figure 11-10. VRTC lower left thorax probe force repeatability for DO9799

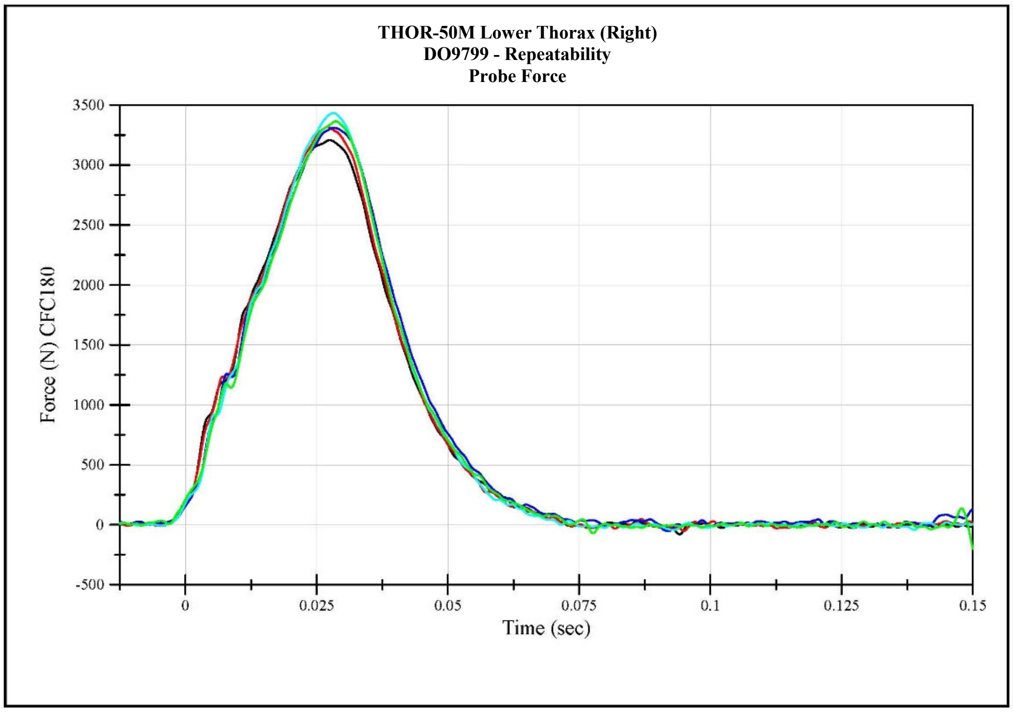

Figure 11-11. VRTC lower right thorax probe force repeatability for DO9799

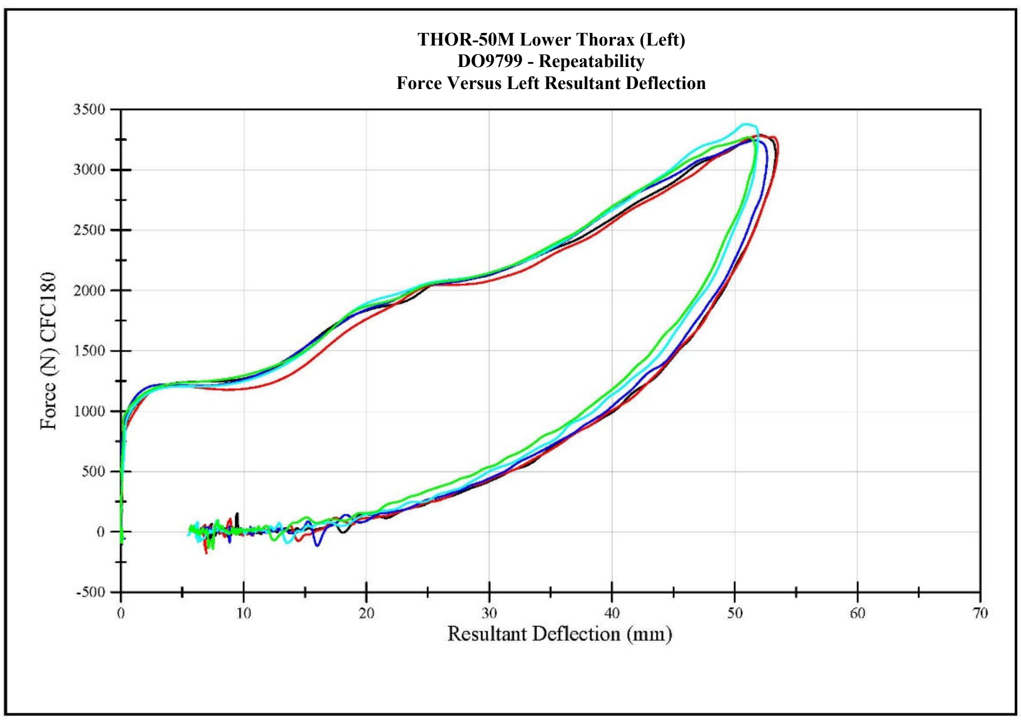

Figure 11-12. VRTC left lower thorax probe force vs. left resultant deflection repeatability for DO9799

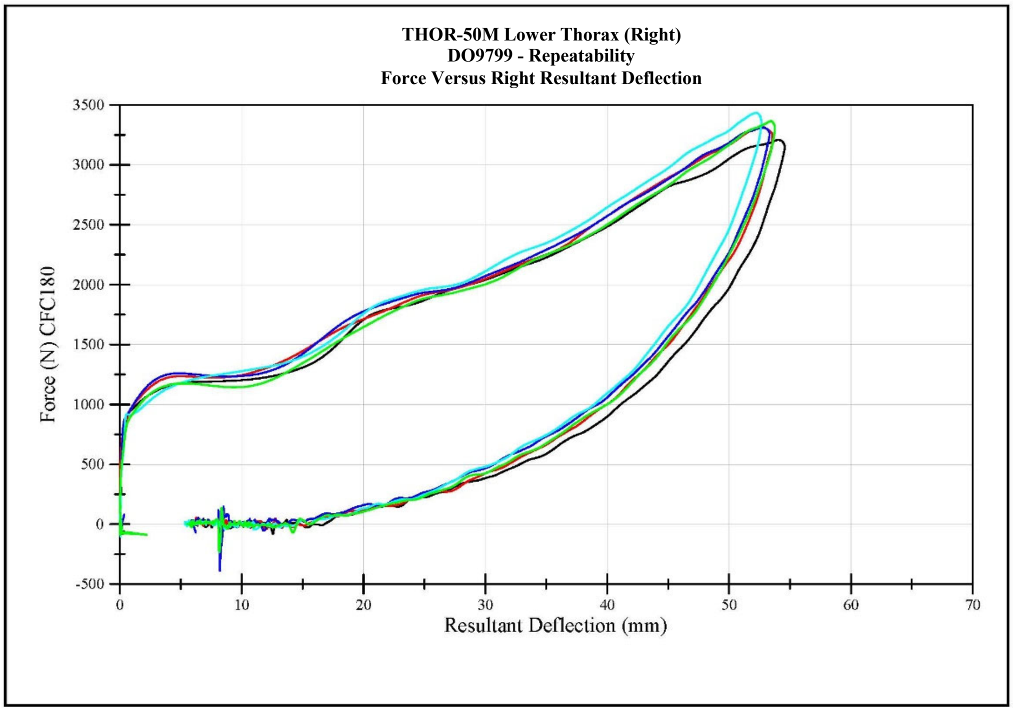

Figure 11-13. VRTC right lower thorax probe force vs. right resultant deflection repeatability for DO9799

11.2.4 THOR-50M DO9799 Testing at Humanetics

Repeatability results at Humanetics for the lower thorax qualification of DO9799 yielded CV values all below 5 percent (Table 11-4, Figure 11-14 to Figure 11-17).

Table 11-4. Humanetics THOR-50M DO9799 Lower Thorax Repeatability Results

Test Number	Impact Side	Left or Right Resultant Deflection at Peak Force (mm)	Peak Probe Force (N)
268	**Left Side**	51.1	3465
269		51.1	3474
270		51.3	3519
271		52.8	3503
272		49.0	3514
274		50.1	3465
Mean		**50.9**	**3490**
Std. Dev.		**1.3**	**25**
CV		**2.5%**	**0.7%**
275	**Right Side**	50.8	3707
276		51.0	3857
277		53.5	3722
278		52.6	3702
279		52.4	3774
280		51.6	3774
Mean		**52.0**	**3756**
Std. Dev.		**1.0**	**59**
CV		**2.0%**	**1.6%**

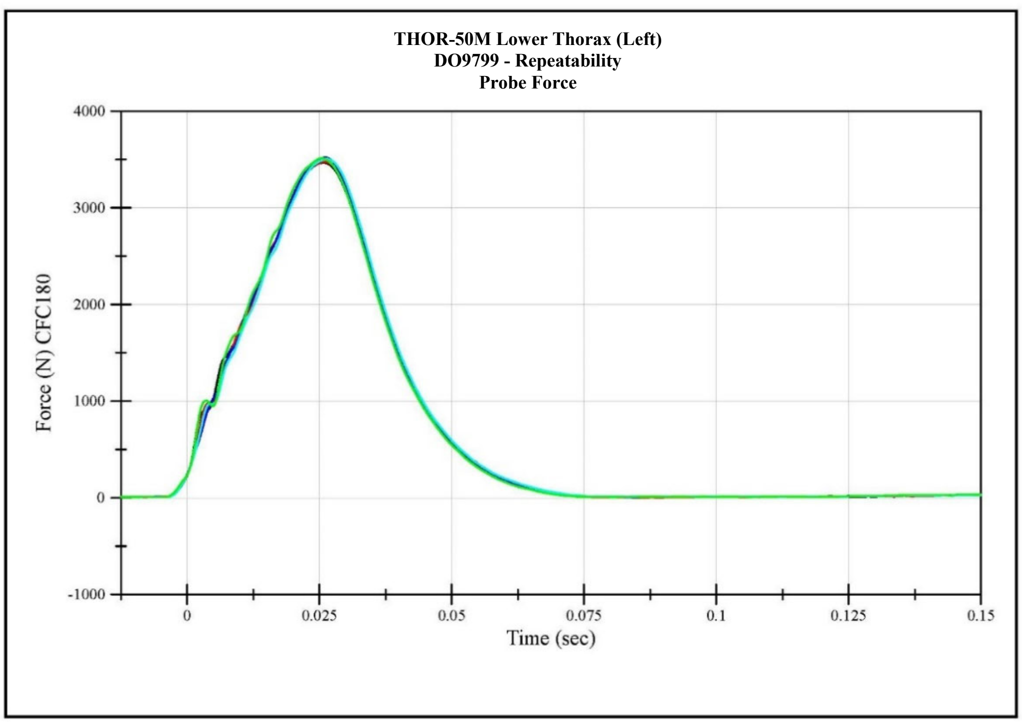

Figure 11-14. Humanetics lower left thorax probe force repeatability for DO9799

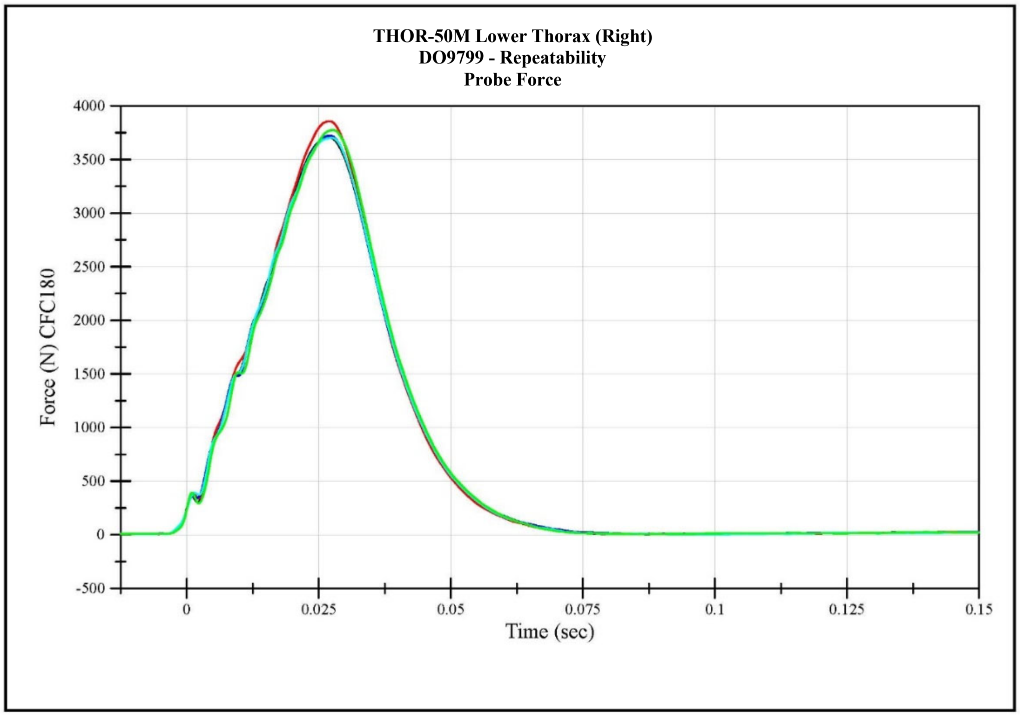

Figure 11-15. Humanetics lower right thorax probe force repeatability for DO9799

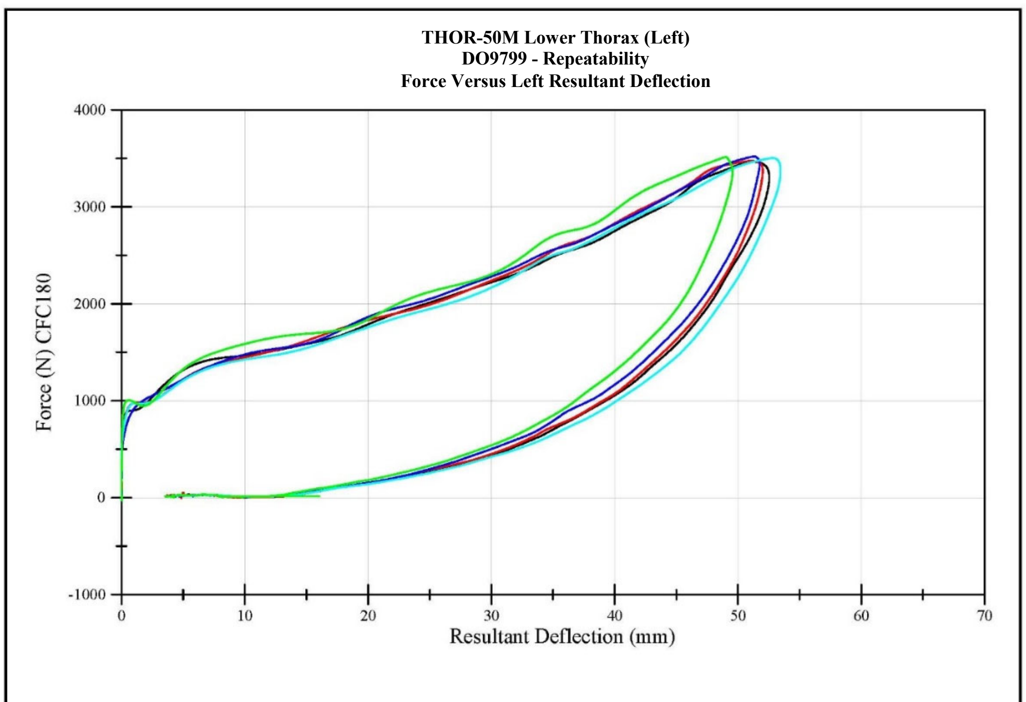

Figure 11-16. Humanetics left lower thorax probe force vs. left resultant deflection repeatability for DO9799

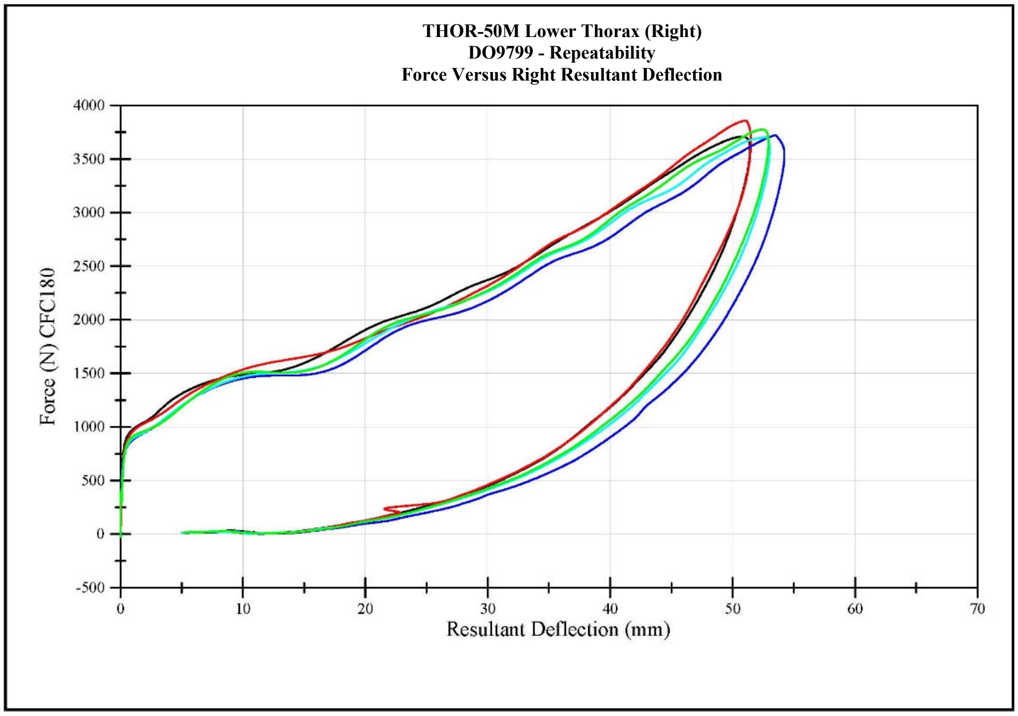

Figure 11-17. Humanetics right lower thorax probe force vs. right resultant deflection repeatability for DO9799

11.2.5 THOR-50M DO9799 Testing at Calspan

Repeatability results at Calspan for the lower thorax qualification of DO9799 yielded CV values all below 5 percent with the exception of the left and right deflections which were above 5 percent but less than 10 percent (Table 11-5, Figure 11-18 to Figure 11-21).

Table 11-5. Calspan THOR-50M Lower Thorax Repeatability Results for DO9799

Test Number	Impact Side	Left or Right Resultant Deflection at Peak Force (mm)	Peak Probe Force (N)
20160630113226	**Left Side**	57.3	3390
20160630120443		62.0	3225
20160630124236		54.5	3626
20160630131644		57.3	3309
20160630134843		51.9	3559
Mean		**56.6**	**3422**
Std. Dev.		**3.8**	**168**
CV		**6.7%**	**4.9%**
20160630145115	**Right Side**	45.9	3637
20160630155233		51.9	3607
20160630162409		41.3	3722
20160630165709		47.3	3467
Mean		**46.6**	**3608**
Std. Dev.		**4.4**	**106**
CV		**9.4%**	**2.9%**

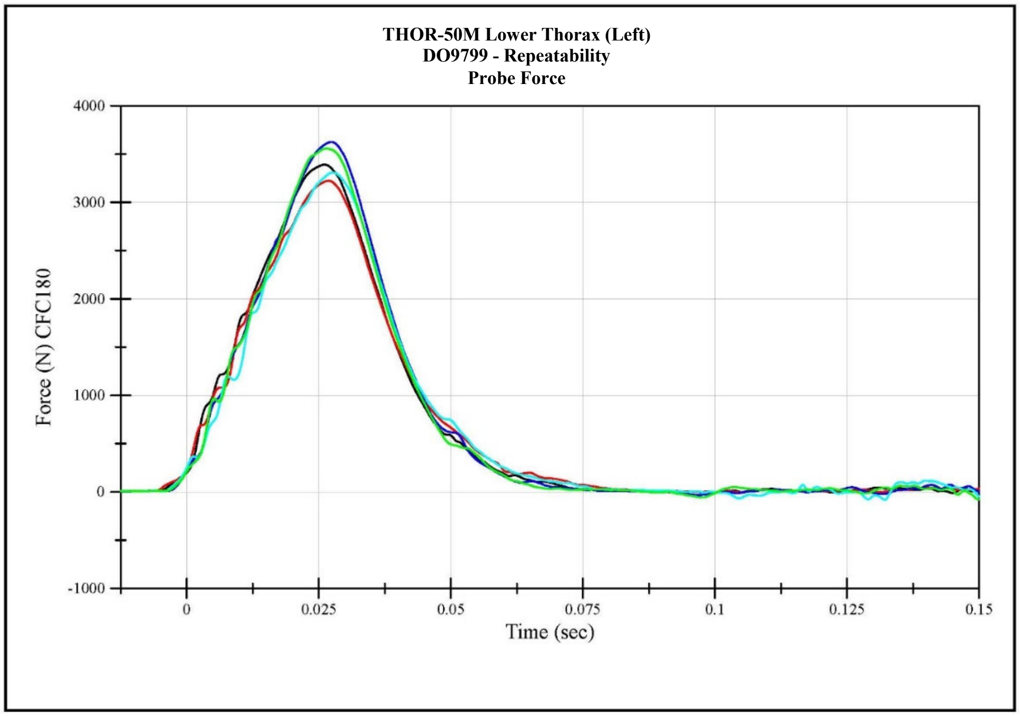

Figure 11-18. Calspan lower left thorax probe force repeatability for DO9799

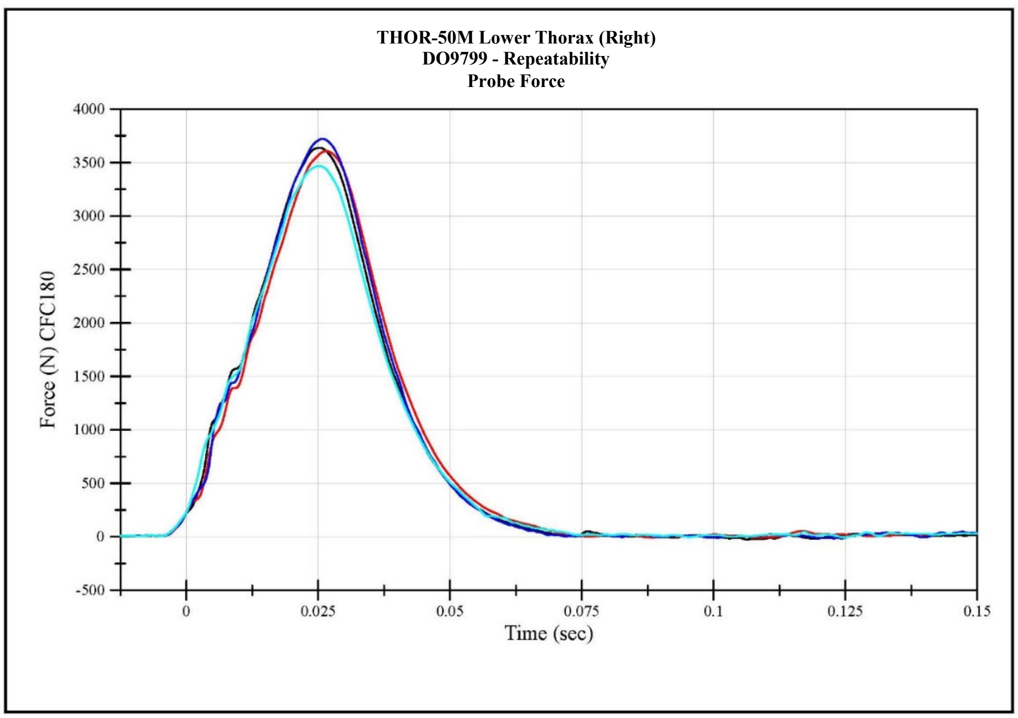

Figure 11-19. Calspan lower right thorax probe force repeatability for DO9799

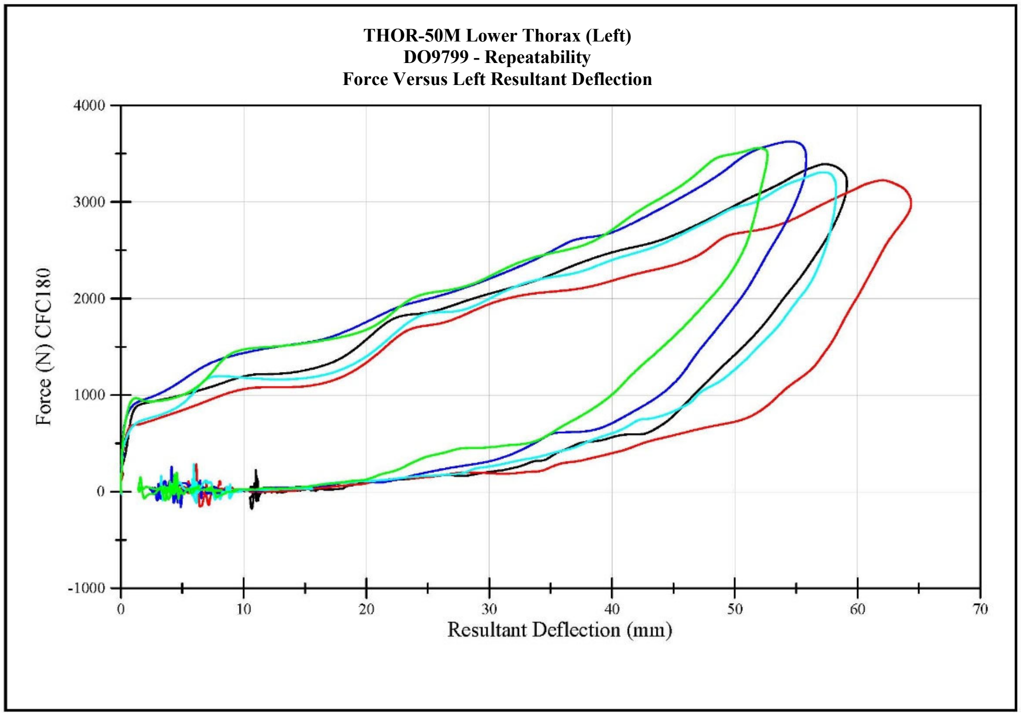

Figure 11-20. Calspan left lower thorax probe force vs. left resultant deflection repeatability for DO9799

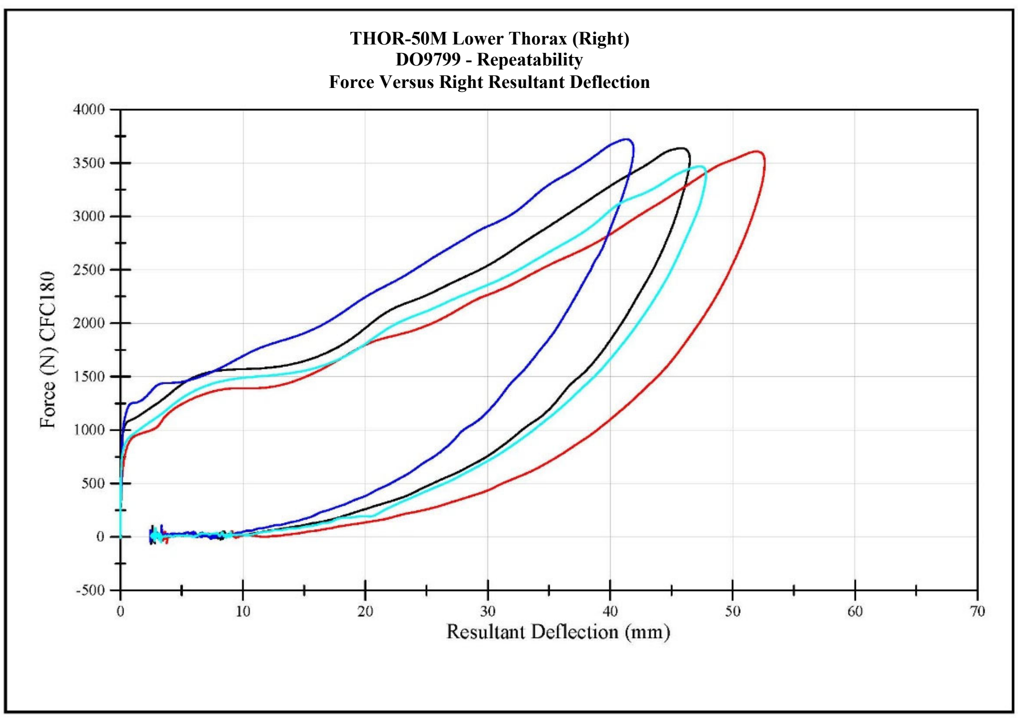

Figure 11-21. Calspan right lower thorax probe force vs. right resultant deflection repeatability for DO9799

11.3 Lower Thorax Dummy Reproducibility Results

Dummy Reproducibility results at VRTC for lower thorax qualification tests at VRTC all displayed CV values below 5 percent (Table 11-6).

Table 11-6. THOR-50M Lower Thorax Dummy Reproducibility Results

Test Number	Impact Side	Test Number	Left or Right Resultant Deflection at Peak Force (mm)	Peak Probe Force (N)
VRTC DL9207	**Left Side**	**020315_01**	47.3	3539
		020315_02	48.7	3444
		020315_03	50.5	3430
		020315_04	48.0	3523
		020315_05	47.9	3541
	Right Side	**020315_01**	49.3	3443
		020315_02	49.0	3319
		020315_03	48.9	3360
		020315_04	50.5	3360
		020415_05	48.6	3318
VRTC DO9798	**Left Side**	**080515_01**	47.1	3353
		080515_02	47.6	3529
		080515_03	46.8	3544
		080515_04	48.0	3547
		080515_05	48.8	3521
	Right Side	**080515_01**	54.0	3478
		080615_02	49.6	3577
		080615_03	52.5	3551
		080615_04	52.5	3611
		080615_05	52.9	3584
VRTC DO9799	**Left Side**	**062315_01**	52.1	3287
		062315_02	52.0	3283
		062415_03	51.6	3243
		062415_05	50.9	3378
		062415_06	51.1	3269
	Right Side	**062315_01**	54.0	3209
		062315_02	52.7	3316
		062315_03	52.7	3311
		062315_04	52.2	3435
		062315_05	53.4	3366
Mean			**50.4**	**3422**
Std. Dev.			**2.2**	**117**
CV			**4.5%**	**3.4%**

11.4 Lab-to-Lab Variability Analysis

The results for left and right lower thorax qualification tests from each lab are presented in Table 11-7 and Table 11-8. The last four rows of the tables show the *Test Reproducibility* results when data from all three labs are combined. The results for the resultant deflection at the time of the peak probe force (for both the left and right sides) display CV values above 5 percent but less than 10 percent; due to technical issues there were only four right-side tests at Calspan.

Table 11-7. THOR-50M Lower Left Thorax Lab-to Lab Variability Results

Test Number	Impact Side	Left Resultant Deflection at Peak Force (mm)	Peak Probe Force (N)
VRTC DO9799	Left Side	52.1	3287
		52.0	3283
		51.6	3243
		50.9	3378
		51.1	3269
Humanetics DO9799	Left Side	51.1	3465
		51.1	3474
		51.3	3519
		52.8	3503
		49.0	3514
		50.1	3465
Calspan DO9799	Left Side	57.3	3390
		62.0	3225
		54.5	3626
		57.3	3309
		51.9	3559
Test Reproducibility Left Side DO9799			
Mean		**52.9**	**3407**
Std. Dev.		**3.4**	**125**
CV		**6.3%**	**3.7%**

Table 11-8. THOR-50M Lower Right Thorax Lab-to Lab Variability Results

Test Number	Impact Side	Right Resultant Deflection at Peak Force (mm)	Peak Probe Force (N)
VRTC DO9799	Right Side	54.0	3209
		52.7	3316
		52.7	3311
		52.2	3435
		53.4	3366
Humanetics DO9799	Right Side	50.8	3707
		51.0	3857
		53.5	3722
		52.6	3702
		52.4	3774
		51.6	3774
Calspan DO9799	Right Side	45.9	3637
		51.9	3607
		41.3	3722
		47.3	3467
Lab-to-Lab Variability Right Side DO9799			
Mean		**50.9**	**3574**
Std. Dev.		**3.5**	**205**
CV		**6.8%**	**5.7%**

11.5 Corridor Development

All the data used to determine the lower thorax qualification corridors are shown in Table 11-9. The qualification corridors were calculated using the mean plus or minus 10 percent of the peak for the specified measured or calculated channels (Table 11-10).

Table 11-9. THOR-50M Lower Thorax Qualification Corridor Results

Test Number	Impact Side	Test Number	Left or Right Resultant Deflection at Peak Force (mm)	Peak Probe Force (N)
VRTC DL9207	**Left Side**	**020315_01**	47.3	3539
		020315_02	48.7	3444
		020315_03	50.5	3430
		020315_04	48.0	3523
		020315_05	47.9	3541
	Right Side	**020315_01**	49.3	3443
		020315_02	49.0	3319
		020315_03	48.9	3360
		020315_04	50.5	3360
		020415_05	48.6	3318
VRTC DO9798	**Left Side**	**080515_01**	47.1	3353
		080515_02	47.6	3529
		080515_03	46.8	3544
		080515_04	48.0	3547
		080515_05	48.8	3521
	Right Side	**080515_01**	54.0	3478
		080615_02	49.6	3577
		080615_03	52.5	3551
		080615_04	52.5	3611
		080615_05	52.9	3584
VRTC DO9799	**Left Side**	**062315_01**	52.1	3287
		062315_02	52.0	3283
		062415_03	51.6	3243
		062415_05	50.9	3378
		062415_06	51.1	3269
	Right Side	**062315_01**	54.0	3209
		062315_02	52.7	3316
		062315_03	52.7	3311
		062315_04	52.2	3435
		062315_05	53.4	3366
Humanetics DO9799	**Left Side**	**268**	51.1	3465
		269	51.1	3474
		270	51.3	3519
		271	52.8	3503
		272	49.0	3514
		274	50.1	3465
	Right Side	**275**	50.8	3707
		276	51.0	3857
		277	53.5	3722
		278	52.6	3702
		279	52.4	3774
		280	51.6	3774
Calspan DO9799	**Left Side**	**20160630113226**	57.3	3390
		20160630120443	62.0	3225
		20160630124236	54.5	3626
		20160630131644	57.3	3309
		20160630134843	51.9	3559
	Right Side	**20160630145115**	45.9	3637
		20160630155233	51.9	3607
		20160630162409	41.3	3722
		20160630165709	47.3	3467
Mean			**50.9**	**3484**
Std. Dev.			**3.2**	**155**
CV			**6.4%**	**4.5%**

Table 11-10. Lower Thorax Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Impact Velocity	**m/s**	4.25	4.35	4.30	
Peak Probe Force	**N**	3136	3832	3484	10%
Left or Right Resultant Deflection at Peak Force	**mm**	45.8	56.0	50.9	10%

Discussion. Given the asymmetric setup of this test, test labs may need to be diligent on aligning the dummy with the impact probe. Otherwise, they may experience *Test Repeatability* difficulties. This was evident at Calspan where four of their nine tests were not within ±10% of the target for deflection (as seen by the yellow highlights in Table 11-9). In Figure 11-20 and Figure 11-21, Calspan's force versus deflection plots show a clear test-to-test disparity on the IR-TRACC displacement measurements (CV of 6.7% for left, 9.4% for right). Since VRTC and Humanetics did not experience this problem, the test setup issue appears to be isolated with Calspan.

The test-by-test probe force levels at Calspan were also comparatively variable, with CVs of 2.9% for right and 4.9% for left. At VRTC and Humanetics, there was almost no variation in the force levels (CVs less than 2.5% for all tests). There was also a definitive left versus right disparity at Calspan wherein left side deflection measurements were all lower. This was not seen at Humanetics or VRTC. However, the Calspan average of left and right deflections was nearly the same as those at VRTC and Humanetics (about 52 mm), which provides further indication that the dummy may have been misaligned at Calspan.

Aside from Calspan's setup issues, there was a minor *Test Reproducibility* issue. As seen in Table 11-7 and Table 11-8, probe force levels at Humanetics were high relative to those at VRTC and Calspan, slightly more so for the right aspect resulting in a CV of 5.7%. However, only one of twelve tests at Humanetics was not within ±10% of the target for force (indicated by a yellow highlight in Table 11-9), so this does not appear to be overly concerning.

At VRTC and Humanetics, repeat tests on individual units were highly uniform (CVs below 5%) for all measurements. Also, *Dummy Reproducibility* in tests at VRTC also displayed CVs below 5 percent as seen in Table 11-6. Thus, *Dummy Repeatability* and *Dummy Reproducibility* do not appear to pose any problems in attaining the target response margin of ± 10 percent.

12 Lower Abdomen

12.1 Methodology

Repeatability and reproducibility tests were performed using the lower abdomen qualification procedures described in the *THOR-50M Qualification Procedures Manual*. These tests utilize a rectangular, horizontally-oriented rigid lower abdomen probe face (drawing #DL472-3000) attached to an impactor (total mass of 32.00 ±0.02 kg) to impact the lower abdomen of the THOR-50M (Figure 12-1). The 3.30 ± 0.05 m/s impact is centered at the level of the 3D IR-TRACC attachments to the anterior surface of the lower abdomen. The abdomen deflections are calculated *in the local spine coordinate system* for both the left and right IR-TRACCs to examine the force-deflection response of the lower abdomen. The X-axis deflections of the left and right IR-TRACCs were also assessed individually.

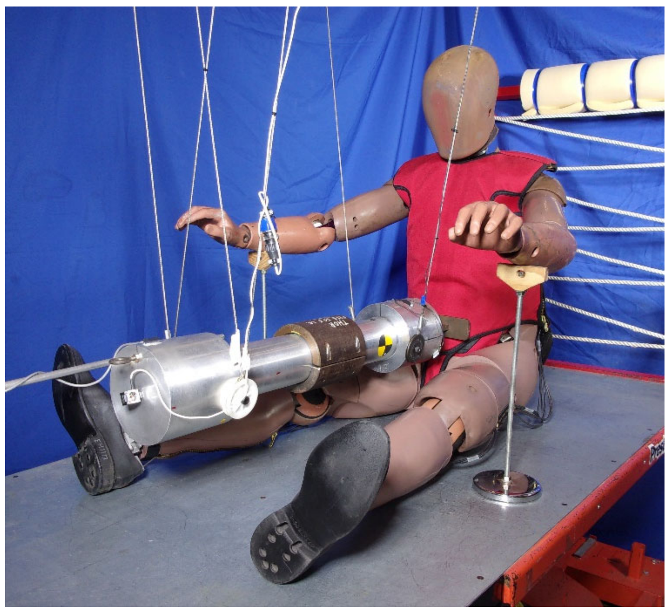

Figure 12-1. Lower abdomen test setup

The lower abdomen bag was redesigned to address issues with the foam fit and IR-TRACC placement; in addition, drawings were revised with more details to ensure repeatable manufacturing. The lower abdomen repeatability and reproducibility tests were conducted using the most recent version of the abdomen bag, as described in the *THOR-50M Drawing Package.* To use the most recent version of the abdomen bag, this testing was performed later and all three of the THOR-50M dummies were not available. Therefore, DL9207 was used with three different lower abdomen assemblies. The same lower abdomen bracket and instrumentation were used in each assembly, but the front foam, rear foam, and abdomen bag were different for each assembly, as shown in Table 12-1. At the other two labs, the same foam assemblies were installed into DO9799 since DL9207 was not available at the time. The comparisons should still be valid since the foams, rather than the ATD structure, are the major source of variability in lower abdomen tests. During these tests the X-axis deflection (for both left and right sides) at the time of peak probe force, and probe force were measured.

Table 12-1. Lower Abdomen Assemblies

Lab	Abdomen Assembly	Dummy	Front Foam Serial Number	Rear Foam Serial Number	Lower Abdomen Bag Serial Number
VRTC	Lower Abdomen Assembly #1	DL9207	006	DP3449	CC1
VRTC	Lower Abdomen Assembly #2	DL9207	002	DP3441	CC2
VRTC	Lower Abdomen Assembly #3	DL9207	009	DP3443	472-4763-5
Humanetics	Lower Abdomen Assembly #3	DO9799	009	DP3443	472-4763-5
Calspan	Lower Abdomen Assembly #3	DO9799	009	DP3443	472-4763-5

12.2 Lower Abdomen Repeatability Results

Sections 12.2.1 to 12.2.5 illustrate the results of the lower abdomen impact repeatability tests. Each section contains a table providing the test data, followed by plot overlays of the five repeat tests conducted at all three labs. Note that the data in the tables containing the results of each test series are listed sequentially, with the test at the top of the table beginning the test series.

12.2.1 THOR-50M DL9207 Lower Abdomen Assembly #1 Testing at VRTC

Repeatability results at VRTC for the lower abdomen qualification of DL9207 (with lower abdomen assembly #1) yielded CV values below 5 percent for the peak probe force, and the left and right deflections combined is above 5 percent, but less than 10 percent due to an apparent right versus left disparity in the deflection measurements (Table 12-2 and Figure 12-2). This is discussed in section 12.5

Table 12-2. VRTC THOR-50M DL9207 with Lower Abdomen Assembly #1 Lower Abdomen Repeatability Results

Test Number	Peak Probe Force (N)	Lower Left Abdomen X-axis Deflection at Time of Peak Force (mm)	Lower Right Abdomen X-axis Deflection at Time of Peak Force (mm)	Difference Between Peak Left & Right X-axis Deflections (mm)
160815-1	2859	-78.0	-86.0	8.0
160815-3	2934	-77.9	-85.7	7.7
160815-4	2941	-77.8	-89.4	11.6
160815-5	2976	-80.8	-88.6	7.8
160815-6	2972	-80.9	-88.5	7.6
Mean	**2936**	**-83.3**		**N/A**
Std. Dev.	**47**	**4.8**		**N/A**
CV	**1.6%**	**5.7%**		**N/A**

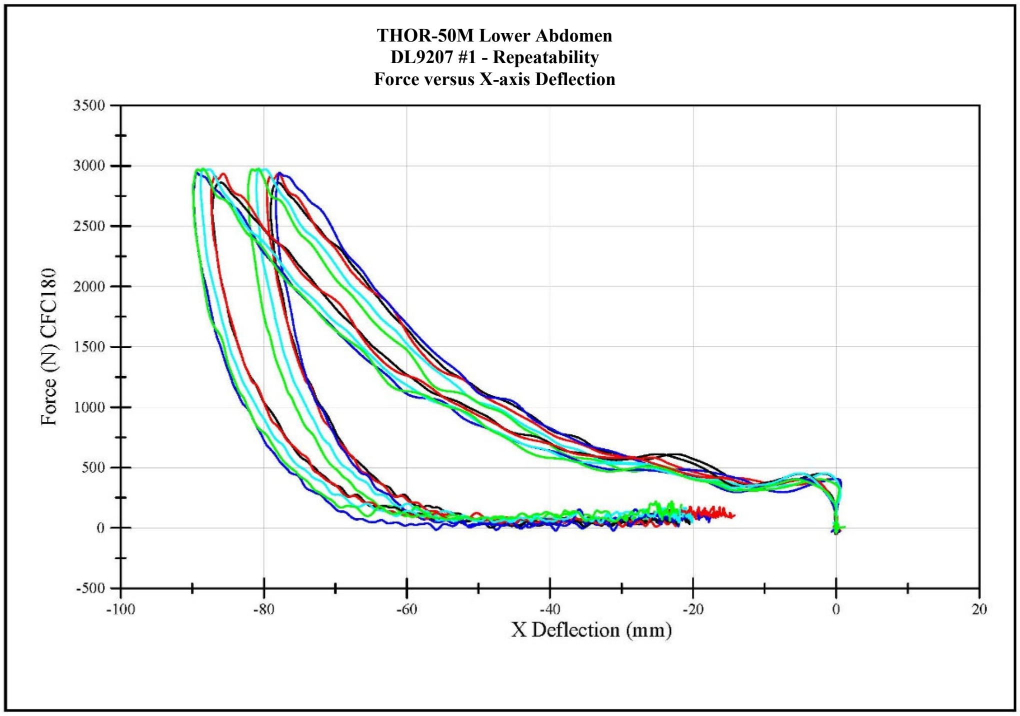

Figure 12-2. VRTC lower abdomen force vs. X-axis deflection repeatability DL9207 Lower Abdomen Assembly #1

12.2.2 THOR-50M DL9207 Lower Abdomen Assembly #2 Testing at VRTC

Repeatability results at VRTC for the lower abdomen qualification of DL9207 (with lower abdomen assembly #2) yielded CV values below 5 percent for the peak probe force, and the left and right deflections combined is above 5 percent but less than 10 percent due to an apparent right versus left disparity in the deflection measurements (Table 12-3 and Figure 12-3). This is discussed in section 12.5.

Table 12-3. VRTC THOR-50M DL9207 with Lower Abdomen Assembly #2 Lower Abdomen Repeatability Results

Test Number	Peak Probe Force (N)	Lower Left Abdomen X-axis Deflection at Time of Peak Force (mm)	Lower Right Abdomen X-axis Deflection at Time of Peak Force (mm)	Difference Between Peak Left & Right X-axis Deflections (mm)
160816-1	2843	-79.3	-88.0	8.7
160816-3	2905	-79.3	-86.6	7.3
160816-5	2929	-80.5	-89.8	9.3
160816-6	2878	-80.7	-88.1	7.3
160816-8	2889	-79.6	-87.8	8.2
Mean	**2889**	**-84.0**		**N/A**
Std. Dev.	**32**	**4.4**		**N/A**
CV	**1.1%**	**5.2%**		**N/A**

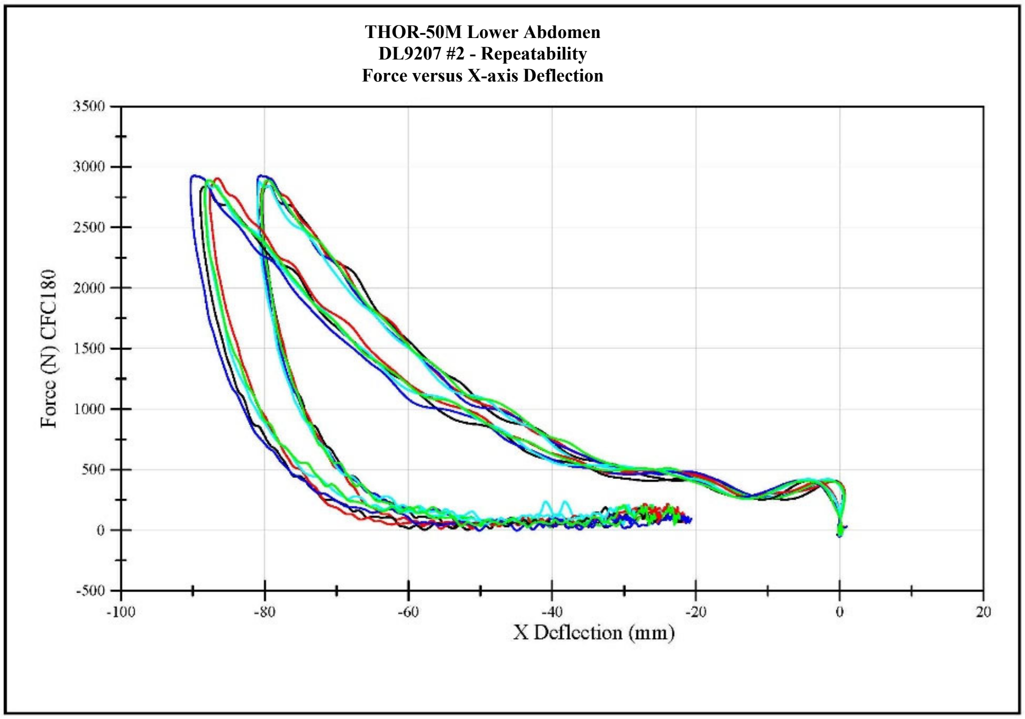

Figure 12-3. VRTC lower abdomen force vs. X-axis deflection repeatability DL9207 Lower Abdomen Assembly #2

12.2.3 THOR-50M DL9207 Lower Abdomen Assembly #3 Testing at VRTC

Repeatability results at VRTC for the lower abdomen qualification of DL9207 (with lower abdomen assembly #3) yielded CV values below 5 percent for the peak probe force, and the left and right deflections combined is above 5 percent but less than 10 percent due to an apparent right versus left disparity in the deflection measurements (Table 12-4 and Figure 12-4). This is discussed in section 12.5.

Table 12-4. VRTC THOR-50M DL9207 with Lower Abdomen Assembly #3 Lower Abdomen Repeatability Results

Test Number	Peak Probe Force (N)	Lower Left Abdomen X-axis Deflection at Time of Peak Force (mm)	Lower Right Abdomen X-axis Deflection at Time of Peak Force (mm)	Difference Between Peak Left & Right X-axis Deflections (mm)
160816-12	2734	-79.7	-86.7	7.1
160816-13	2959	-82.5	-89.4	6.8
160816-14	2979	-83.1	-90.5	7.4
160817-1	2956	-81.6	-90.9	9.3
160817-2	2953	-82.9	-90.5	7.6
Mean	**2916**	**-85.8**		**N/A**
Std. Dev.	**102**	**4.3**		**N/A**
CV	**3.3%**	**5.0%**		**N/A**

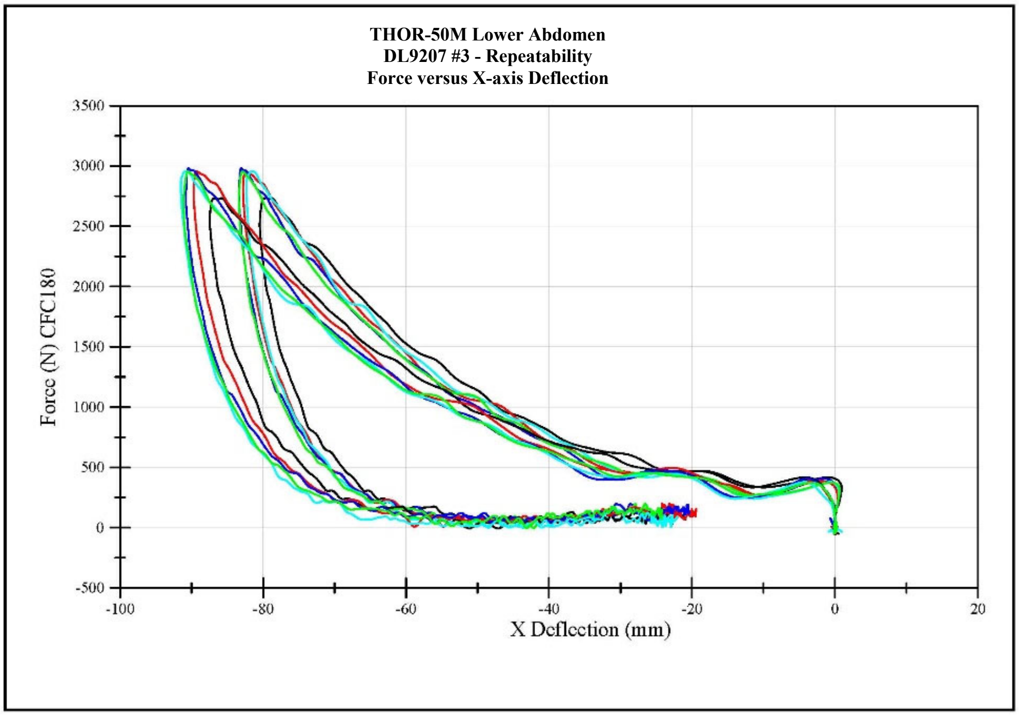

Figure 12-4. VRTC lower abdomen force vs. X-axis deflection repeatability DL9207 Lower Abdomen Assembly #3

12.2.4 THOR-50M DO9799 Lower Abdomen Assembly #3 Testing at Humanetics

Repeatability results at Humanetics for the lower abdomen qualification of DO9799 (with lower abdomen assembly #3) yielded CV values all below 5 percent for the individual measurements (Table 12-5 and Figure 12-5), indicating that the right and left aspects are properly aligned.

Table 12-5. Humanetics THOR-50M DO9799 with Lower Abdomen Assembly #3 Lower Abdomen Repeatability Results

Test Number	Peak Probe Force (N)	Lower Left Abdomen X-axis Deflection at Time of Peak Force (mm)	Lower Right Abdomen X-axis Deflection at Time of Peak Force (mm)	Difference Between Peak Left & Right X-axis Deflections (mm)
1107	2745	-78.2	-79.4	1.2
1108	2872	-81.4	-79.2	-2.2
1111	2879	-83.0	-83.3	0.3
1115	2918	-83.3	-85.6	2.3
1119	2913	-85.5	-84.3	-1.2
1122	3044	-87.7	-84.2	-3.5
Mean	**2895**	**-82.9**		**N/A**
Std. Dev.	**96**	**2.9**		**N/A**
CV	**3.3%**	**3.5%**		**N/A**

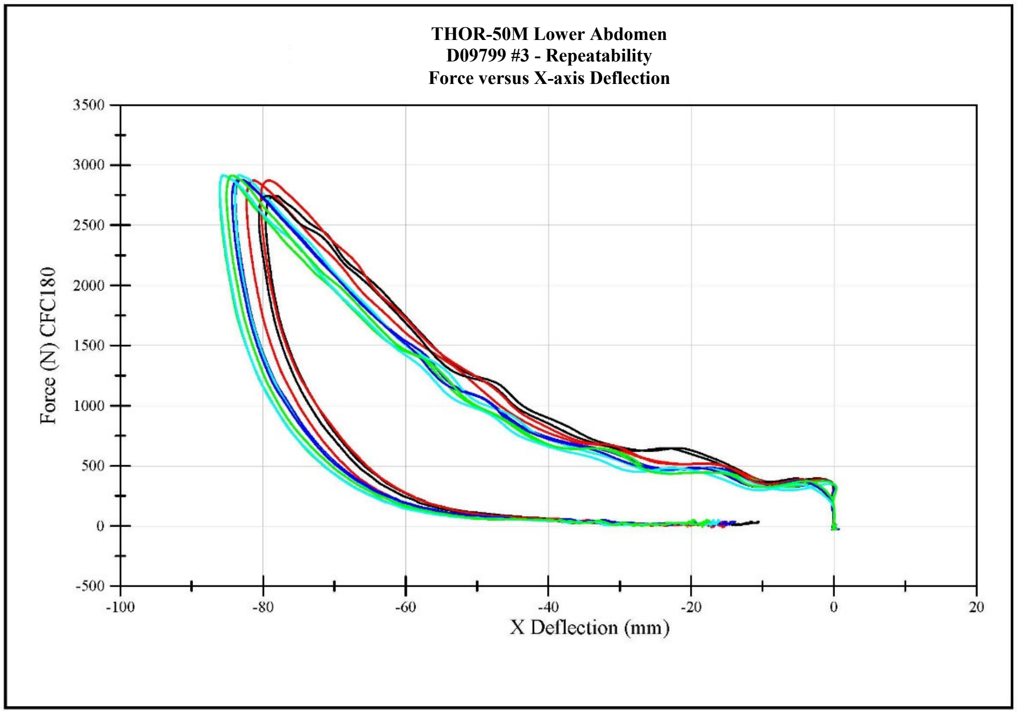

Figure 12-5. Humanetics lower abdomen force vs. X-axis deflection repeatability DO9799 Abdomen Assembly #3

12.2.5 THOR-50M DO9799 Lower Abdomen Assembly #3 Testing at Calspan

Repeatability results at Calspan for the lower abdomen qualification of DO9799 (with lower abdomen assembly #3) yielded CV values below 5 percent for the peak probe force, and the left and right deflections combined is above 5 percent but less than 10 percent due to an apparent right versus left disparity in the deflection measurements (Table 12-6 and Figure 12-6). This is discussed in section 12.5.

Table 12-6. Calspan THOR-50M DO9799 with Lower Abdomen Assembly #3 Lower Abdomen Repeatability Results

Test Number	Peak Probe Force (N)	Lower Left Abdomen X-axis Deflection at Time of Peak Force (mm)	Lower Right Abdomen X-axis Deflection at Time of Peak Force (mm)	Difference Between Peak Left & Right X-axis Deflections (mm)
20160701070836	2802	-79.7	-82.7	3.1
20160701073954	2914	-82.4	-82.9	0.5
20160701081037	2979	-81.7	-74.3	-7.5
20160701084126	2988	-81.7	-72.1	-9.7
20160701091215	3113	-79.5	-73.9	-5.6
Mean	**2959**	**-79.1**		**N/A**
Std. Dev.	**114**	**4.1**		**N/A**
CV	**3.8%**	**5.2%**		**N/A**

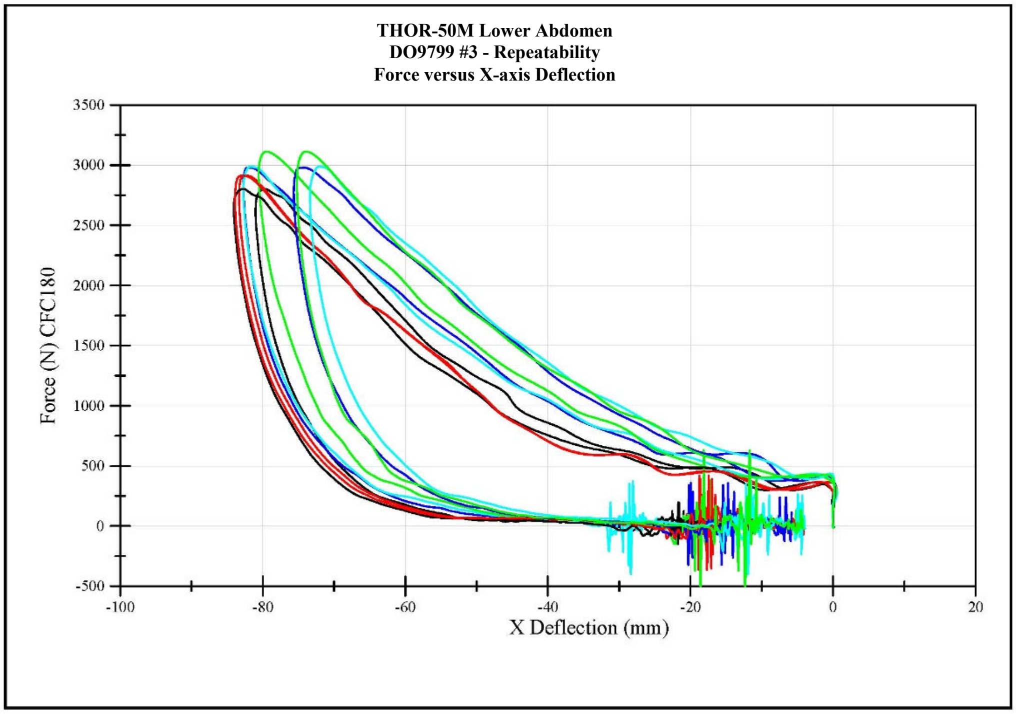

Figure 12-6. Calspan lower abdomen force vs. X-axis deflection repeatability DO9799 Abdomen Assembly #3

12.3 Lower Abdomen Dummy Reproducibility Results

Dummy Reproducibility results at VRTC for the lower abdomen qualification yielded CV values below 5 percent for the peak probe force, and the left and right deflections combined is above 5 percent but less than 10 percent due to an apparent right versus left disparity in the deflection measurements (Table 12-7). Thus, although the test results are highly reproducible, a clear right versus left discrepancy exists. The cause of this disparity is a misalignment in VRTC's test setup procedure. This is considered a *Test Reproducibility* issue and is discussed in section 12.5.

Table 12-7. THOR-50M Lower Abdomen Dummy Reproducibility Results

Dummy Number	Test Number	Peak Probe Force (N)	Lower Left Abdomen X-axis Deflection at Time of Peak Force (mm)	Lower Right Abdomen X-axis Deflection at Time of Peak Force (mm)	Difference Between Peak Left & Right X-axis Deflections (mm)
DL9207 VRTC SN=CC1 F=006 R=DP3449	**160815-1**	2859	-78.0	-86.0	8.0
	160815-3	2934	-77.9	-85.7	7.7
	160815-4	2941	-77.8	-89.4	11.6
	160815-5	2976	-80.8	-88.6	7.8
	160815-6	2972	-80.9	-88.5	7.6
DL9207 VRTC SN=CC2 F=002 R=DP3441	**160816-1**	2843	-79.3	-88.0	8.7
	160816-3	2905	-79.3	-86.6	7.3
	160816-5	2929	-80.5	-89.8	9.3
	160816-6	2878	-80.7	-88.1	7.3
	160816-8	2889	-79.6	-87.8	8.2
DL9207 VRTC SN=472-4763-5 F=009 R=DP3443	**160816-12**	2734	-79.7	-86.7	7.1
	160816-13	2959	-82.5	-89.4	6.8
	160816-14	2979	-83.1	-90.5	7.4
	160817-1	2956	-81.6	-90.9	9.3
	160817-2	2953	-82.9	-90.5	7.6
Mean		**2914**	**-84.4**		**N/A**
Std. Dev.		**66**	**4.5**		**N/A**
CV		**2.3%**	**5.3%**		**N/A**

12.4 Lab-to-Lab Variability Analysis

The identification information for the abdomen foam assembly used in the lab-to-lab variability tests is provided in Table 12-8. At VRTC, THOR-50M serial number DL9207 was used with this lower abdomen assembly. At the two other labs, the same foam assemblies were installed into DO9799 since DL9207 was not available at the time. The comparisons should still be valid since the foams, rather than the ATD structure, are the major source of variability in lower abdomen tests.

Table 12-8. Lab-to-Lab Lower Abdomen Assembly

	Front Foam Serial Number	Rear Foam Serial Number	Lower Abdomen Bag Serial Number
Lower Abdomen Assembly #3	009	DP3443	472-4763-5

The results for *Test Reproducibility* for the lower abdomen qualification tests are presented in the last four rows of Table 12-9 for all three labs combined. In this analysis, a single CV is calculated for the left and right X deflections combined since they should be the same and their differences should be zero in a symmetrical impact scenario. Although the probe force yields a CV below 5 percent, the CV for the combined right and left deflection is above 5 percent but less than 10 percent. This is attributed to setup variations which allowed a non-symmetrical impact.

As seen earlier, the right versus left differences for the abdomen tested at VRTC have a much higher mean (7.6 mm) than at the other two labs. In addition, the VRTC difference data is all positive, indicating that the deflection on the right side is consistently larger than that on the left.

Table 12-9. THOR-50M Lower Abdomen Lab-to-Lab Variability Results

Dummy Number	Peak Probe Force (N)	Lower Left Abdomen X-axis Deflection at Time of Peak Force (mm)	Lower Right Abdomen X-axis Deflection at Time of Peak Force (mm)	Difference Between Peak Left & Right X-axis Deflections (mm)
DL9207 VRTC SN=472-4763-5 F=009 R=DP3443	**2734**	-79.7	-86.7	7.1
	2959	-82.5	-89.4	6.8
	2979	-83.1	-90.5	7.4
	2956	-81.6	-90.9	9.3
	2953	-82.9	-90.5	7.6
DO9799 Humanetics SN=472-4763-5 F=009 R=DP3443	**2745**	-78.2	-79.4	1.2
	2872	-81.4	-79.2	-2.2
	2879	-83.0	-83.3	0.3
	2918	-83.3	-85.6	2.3
	2913	-85.5	-84.3	-1.2
	3044	-87.7	-84.2	-3.5
DO9799 Calspan SN=472-4763-5 F=009 R=DP3443	**2802**	-79.7	-82.7	3.1
	2914	-82.4	-82.9	0.5
	2979	-81.7	-74.3	-7.5
	2988	-81.7	-72.1	-9.7
	3113	-79.5	-73.9	-5.6
Test Reproducibility				
Mean	**2922**	**-82.6**		**N/A**
Std. Dev.	**100**	**4.5**		**N/A**
CV	**3.4%**	**5.5%**		**N/A**

12.5 Corridor Development

All the data used to determine the lower abdomen qualification corridors is shown in Table 12-10. The qualification corridors were calculated using the mean plus or minus 10 percent of the peak for the specified measured or calculated channels, with the exception of the difference between the left and right abdomen X deflections which was ±10% (±8mm) of the mean of the peak upper left and right X-axis deflections.

Table 12-10. THOR-50M Lower Abdomen Qualification Corridor Results

Dummy Number	Test Number	Peak Probe Force (N)	Lower Left Abdomen X-axis Deflection at Time of Peak Force (mm)	Lower Right Abdomen X-axis Deflection at Time of Peak Force (mm)	Difference Between Peak Left & Right X-axis Deflections (mm)
DL9207 VRTC SN=CC1 F=006 R=DP3449	**160815-1**	2859	-78.0	-86.0	8.0
	160815-3	2934	-77.9	-85.7	7.7
	160815-4	2941	-77.8	-89.4	11.6
	160815-5	2976	-80.8	-88.6	7.8
	160815-6	2972	-80.9	-88.5	7.6
DL9207 VRTC SN=CC2 F=002 R=DP3441	**160816-1**	2843	-79.3	-88.0	8.7
	160816-3	2905	-79.3	-86.6	7.3
	160816-5	2929	-80.5	-89.8	9.3
	160816-6	2878	-80.7	-88.1	7.3
	160816-8	2889	-79.6	-87.8	8.2
DL9207 VRTC SN=472-4763-5 F=009 R=DP3443	**160816-12**	2734	-79.7	-86.7	7.1
	160816-13	2959	-82.5	-89.4	6.8
	160816-14	2979	-83.1	-90.5	7.4
	160817-1	2956	-81.6	-90.9	9.3
	160817-2	2953	-82.9	-90.5	7.6
DO9799 Humanetics	**1107**	2745	-78.2	-79.4	1.2
	1108	2872	-81.4	-79.2	-2.2
	1111	2879	-83.0	-83.3	0.3
	1115	2918	-83.3	-85.6	2.3
	1119	2913	-85.5	-84.3	-1.2
	1122	3044	-87.7	-84.2	-3.5
DO9799 Calspan	**20160701070836**	2802	-79.7	-82.7	3.1
	20160701073954	2914	-82.4	-82.9	0.5
	20160701081037	2979	-81.7	-74.3	-7.5
	20160701084126	2988	-81.7	-72.1	-9.7
	20160701091215	3113	-79.5	-73.9	-5.6
Mean		**2918**	**-83.0**		**N/A**
Std. Dev.		**83**	**4.5**		**N/A**
CV		**2.8%**	**5.4%**		**N/A**

For the difference in X deflections (which is ideally zero), the data from all labs (Table 12-10) shows that the range for the difference between left and right X deflections was -9.7 to 11.6 mm. Further investigation shows that the VRTC deflection difference data from all tests is positive, indicating that the deflection on the right side is consistently larger than that on the left; furthermore, it has a higher average magnitude. Physically examining VRTC's test setup showed that the ATD was consistently slightly rotated about the Z-axis in these tests (note that this has been corrected at the VRTC lab); thus, equidistance from the probe on the left and right sides was affected. The main contributor to this result is that in the VRTC test data, all the right X-axis deflections are larger than the left X-axis deflections (*at least* 6.8 mm larger). In the Humanetics and Calspan data, the distribution is more evenly split left-to-right.

Table 12-11 summarizes the lower abdomen qualification response requirements. Since both left and right deflections are included in the calculation of the deflection specification, the large differences in left and right deflection at the VRTC lab will not prohibit using that data to determine a deflection range.

Table 12-11. Lower Abdomen Response Requirements

<table>
<tr><th>Parameter</th><th>Units</th><th>Min.</th><th>Max.</th><th>Nominal Target</th><th>Corridor Width ±%</th></tr>
<tr><td>Impact Velocity</td><td>m/s</td><td>3.25</td><td>3.35</td><td>3.30</td><td></td></tr>
<tr><td>Peak Probe Force</td><td>N</td><td>2626</td><td>3210</td><td>2918</td><td>10%</td></tr>
<tr><td>Lower Left Abdomen X-axis Deflection at Time of Peak Force</td><td rowspan="2">mm</td><td rowspan="2">-91.3</td><td rowspan="2">-74.7</td><td rowspan="2">-83.0</td><td rowspan="2">10%</td></tr>
<tr><td>Lower Right Abdomen X-axis Deflection at Time of Peak Force</td></tr>
<tr><td>Difference Between Peak Left & Right X-axis Deflections</td><td>mm</td><td>-8</td><td>8</td><td>0</td><td>± 10% of the mean of X-axis deflection</td></tr>
</table>

Discussion. At VRTC and Humanetics, repeat tests on individual units were highly uniform (CVs below 5 percent) for all measurements. Also, *Dummy Reproducibility* in tests at VRTC also displayed CVs below 5 percent as seen in (Table 12-7). Thus, *Dummy/Test Repeatability*, and *Dummy Reproducibility* do not appear to pose any problems in attaining the target response margin of ± 10 percent.

However, labs may have difficulty attaining the response if the test set-up is not sufficiently symmetric. A distinct right versus left misalignment was observed at VRTC that affected the test results. A left versus right discrepancy at Calspan was also apparent in some of the tests. This is a *Test Reproducibility* issue and may affect test labs in the future. However, once the dummy is properly aligned (as it was at Humanetics), labs should be able to attain the desired response.

Aside from the left versus right issue, when the left and right peak displacements from each respective test site are averaged together the average peak abdominal displacement at Calspan (79 mm) was low relative to VRTC (86 mm) and Humanetics (83 mm). In two of their tests, deflections were below the target response by more than 10 percent even though the left versus right difference was less than 8 mm. Thus, in the future, test labs such as Calspan's may need to experiment with set-ups and dummy positioning to assure they are within allowable tolerances.

13 Knee

13.1 Methodology

Repeatability and reproducibility tests were performed using the knee 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 joint at 2.20 ± 0.05 m/s (Figure 13-1). During these tests, the femur Z-axis force and knee deflection at peak femur force were measured.

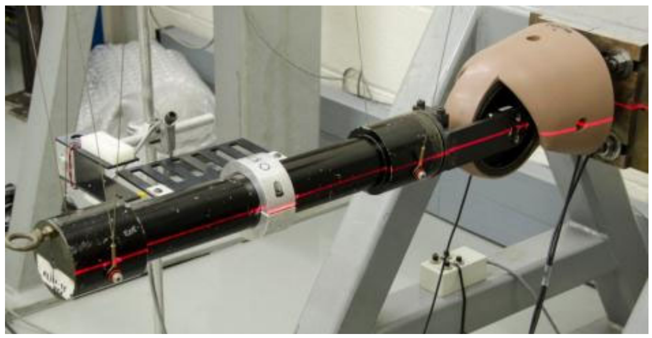

Figure 13-1. Knee impact test setup

13.2 Knee Repeatability Results

Sections 13.2.1 to 13.2.10 illustrate the results of the knee impact repeatability tests. Each section contains a table providing the test data, followed by plot overlays of the five repeat tests conducted at all three labs. Note that the data in the tables containing the results of each test series are listed sequentially, with the test at the top of the table beginning the test series.

13.2.1 THOR-50M DL9207 Left Knee Testing at VRTC

Repeatability results at VRTC for the left knee qualification of DL9207 (C2102639B) yielded CV values all below 5 percent (Table 13-1 and Figure 13-2 to Figure 13-3).

Table 13-1. VRTC THOR-50M DL9207 Left Knee (C2102639B) Repeatability Results

Test Number	Peak Femur Fz (N)	Knee Deflection at Peak Femur Force (mm)
062314_01	-6804	-20.5
062314_02	-7041	-20.7
062314_03	-7042	-20.7
062314_04	-7032	-20.6
062314_05	-7029	-20.6
Mean	**-6990**	**-20.6**
Std. Dev.	**104**	**0.1**
CV	**1.5%**	**0.4%**

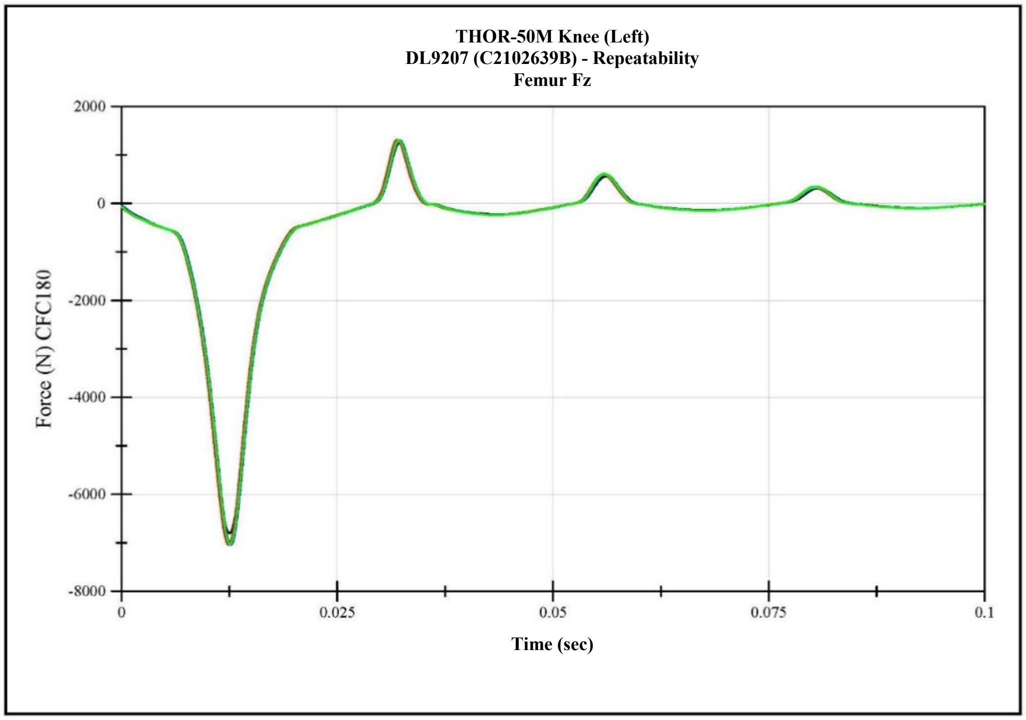

Figure 13-2. VRTC left knee femur force repeatability for DL9207

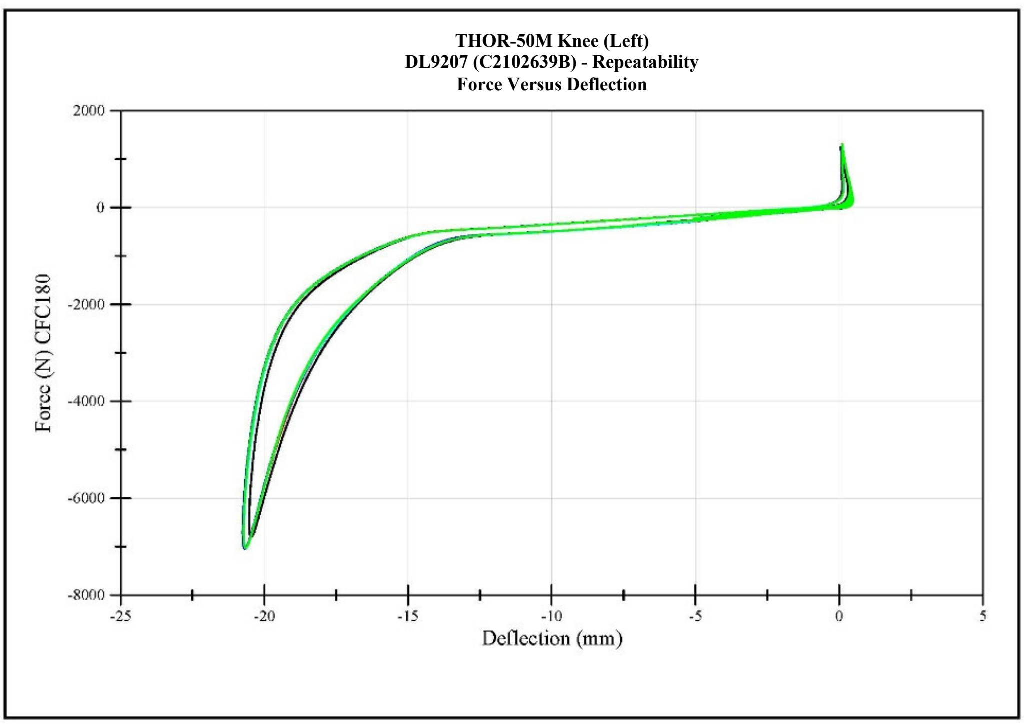

Figure 13-3. VRTC left knee femur force vs. knee deflection repeatability for DL9207

13.2.2 THOR-50M DL9207 Right Knee Testing at VRTC

Repeatability results at VRTC for the right knee qualification of DL9207 (I1807966B) yielded CV values all below 5 percent (Table 13-2 and Figure 13-4 and Figure 13-5).

Table 13-2. VRTC THOR-50M DL9207 Right Knee (I1807966B) Repeatability Results

Test Number	Peak Femur Fz (N)	Knee Deflection at Peak Femur Force (mm)
062414_01	-6938	-20.0
062414_02	-7026	-20.1
062414_03	-7078	-20.1
062414_04	-7093	-19.6
062414_05	-7053	-19.7
Mean	**-7037**	**-19.9**
Std. Dev.	**61**	**0.2**
CV	**0.9%**	**1.1%**

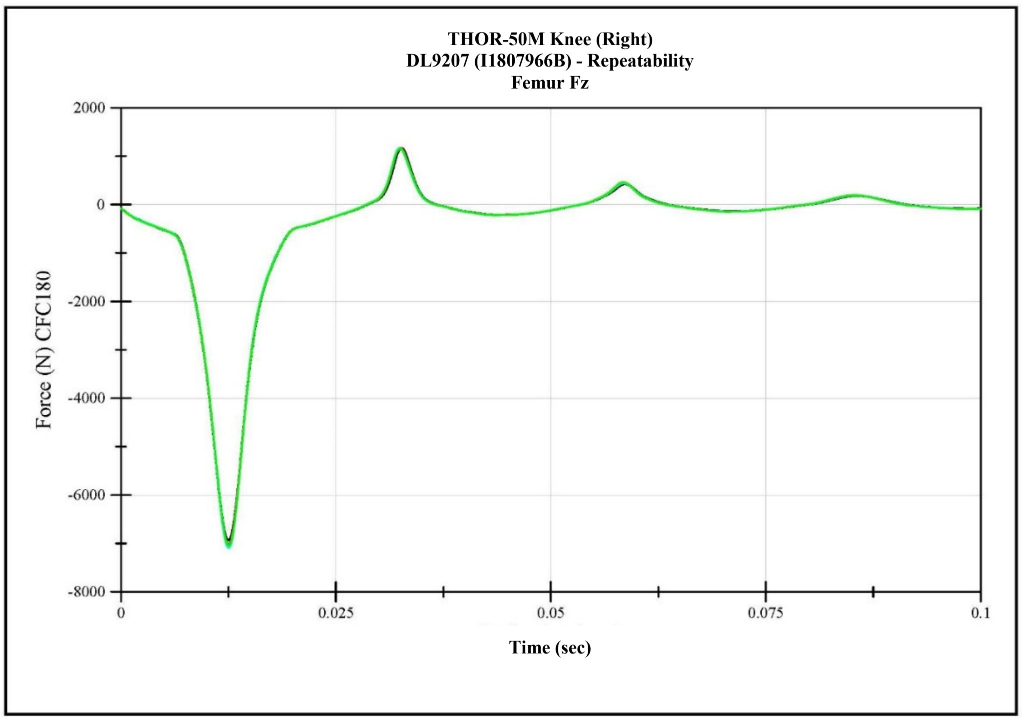

Figure 13-4. VRTC right knee femur force repeatability for DL9207

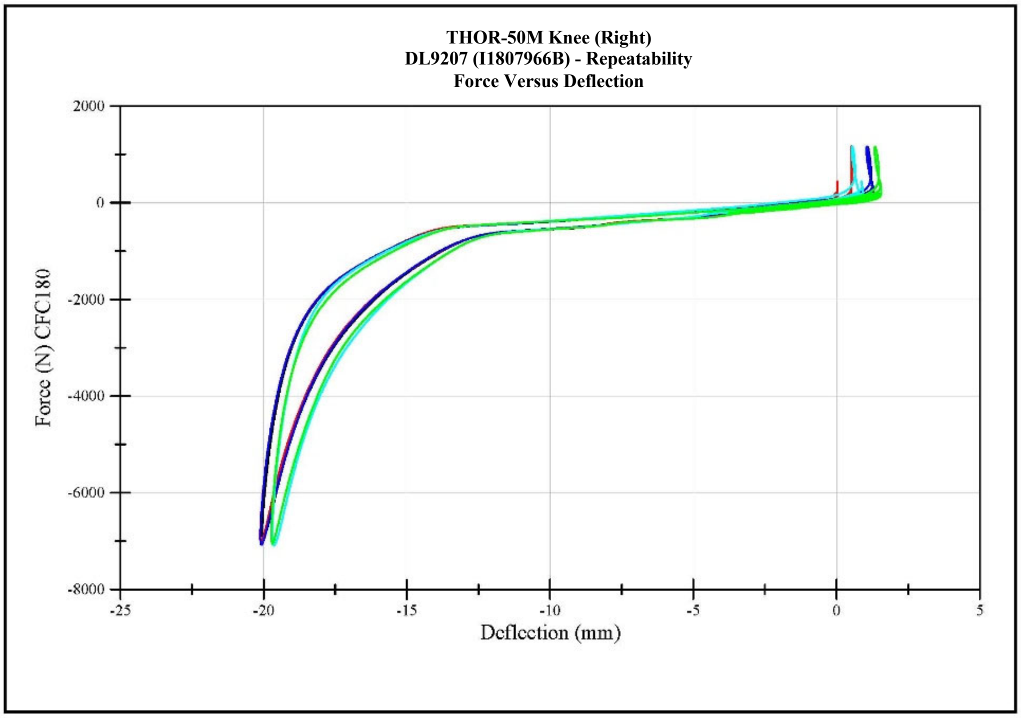

Figure 13-5. VRTC right knee femur force vs. knee deflection repeatability for DL9207

13.2.3 THOR-50M DO9798 Left Knee Testing at VRTC

Repeatability results at VRTC for the left knee qualification of DO9798 (13073811) yielded CV values all below 5 percent (Table 13-3 and Figure 13-6 to Figure 13-7).

Table 13-3. VRTC THOR-50M DO9798 Left Knee (13073811) Repeatability Results

Test Number	Peak Femur Fz (N)	Knee Deflection at Peak Femur Force (mm)
060414_01	-6751	-20.3
060414_02	-6697	-20.3
060414_03	-6758	-20.4
060414_04	-6634	-20.2
060414_05	-6643	-20.3
Mean	**-6697**	**-20.3**
Std. Dev.	**58**	**0.1**
CV	**0.9%**	**0.3%**

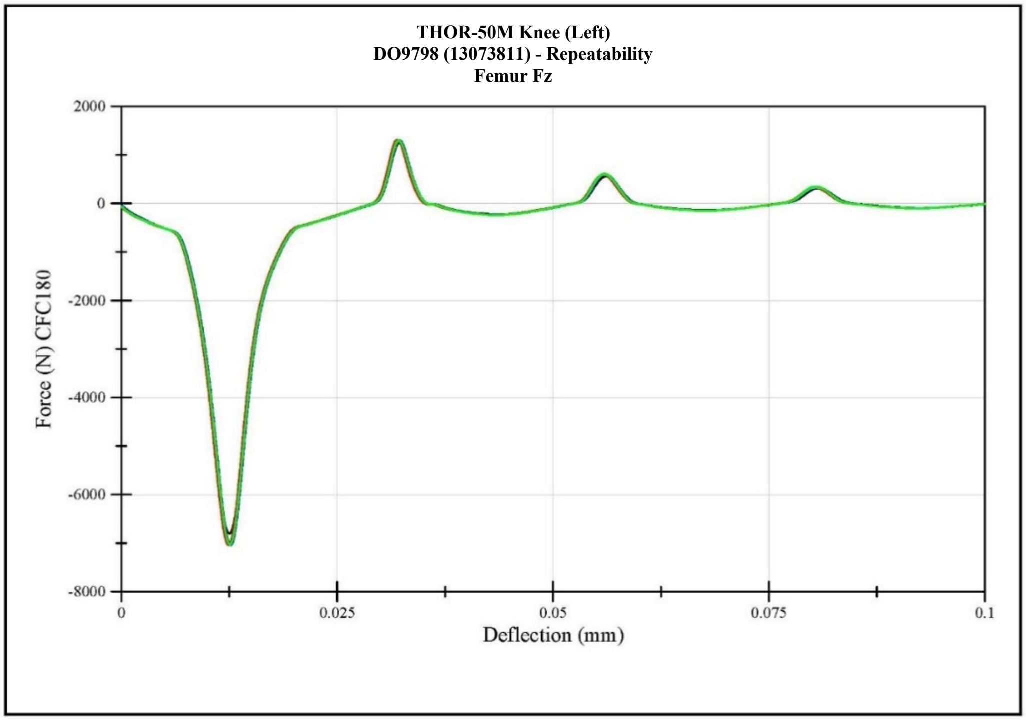

Figure 13-6. VRTC left knee femur force repeatability for DO9798

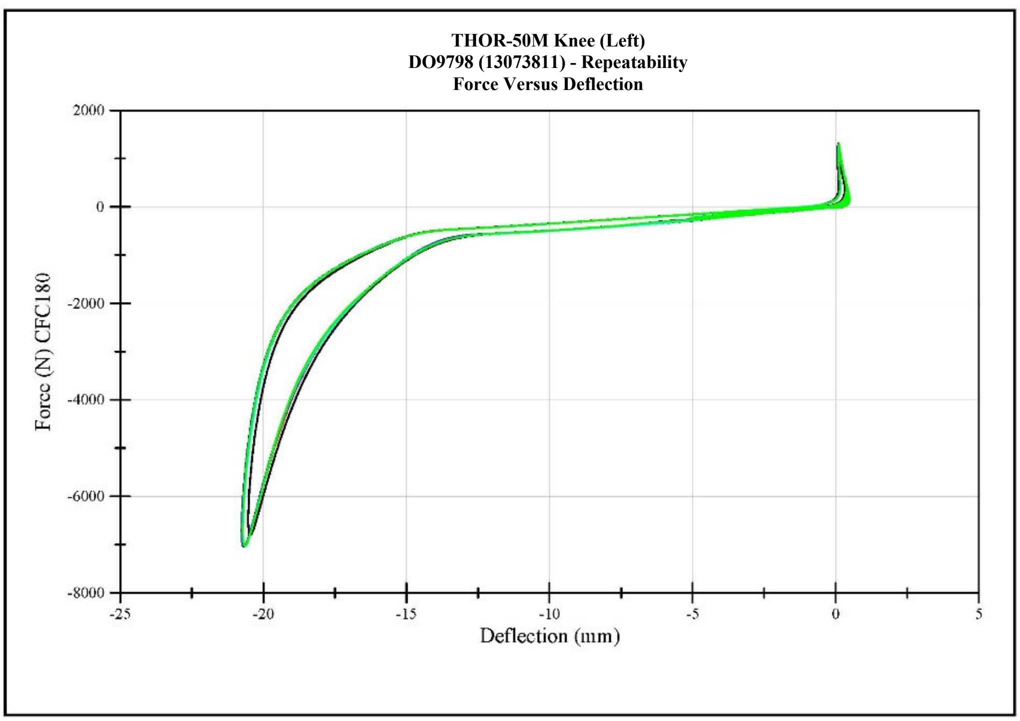

Figure 13-7. VRTC left knee femur force vs. knee deflection repeatability for DO9798

13.2.4 THOR-50M DO9798 Right Knee Testing at VRTC

Repeatability results at VRTC for the right knee qualification of DO9798 (13073814) yielded CV values all below 5 percent (Table 13-4 and Figure 13-8 and Figure 13-9).

Table 13-4. VRTC THOR-50M DO9798 Right Knee (13073814) Repeatability Results

Test Number	Peak Femur Fz (N)	Knee Deflection at Peak Femur Force (mm)
062514_01R	-6736	-20.0
062514_02R	-6710	-20.0
062514_03R	-6685	-20.0
062514_04R	-6660	-20.0
062514_05R	-6651	-20.1
Mean	**-6689**	**-20.0**
Std. Dev.	**35**	**0.02**
CV	**0.5%**	**0.1%**

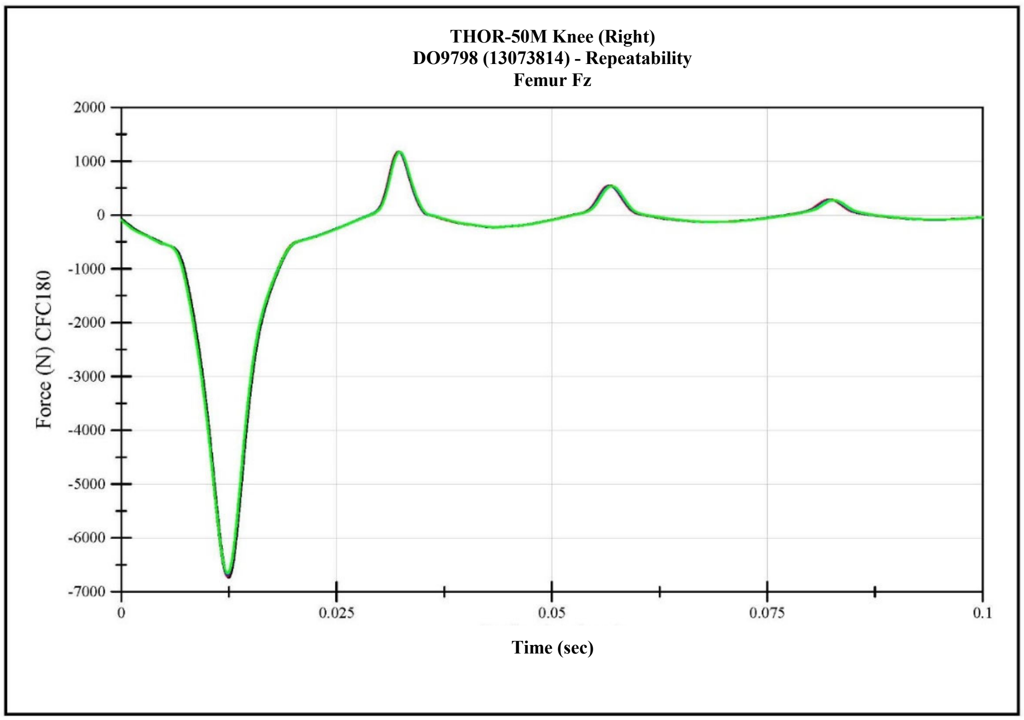

Figure 13-8. VRTC right knee femur force repeatability for DO9798

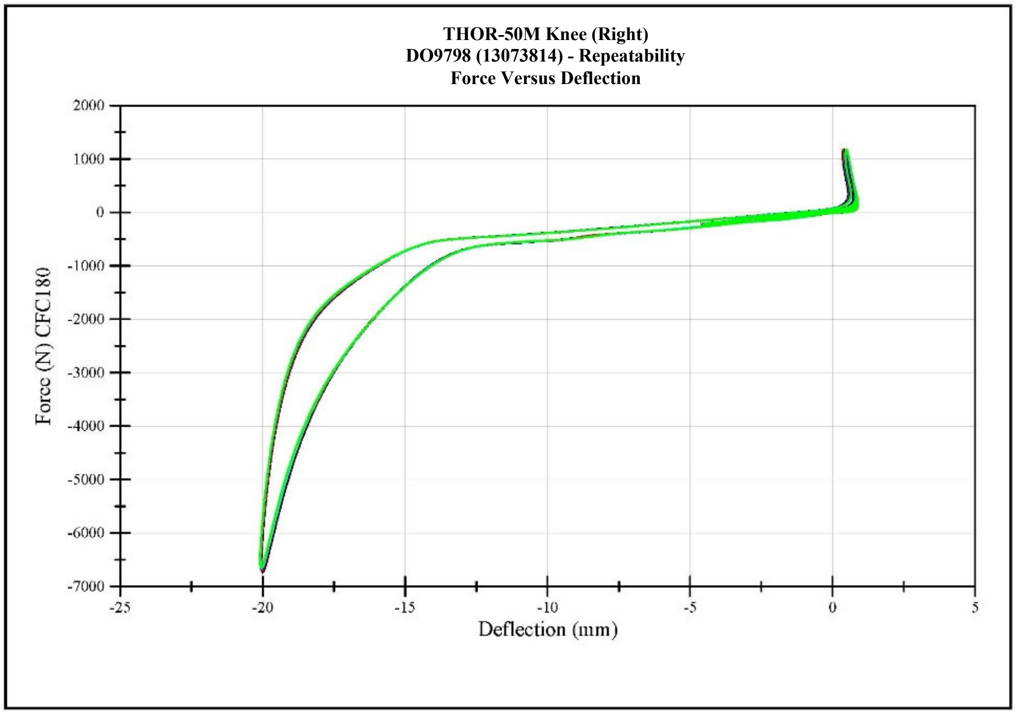

Figure 13-9. VRTC right knee femur force vs. knee deflection repeatability for DO9798

13.2.5 THOR-50M DO9799 Left Knee Testing at VRTC

Repeatability results at VRTC for the left knee qualification of DO9799 (13063666) yielded CV values all below 5 percent (Table 13-5 and Figure 13-10 to Figure 13-11).

Table 13-5. VRTC THOR-50M DO9799 Left Knee (13063666) Repeatability Results

Test Number	Peak Femur Fz (N)	Knee Deflection at Peak Femur Force (mm)
062514_01L	-6065	-20.1
062514_02L	-6442	-20.5
062514_03L	-6420	-20.5
062514_04L	-6438	-20.5
062514_05L	-6401	-20.5
Mean	**-6353**	**-20.4**
Std. Dev.	**162**	**0.2**
CV	**2.5%**	**0.9%**

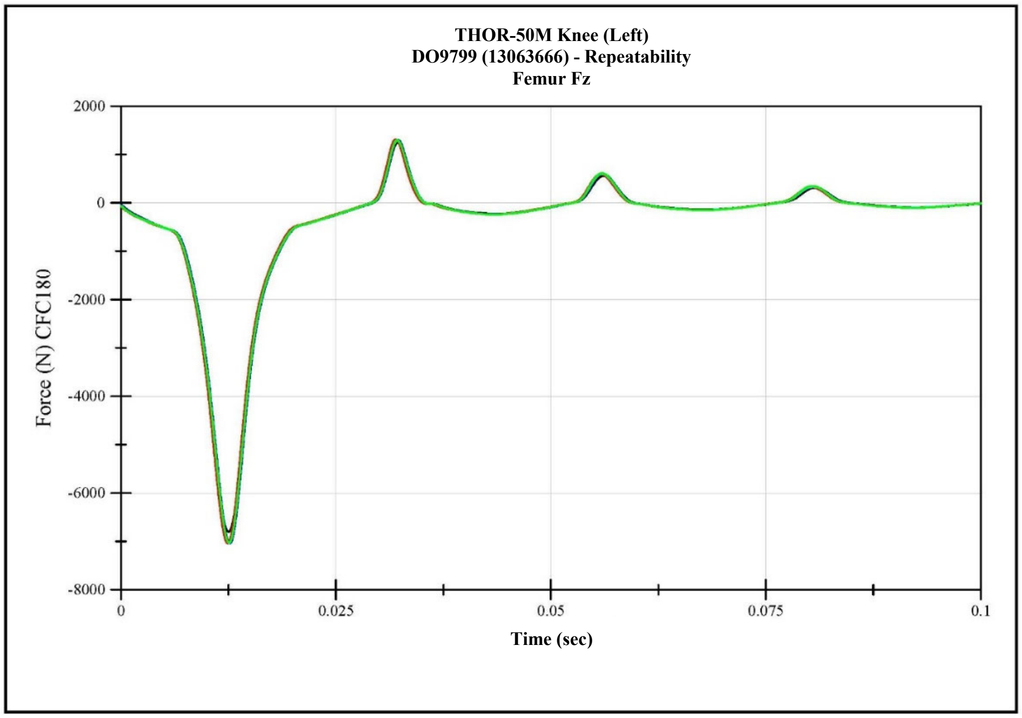

Figure 13-10. VRTC left knee femur force repeatability for DO9799

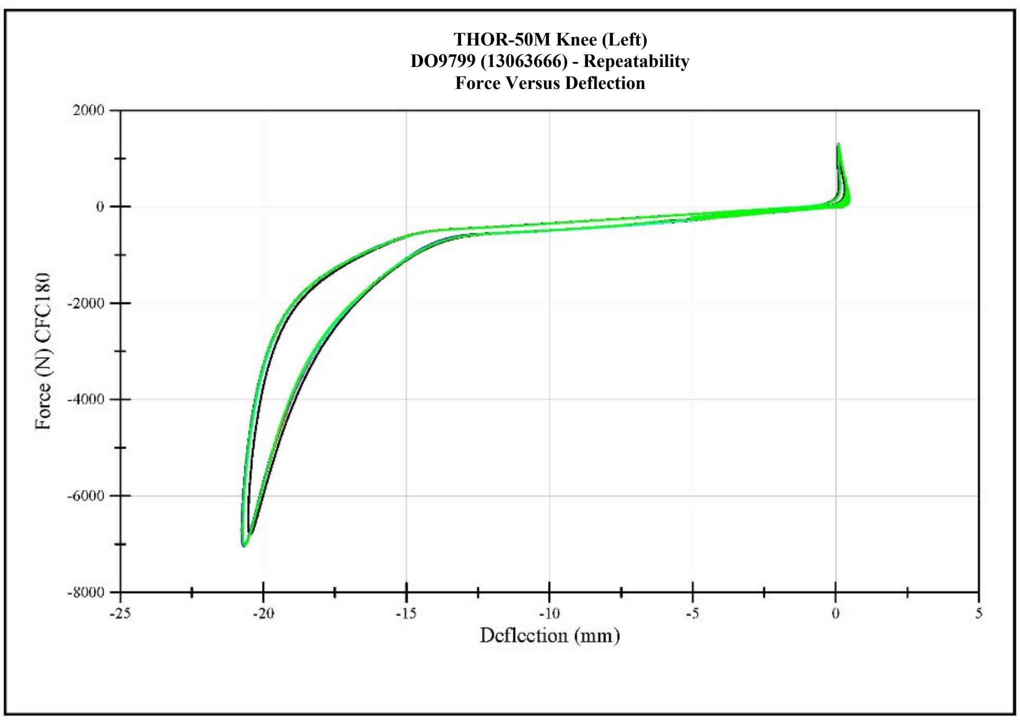

Figure 13-11. VRTC left knee femur force vs. knee deflection repeatability for DO9799

13.2.6 THOR-50M DO9799 Right Knee Testing at VRTC

Repeatability results at VRTC for the right knee qualification of DO9799 (13074086) yielded CV values all below 5 percent (Table 13-6 and Figure 13-12 though Figure 13-13).

Table 13-6. VRTC THOR-50M DO9799 Right Knee (13074086) Repeatability Results

Test Number	Peak Femur Fz (N)	Knee Deflection at Peak Femur Force (mm)
060514_01	-5932	-20.7
060514_02	-6229	-21.0
060514_03	-6228	-21.0
060514_04	-6167	-21.0
060514_05	-6172	-21.0
Mean	**-6145**	**-20.9**
Std. Dev.	**123**	**0.1**
CV	**2.0%**	**0.6%**

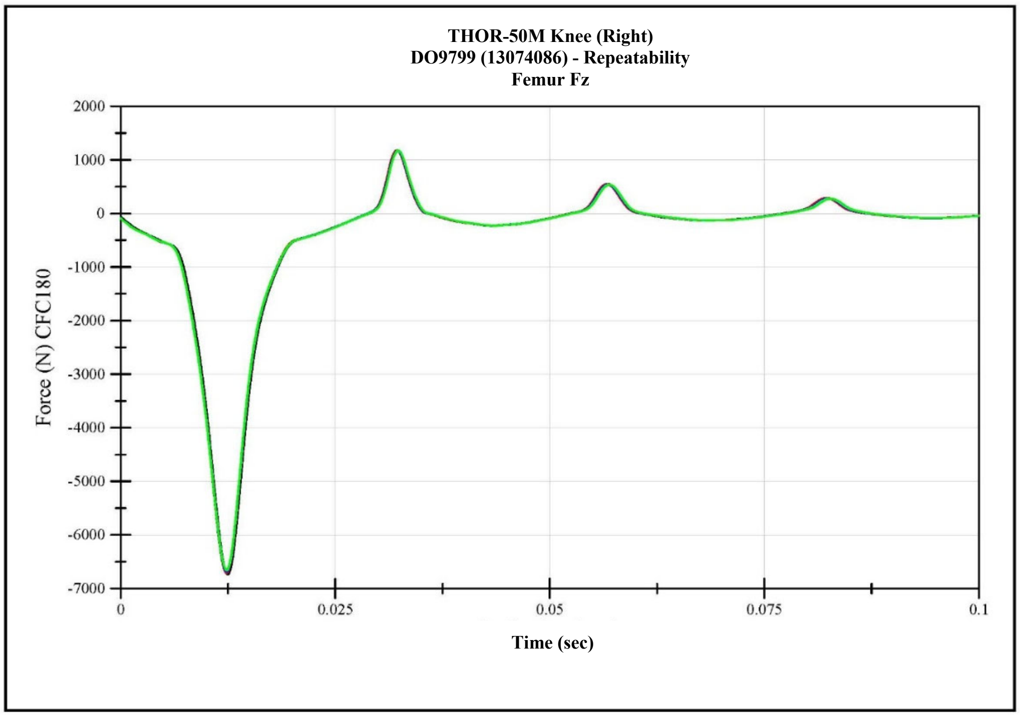

Figure 13-12. VRTC right knee femur force repeatability for DO9799

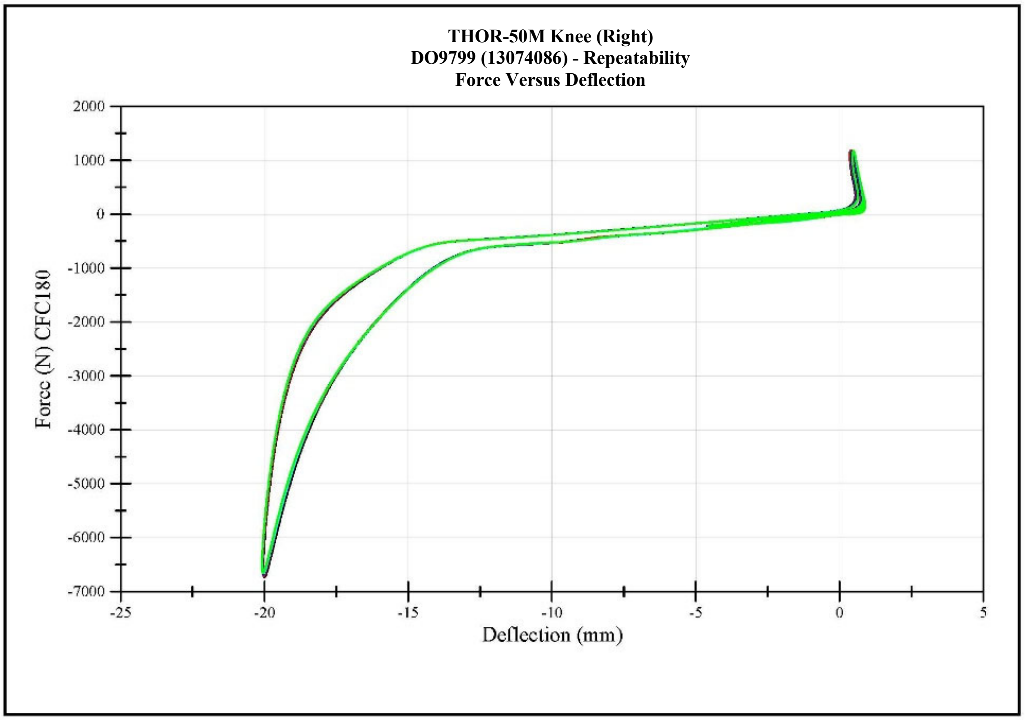

Figure 13-13. VRTC right knee femur force vs. knee deflection repeatability for DO9799

13.2.7 THOR-50M DO9799 Left Knee Testing at Humanetics

Repeatability results at Humanetics for the left knee qualification of DO9799 (13063666) yielded CV values all below 5 percent (Table 13-7 and Figure 13-14 to Figure 13-15).

Table 13-7. Humanetics THOR-50M DO9799 Left Knee (13063666) Repeatability Results

Test Number	Peak Femur Fz (N)	Knee Deflection at Peak Femur Force (mm)
447	-6883	-19.7
449	-6919	-19.7
451	-6902	-19.8
452	-6928	-19.8
455	-6941	-19.8
458	-6986	-19.8
Mean	**-6926**	**-19.8**
Std. Dev.	**35**	**0.03**
CV	**0.5%**	**0.2%**

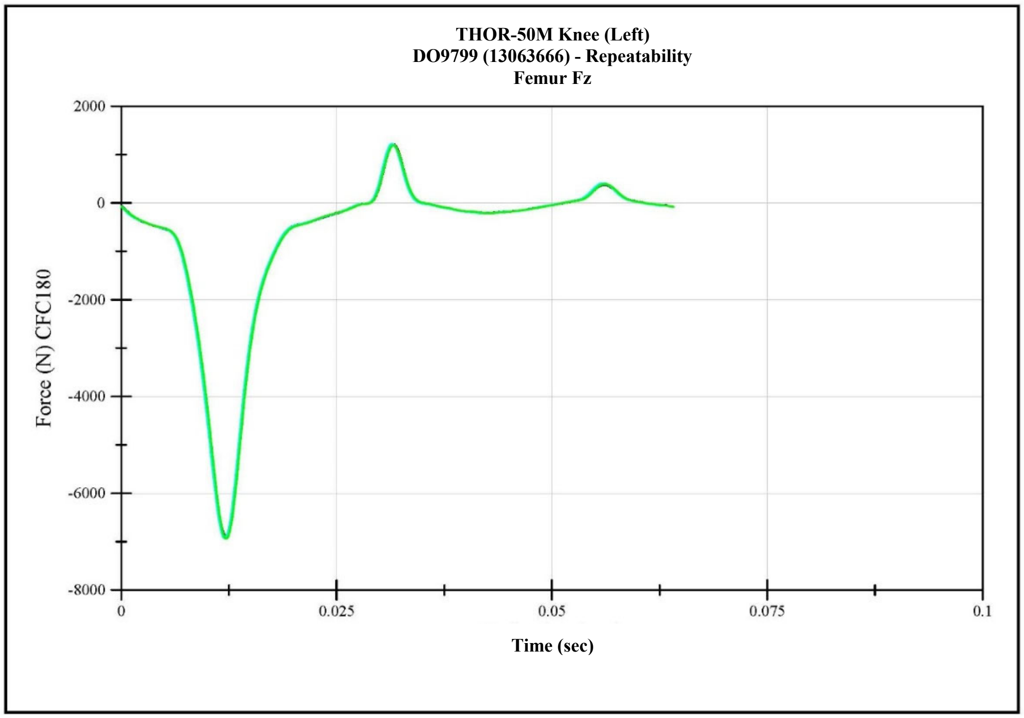

Figure 13-14. Humanetics left knee femur force repeatability for DO9799

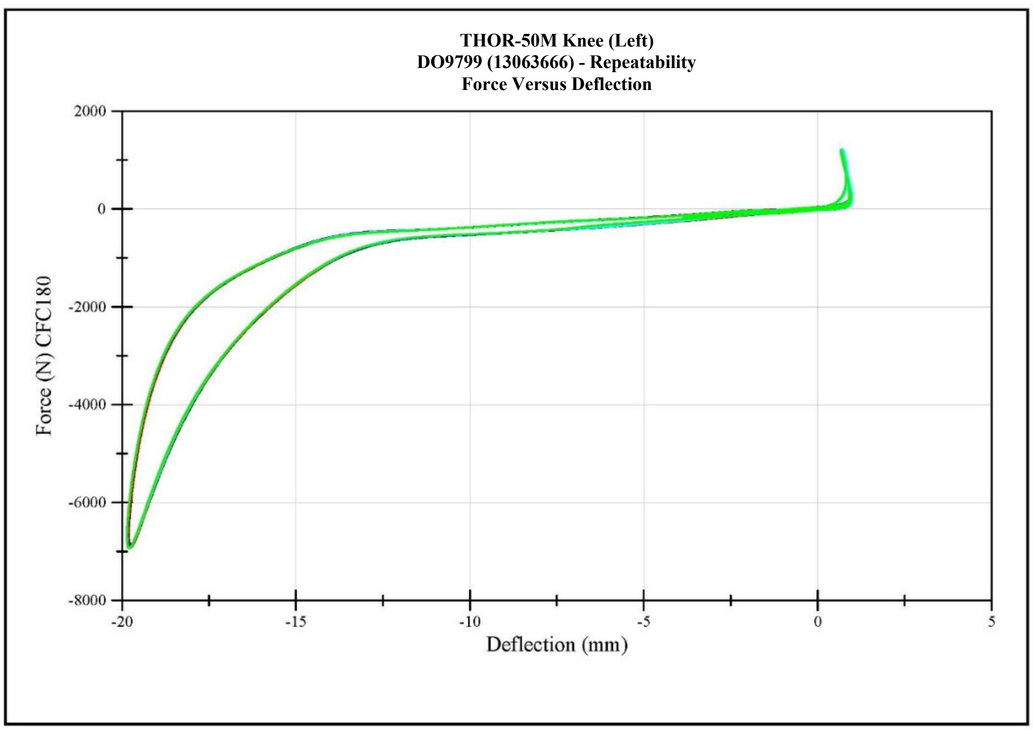

Figure 13-15. Humanetics left knee femur force vs. knee deflection repeatability for DO9799

13.2.8 THOR-50M DO9799 Right Knee Testing at Humanetics

Repeatability results at Humanetics for the right knee qualification of DO9799 (13074086) yielded CV values all below 5 percent (Table 13-8 and Figure 13-16 to Figure 13-17).

Table 13-8. Humanetics THOR-50M DO9799 Right Knee (13074086) Repeatability Results

Test Number	Peak Femur Fz (N)	Knee Deflection at Peak Femur Force (mm)
421	-6261	-20.0
424	-6367	-20.1
426	-6390	-20.1
434	-6395	-20.1
436	-6101	-20.0
438	-6376	-20.1
Mean	**-6315**	**-20.1**
Std. Dev.	**116**	**0.1**
CV	**1.8%**	**0.3%**

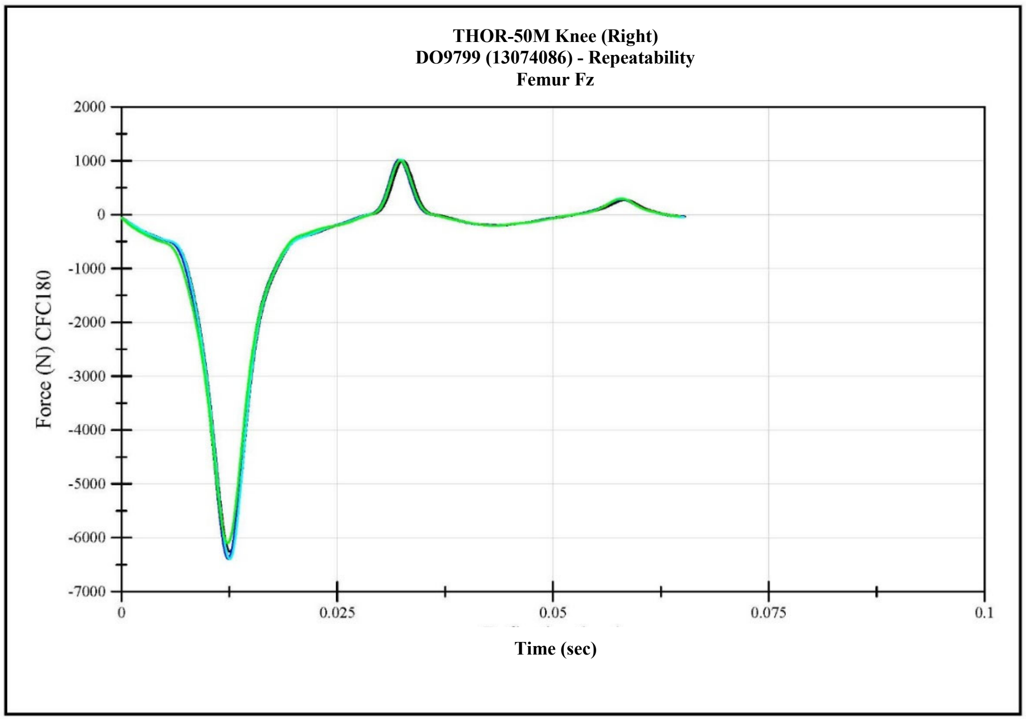

Figure 13-16. Humanetics right knee femur force repeatability for DO9799

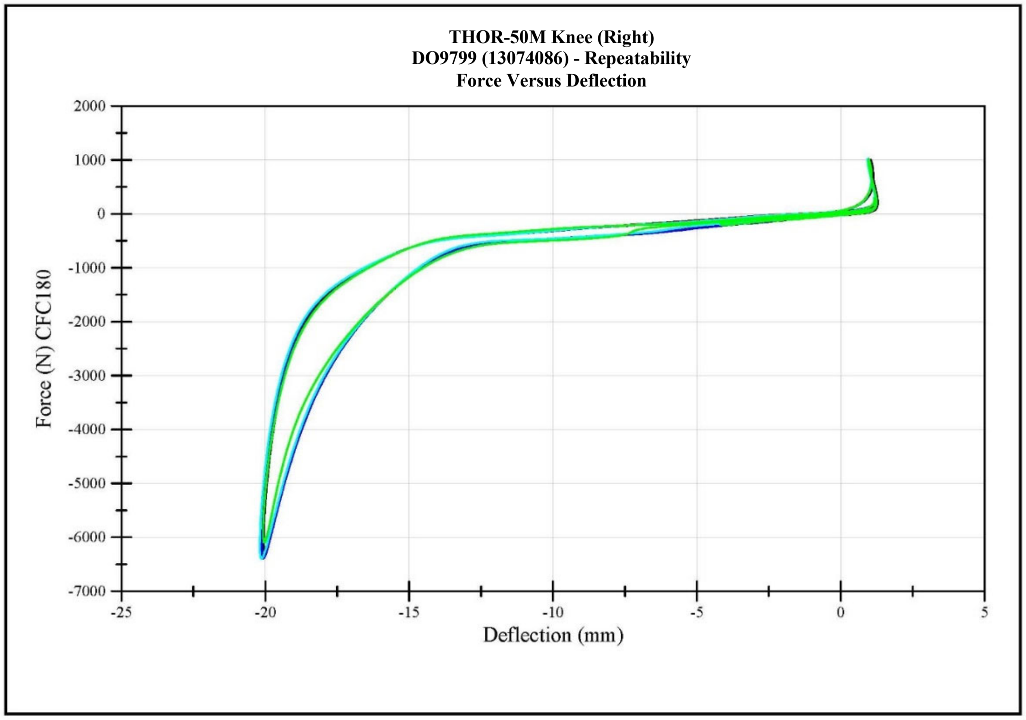

Figure 13-17. Humanetics right knee femur force vs. knee deflection repeatability for DO9799

13.2.9 THOR-50M DO9799 Left Knee Testing at Calspan

Repeatability results at Calspan for the left knee qualification of DO9799 (13063666) yielded CV values all below 5 percent (Table 13-9 and Figure 13-18 to Figure 13-19).

Table 13-9. Calspan THOR-50M DO9799 Left Knee (13063666) Repeatability Results

Test Number	Peak Femur Fz (N)	Knee Deflection at Peak Femur Force (mm)
20160701152921	-5793	-19.9
20160701160120	-6047	-20.0
20160701163206	-6051	-20.0
20160701170322	-6064	-20.0
20160701173521	-6079	-20.1
Mean	**-6007**	**-20.0**
Std. Dev.	**120**	**0.1**
CV	**2.0%**	**0.4%**

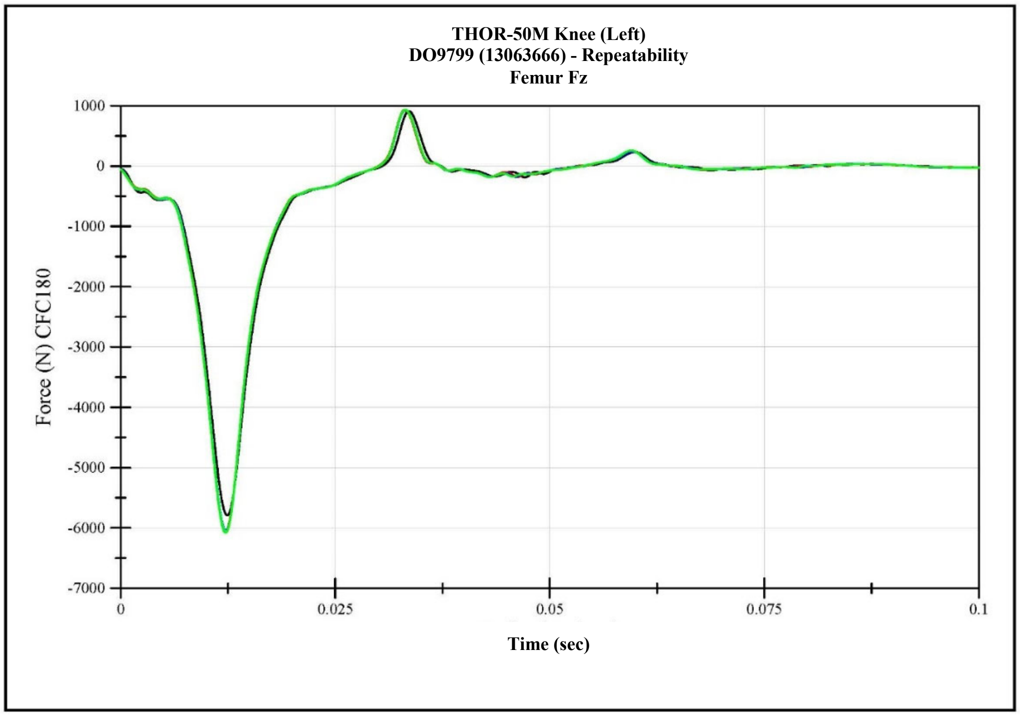

Figure 13-18. Calspan left knee femur force repeatability for DO9799

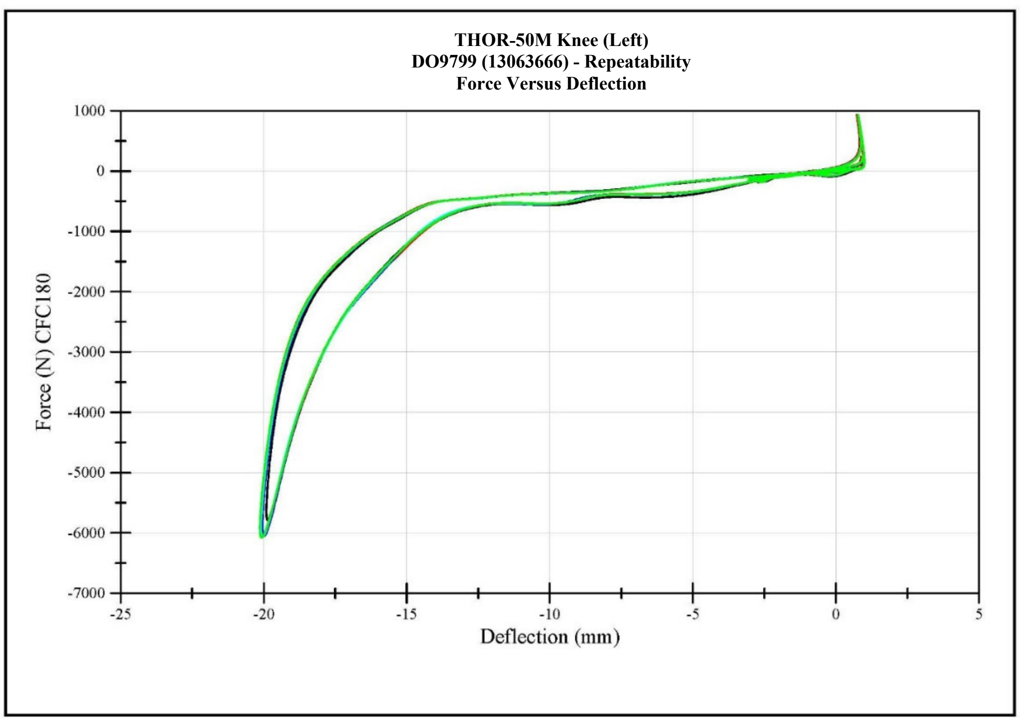

Figure 13-19. Calspan left knee femur force vs. knee deflection repeatability for DO9799

13.2.10 THOR-50M DO9799 Right Knee Testing at Calspan

Repeatability results at Calspan for the right knee qualification of DO9799 (13074086) yielded CV values all below 5 percent (Table 13-10 and Figure 13-20 to Figure 13-21).

Table 13-10. Calspan THOR-50M DO9799 Right Knee (13074086) Repeatability Results

Test Number	Peak Femur Fz (N)	Knee Deflection at Peak Femur Force (mm)
20160701123859	-5446	-19.7
20160701131007	-5785	-19.7
20160701134043	-5987	-19.8
20160701141351	-6018	-19.9
20160701144520	-6018	-19.8
Mean	**-5851**	**-19.8**
Std. Dev.	**246**	**0.1**
CV	**4.2%**	**0.4%**

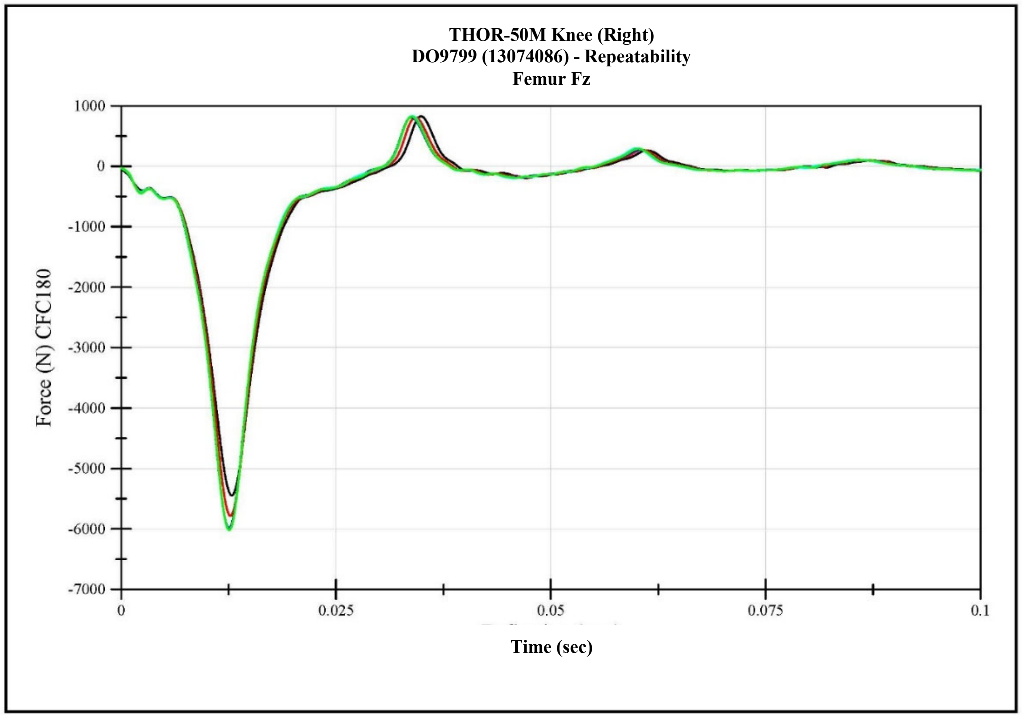

Figure 13-20. Calspan right knee femur force repeatability for DO9799

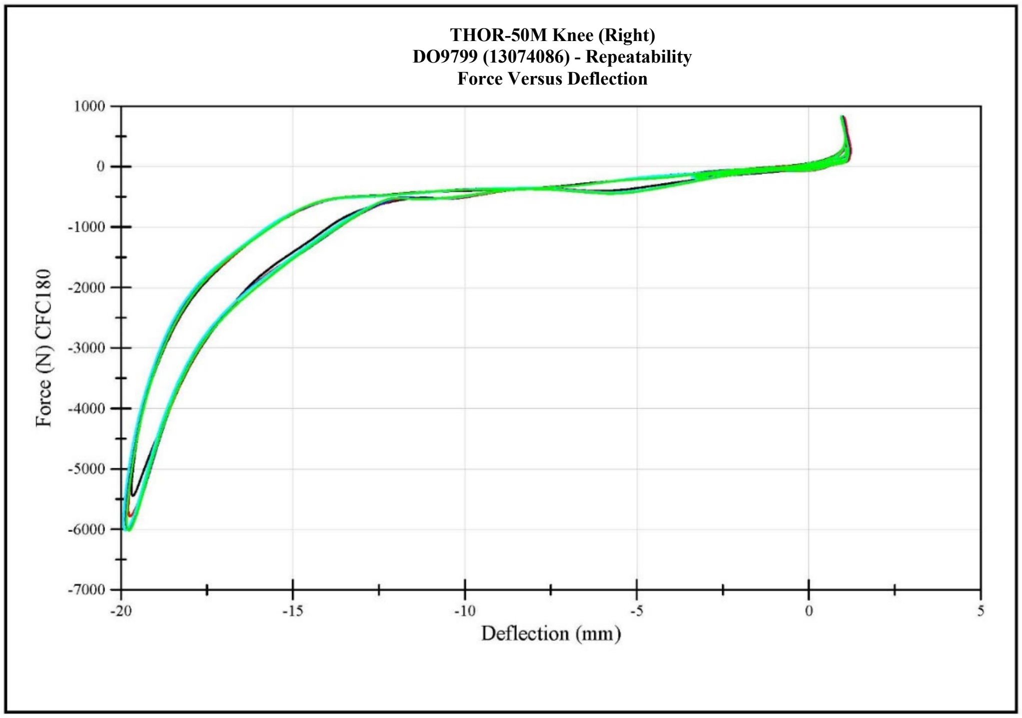

Figure 13-21. Calspan right knee femur force vs. knee deflection repeatability for DO9799

13.3 Knee Dummy Reproducibility Results

Dummy Reproducibility results at VRTC for the knee qualification yielded CV values below 5 percent for the knee deflection at peak femur force, and the peak femur Z-axis force is above 5 percent but less than 10 percent (Table 13-11). Since three dummies were used in this study, data from both left and right legs was included in the reproducibility results, offering 6 sample sets of data instead of the three samples as in many of the other qualification tests in this study.

Table 13-11. THOR-50M Knee Dummy Reproducibility Results

Dummy Number	Knee	Test Number	Peak Femur Fz (N)	Knee Deflection at Peak Femur Force (mm)
VRTC DL9207	**Left (C2102639B)**	**062314_01**	-6804	-20.5
		062314_02	-7041	-20.7
		062314_03	-7042	-20.7
		062314_04	-7032	-20.6
		062314_05	-7029	-20.6
	Right (I1807966B)	**062414_01**	-6938	-20.0
		062414_02	-7026	-20.1
		062414_03	-7078	-20.1
		062414_04	-7093	-19.6
		062414_05	-7053	-19.7
VRTC DO9798	**Left (13073811)**	**060414_01**	-6751	-20.3
		060414_02	-6697	-20.3
		060414_03	-6758	-20.4
		060414_04	-6634	-20.2
		060414_05	-6643	-20.3
	Right (13073814)	**062514_01**	-6736	-20.0
		062514_02	-6710	-20.0
		062514_03	-6685	-20.0
		062514_04	-6660	-20.0
		062514_05	-6651	-20.1
VRTC DO9799	**Left (13063666)**	**062514_01**	-6065	-20.1
		062514_02	-6442	-20.5
		062514_03	-6420	-20.5
		062514_04	-6438	-20.5
		062514_05	-6401	-20.5
	Right (13074086)	**060514_01**	-5932	-20.7
		060514_02	-6229	-21.0
		060514_03	-6228	-21.0
		060514_04	-6167	-21.0
		060514_05	-6172	-21.0
Mean			**-6652**	**-20.4**
Std. Dev.			**337**	**0.4**
CV			**5.1%**	**1.8%**

13.4 Lab-to-Lab Variability Analysis

The results for the knee qualification tests from each lab are presented in Table 13-12 and Table 13-13. The last four rows of the table show the *Test Reproducibility* results when data from all three labs are combined. The left knee qualification test results are shown in Table 13-12 where the CV for left knee deflection was under 5 percent, and the peak femur forces produced a CV above 5 percent but less than 10 percent.

Table 13-12. THOR-50M Left Knee (13063666) Lab-to Lab Variability Results

Dummy Number	Peak Femur Fz (N)	Knee Deflection at Peak Femur Force (mm)
VRTC DO9799 Left Knee (13063666)	-6065	-20.1
	-6442	-20.5
	-6420	-20.5
	-6438	-20.5
	-6401	-20.5
Humanetics DO9799 Left Knee (13063666)	-6883	-19.7
	-6919	-19.7
	-6902	-19.8
	-6928	-19.8
	-6941	-19.8
	-6986	-19.8
Calspan DO9799 Left Knee (13063666)	-5793	-19.9
	-6047	-20.0
	-6051	-20.0
	-6064	-20.0
	-6079	-20.1
Test Reproducibility DO9799 Left Knee (13063666)		
Mean	**-6460**	**-20.0**
Std. Dev.	**413**	**0.3**
CV	**6.4%**	**1.4%**

The right knee qualification test results are shown in Table 13-13 where the CV values for femur force and knee deflection were below 5 percent.

Table 13-13. THOR-50M Right Knee (130740860) Lab-to Lab Variability Results

Dummy Number	Peak Femur Fz (N)	Knee Deflection at Peak Femur Force (mm)
VRTC DO9799 Right Knee (13074086)	-5932	-20.7
	-6229	-21.0
	-6228	-21.0
	-6167	-21.0
	-6172	-21.0
Humanetics DO9799 Right Knee (13074086)	-6261	-20.0
	-6367	-20.1
	-6390	-20.1
	-6395	-20.1
	-6101	-20.0
	-6376	-20.1
Calspan DO9799 Right Knee (13074086)	-5446	-19.7
	-5785	-19.7
	-5987	-19.8
	-6018	-19.9
	-6018	-19.8
Test Reproducibility DO9799 Right Knee (13074086)		
Mean	**-6117**	**-20.2**
Std. Dev.	**254**	**0.5**
CV	**4.1%**	**2.5%**

13.5 Corridor Development

All the data used to determine the knee qualification corridors is shown in Table 13-14. The qualification corridors were calculated using the mean plus or minus 10 percent of the peak for the specified measured or calculated channels (Table 13-15).

Table 13-14. THOR-50M Knee Qualification Corridor Results

Dummy Number	Knee	Test Number	Peak Femur Fz (N)	Knee Deflection at Peak Femur Force (mm)
VRTC DL9207	Left (C2102639B)	062314_01	-6804	-20.5
		062314_02	-7041	-20.7
		062314_03	-7042	-20.7
		062314_04	-7032	-20.6
		062314_05	-7029	-20.6
	Right (I1807966B)	062414_01	-6938	-20.0
		062414_02	-7026	-20.1
		062414_03	-7078	-20.1
		062414_04	-7093	-19.6
		062414_05	-7053	-19.7
VRTC DO9798	Left (13073811)	060414_01	-6751	-20.3
		060414_02	-6697	-20.3
		060414_03	-6758	-20.4
		060414_04	-6634	-20.2
		060414_05	-6643	-20.3
	Right (13073814)	062514_01	-6736	-20.0
		062514_02	-6710	-20.0
		062514_03	-6685	-20.0
		062514_04	-6660	-20.0
		062514_05	-6651	-20.1
VRTC DO9799	Left (13063666)	062514_01	-6065	-20.1
		062514_02	-6442	-20.5
		062514_03	-6420	-20.5
		062514_04	-6438	-20.5
		062514_05	-6401	-20.5
	Right (13074086)	060514_01	-5932	-20.7
		060514_02	-6229	-21.0
		060514_03	-6228	-21.0
		060514_04	-6167	-21.0
		060514_05	-6172	-21.0
Humanetics DO9799	Left (13063666)	447	-6883	-19.7
		449	-6919	-19.7
		451	-6902	-19.8
		452	-6928	-19.8
		455	-6941	-19.8
		458	-6986	-19.8
	Right (13074086)	421	-6261	-20.0
		424	-6367	-20.1
		426	-6390	-20.1
		434	-6395	-20.1
		436	-6101	-20.0
		438	-6376	-20.1
Calspan DO9799	Left (13063666)	20160701152921	-5793	-19.9
		20160701160120	-6047	-20.0
		20160701163206	-6051	-20.0
		20160701170322	-6064	-20.0
		20160701173521	-6079	-20.1
	Right (13074086)	20160701123859	-5446	-19.7
		20160701131007	-5785	-19.7
		20160701134043	-5987	-19.8
		20160701141351	-6018	-19.9
		20160701144520	-6018	-19.8
Mean			**-6506**	**-20.2**
Std. Dev.			**420**	**0.4**
CV			**6.5%**	**1.9%**

Table 13-15. Knee Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Impact Velocity	**m/s**	2.15	2.25	2.20	
Peak Femur Fz	**N**	-7156	-5855	-6506	10%
Knee Deflection at Peak Femur Force	**mm**	-22.2	-18.2	-20.2	10%

Discussion. There were three instances in which a test did not achieve the target response ± 10 percent (highlighted with yellow in Table 13-14); all three occurred at Calspan due to low femur forces. The *Test Reproducibility* assessment (Table 13-12 and Table 13-13) reveals that tests at Humanetics produced the highest femur forces and the tests at Calspan produced the lowest, resulting in CVs of 6.4% (left knee) and 4.1% (right knee). This indicates a slight non-uniformity in how tests are run, lab-to-lab, which could probably improve with greater diligence and experience among labs. This possibility is supported by the uniformly low CVs for *Dummy/Test Repeatability* (i.e., test labs may need to experiment with set-ups and dummy positioning to assure they are within allowable tolerances).

The CV for *Dummy Reproducibility* was above 5 percent but under 10 percent for femur force, but only by a small margin (CV of 5.1%). Moreover, six different knees were used in this assessment (rather than three different units for the other test conditions). Thus, variability due to *Dummy Reproducibility* does not appear to be much of a factor in attaining the target response margin of ± 10 percent since uniformity in six knees (rather than just three) has been demonstrated.

There are no indications that there are problems with *Dummy/Test Repeatability* for this test condition.

14 Upper Leg

14.1 Methodology

Repeatability and reproducibility tests were performed using the upper leg qualification procedures described in the *THOR-50M Qualification Procedures Manual,* with revisions presented during the 2021 proceedings of SAE Government/Industry (Millis, 2021). This test examines the response of the femur to axial impacts at the knee using a 12.00 kg impactor with a 76.2 mm diameter rigid disk impact surface at 3.3 ± 0.05 m/s (Figure 14-1). During these tests the peak probe force, peak femur force, and peak resultant acetabulum force were measured.

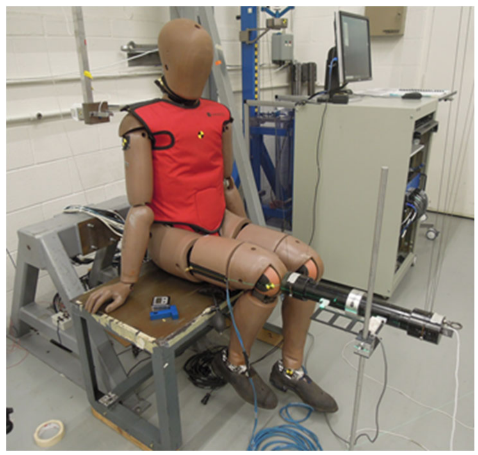

Figure 14-1. Upper leg impact test

14.2 Upper Leg Repeatability Results

Sections 14.2.1 to 14.2.10 illustrate the results of the upper leg impact repeatability tests. Each section contains a table providing the test data, followed by plot overlays of the five repeat tests conducted at three labs. For these tests, the test labs included VRTC, TRC, and Karco. Note that the data in the tables containing the results of each test series are listed sequentially, with the test at the top of the table beginning the test series.

14.2.1 THOR-50M DL9207 Left Upper Leg Testing at VRTC

Repeatability results at VRTC for the left upper leg of DL9207 yielded CV values all below 5 percent (Table 14-1, Figure 14-2 to Figure 14-4).

Table 14-1. VRTC THOR-50M DL9207 Left Upper Leg Repeatability Results

Test Number	Peak Probe Force (N)	Peak Femur Fz (N)	Peak Resultant Acetabulum Force (N)
200716-15	7856	-4525	2685
200716-16	7727	-4524	2779
200716-17	7630	-4563	2699
200716-18	7625	-4516	2829
200716-19	7718	-4531	2818
Mean	**7711**	**-4532**	**2762**
Std. Dev.	**94**	**18**	**67**
CV	**1.2%**	**0.4%**	**2.4%**

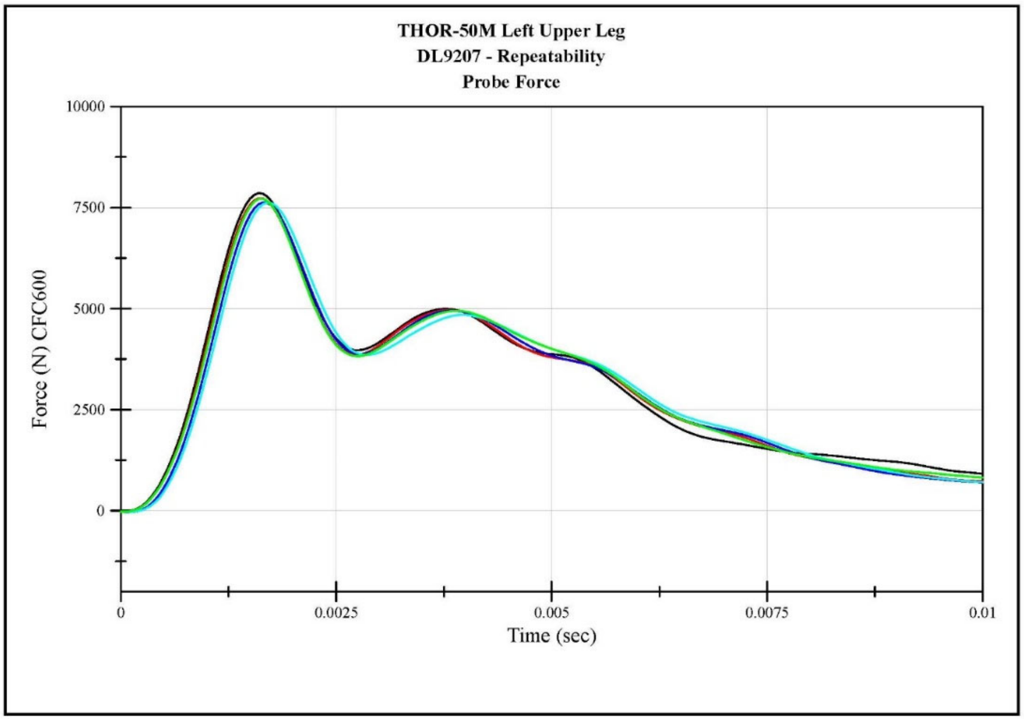

Figure 14-2. VRTC left upper leg probe force repeatability for DL9207

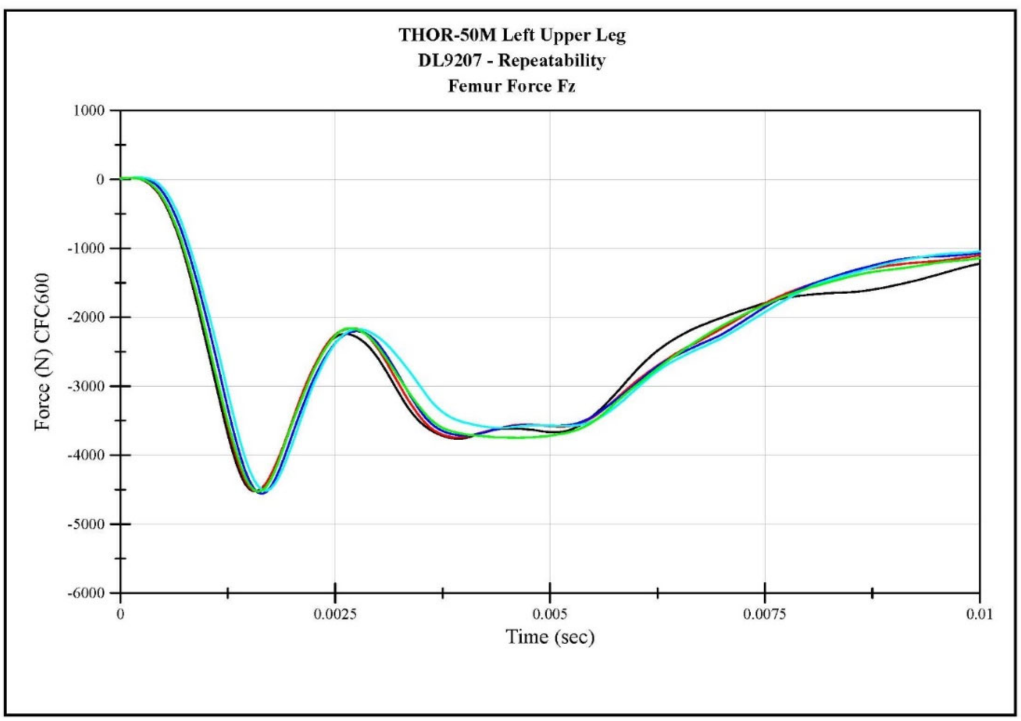

Figure 14-3. VRTC femur force Fz for left upper leg impact repeatability tests for DL9207

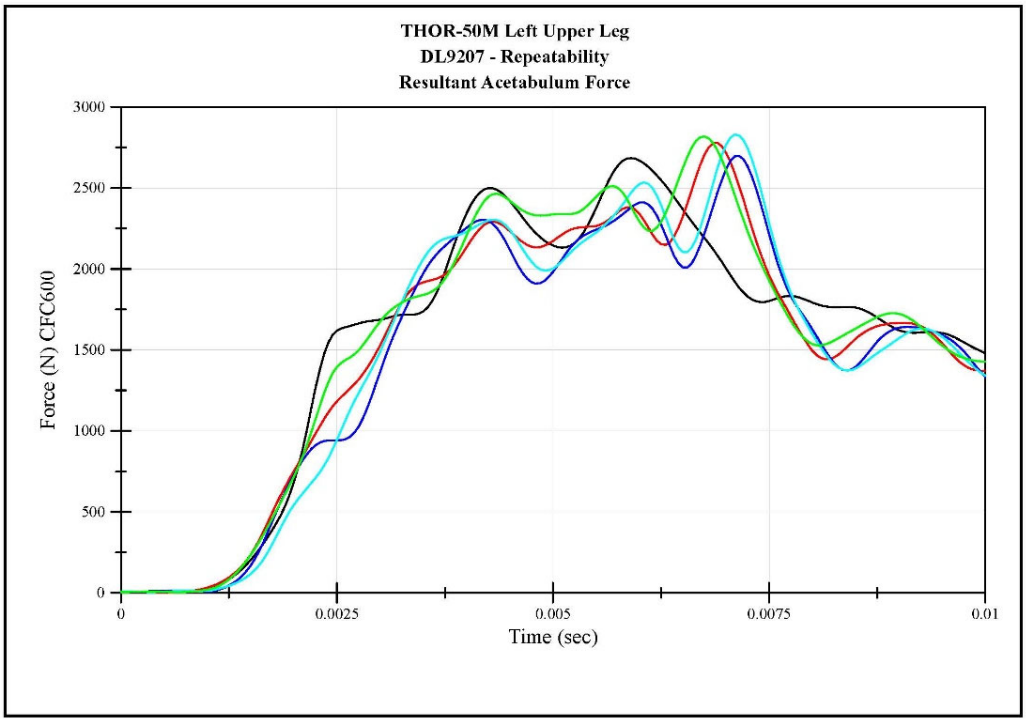

Figure 14-4. VRTC resultant acetabulum force for left upper leg impact repeatability tests for DL9207

14.2.2 THOR-50M DL9207 Right Upper Leg Testing at VRTC

Repeatability results at VRTC for the right upper leg of DL9207 yielded CV values all below 5 percent (Table 14-2, Figure 14-5 to Figure 14-7).

Table 14-2. VRTC THOR-50M DL9207 Right Upper Leg Repeatability Results

Test Number	Peak Probe Force (N)	Peak Femur Fz (N)	Peak Resultant Acetabulum Force (N)
200716-3	7963	-4769	2836
200716-6	7907	-4716	2770
200716-7	7954	-4775	2713
200716-9	7897	-4682	2542
200716-10	8021	-4707	2567
Mean	**7948**	**-4730**	**2685**
Std. Dev.	**50**	**40**	**128**
CV	**0.6%**	**0.9%**	**4.8%**

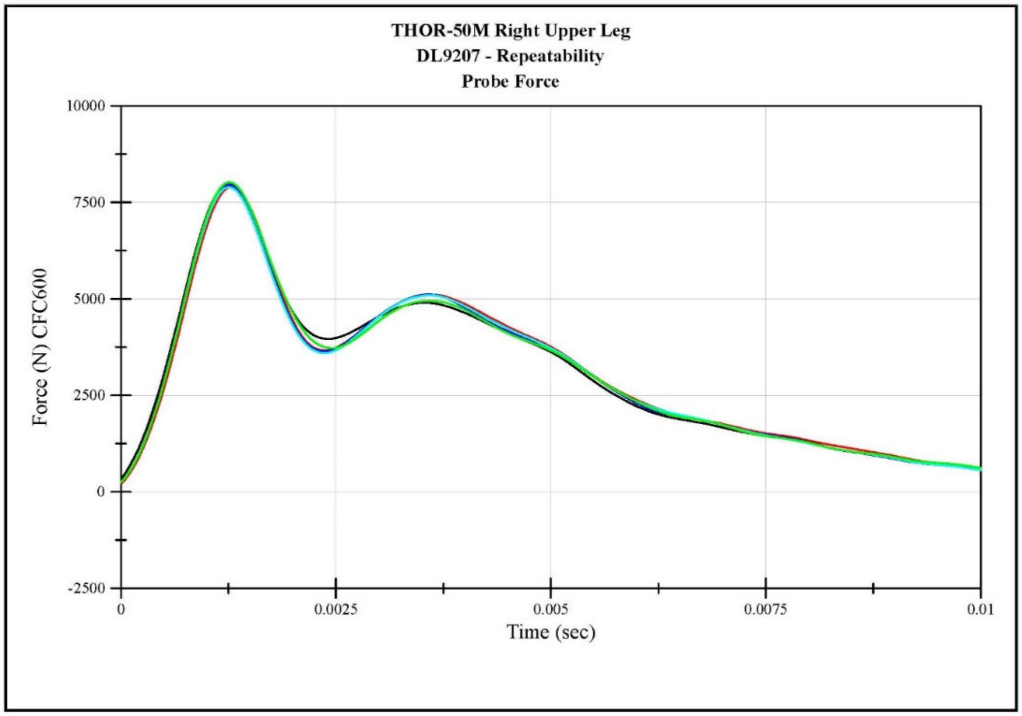

Figure 14-5. VRTC probe force for right upper leg impact repeatability tests for DL9207

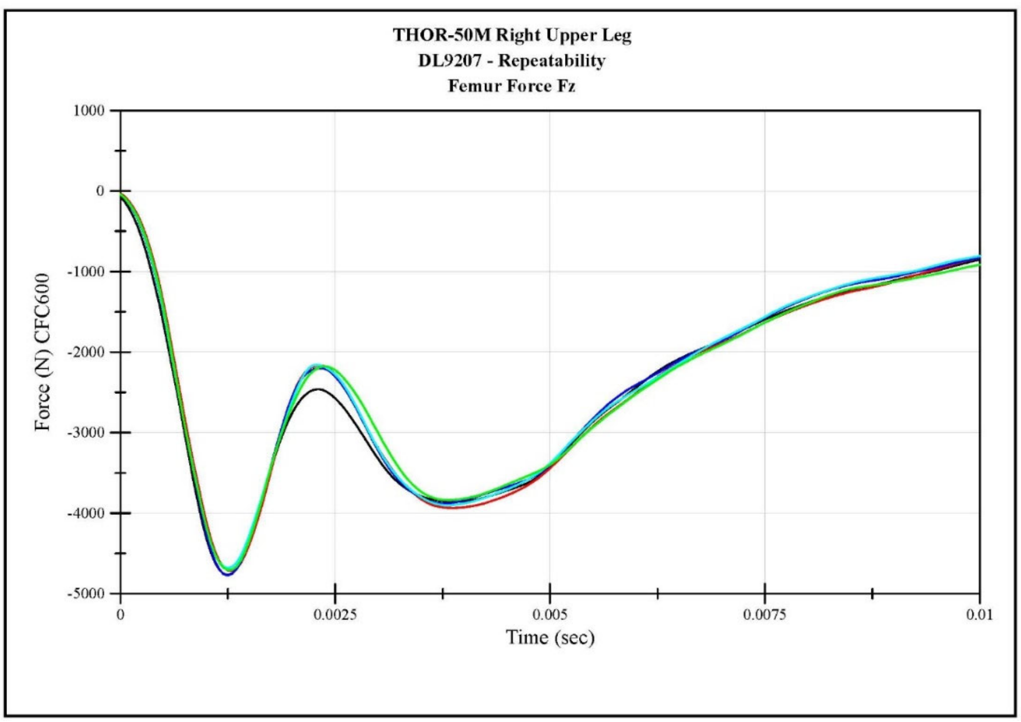

Figure 14-6. VRTC femur force Fz for right upper leg impact repeatability tests for DL9207

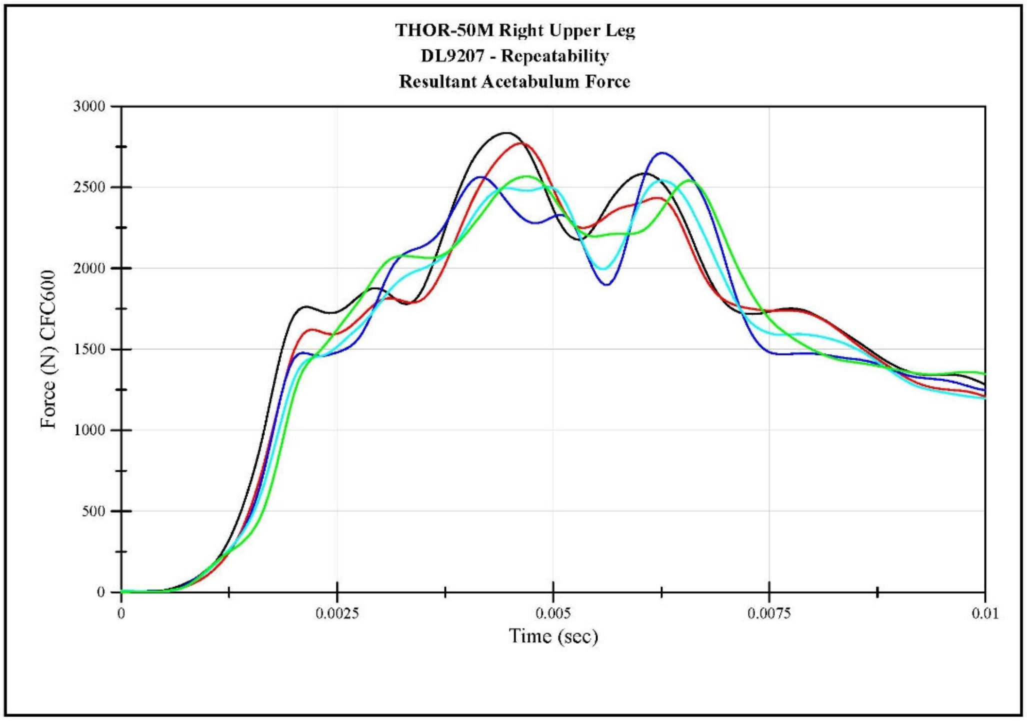

Figure 14-7. VRTC resultant acetabulum force for right upper leg impact repeatability tests for DL9207

14.2.3 THOR-50M EG2595 Left Upper Leg Testing at VRTC

Repeatability results at VRTC for the left upper leg of EG2595 yielded CV values all below 5 percent, with the exception of the peak resultant acetabulum force with a CV of 5.9% (Table 14-3, Figure 14-8 to Figure 14-10).

Table 14-3. VRTC THOR-50M EG2595 Left Upper Leg Repeatability Results

Test Number	**Peak Probe Force (N)**	**Peak Femur Fz (N)**	**Peak Resultant Acetabulum Force (N)**
200206-3	8680	-5098	2990
200206-4	8742	-5027	2604
200206-5	8680	-4990	2688
200206-6	8725	-4988	2643
200206-7	8759	-4974	2620
Mean	**8717**	**-5015**	**2709**
Std. Dev.	**36**	**50**	**160**
CV	**0.4%**	**1.0%**	**5.9%**

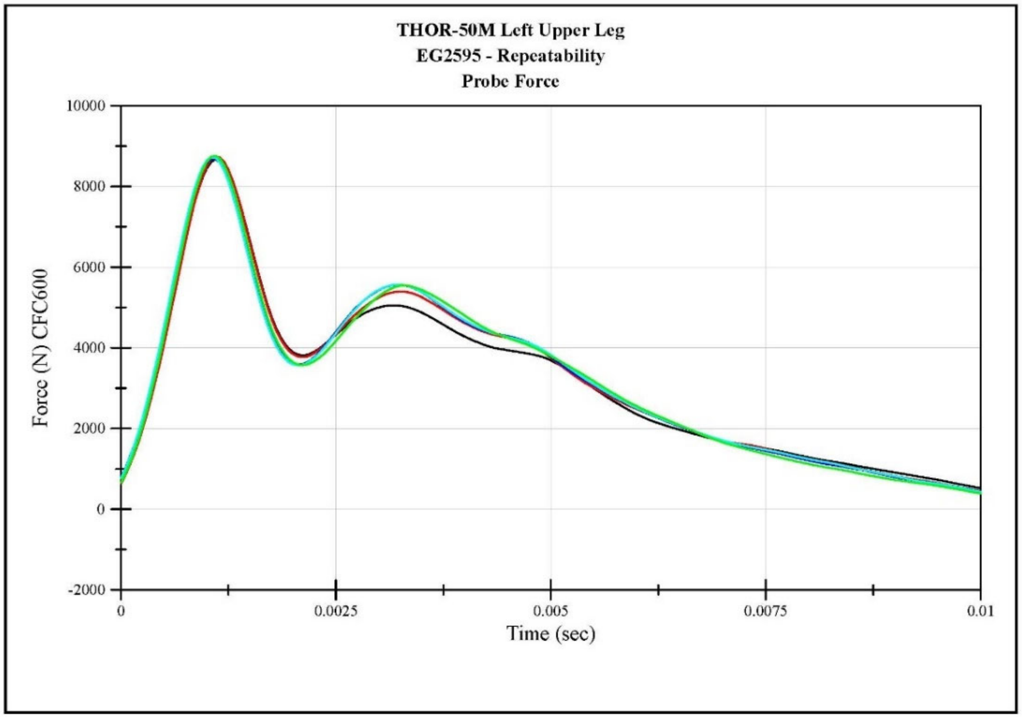

Figure 14-8. VRTC probe force for left upper leg impact repeatability tests for EG2595

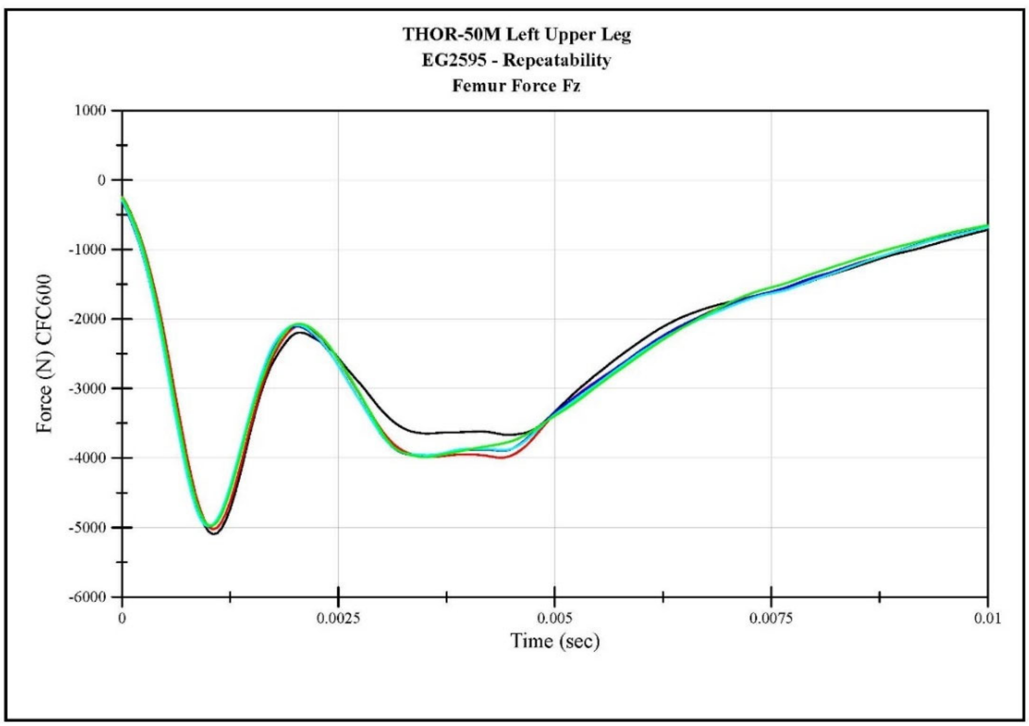

Figure 14-9. VRTC femur force Fz for left upper leg impact repeatability tests for EG2595

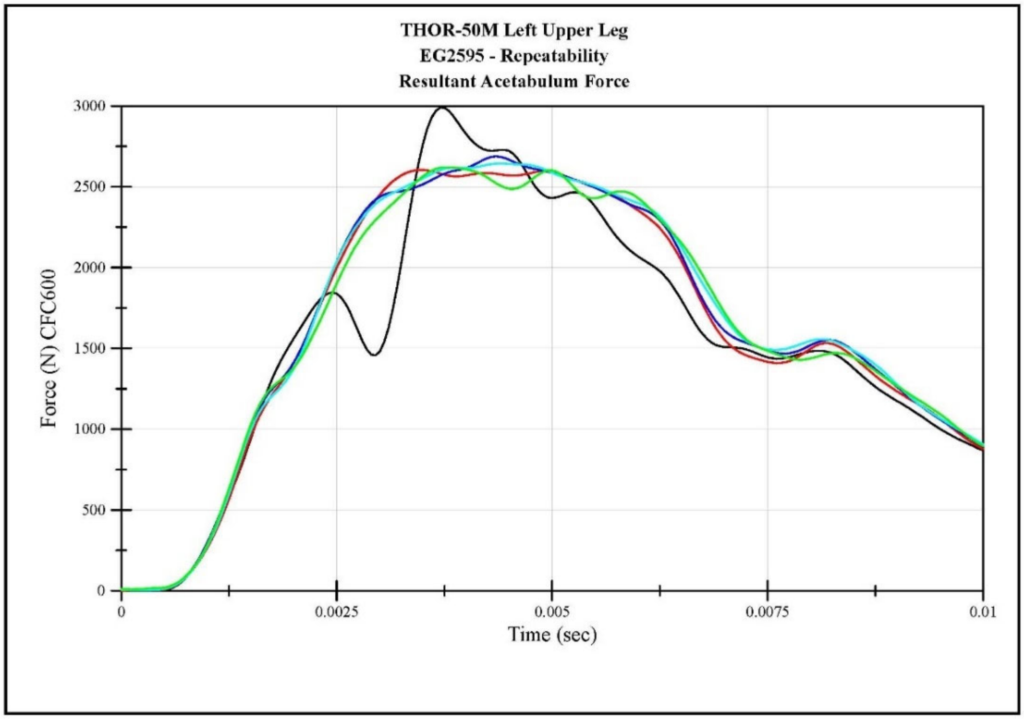

Figure 14-10. VRTC resultant acetabulum force for left upper leg impact repeatability tests for EG2595

14.2.4 THOR-50M EG2595 Right Upper Leg Testing at VRTC

Repeatability results at VRTC for the right upper leg of EG2595 yielded CV values all below 5 percent (Table 14-4, Figure 14-11 to Figure 14-13).

Table 14-4. VRTC THOR-50M EG2595 Right Upper Leg Repeatability Results

Test Number	Peak Probe Force (N)	Peak Femur Fz (N)	Peak Resultant Acetabulum Force (N)
200206-13	8151	-4686	2902
200206-14	8245	-4627	2663
200206-15	8232	-4528	2748
200210-1	8251	-4598	2691
200210-2	8242	-4554	2688
Mean	**8224**	**-4599**	**2738**
Std. Dev.	**42**	**62**	**96**
CV	**0.5%**	**1.4%**	**3.5%**

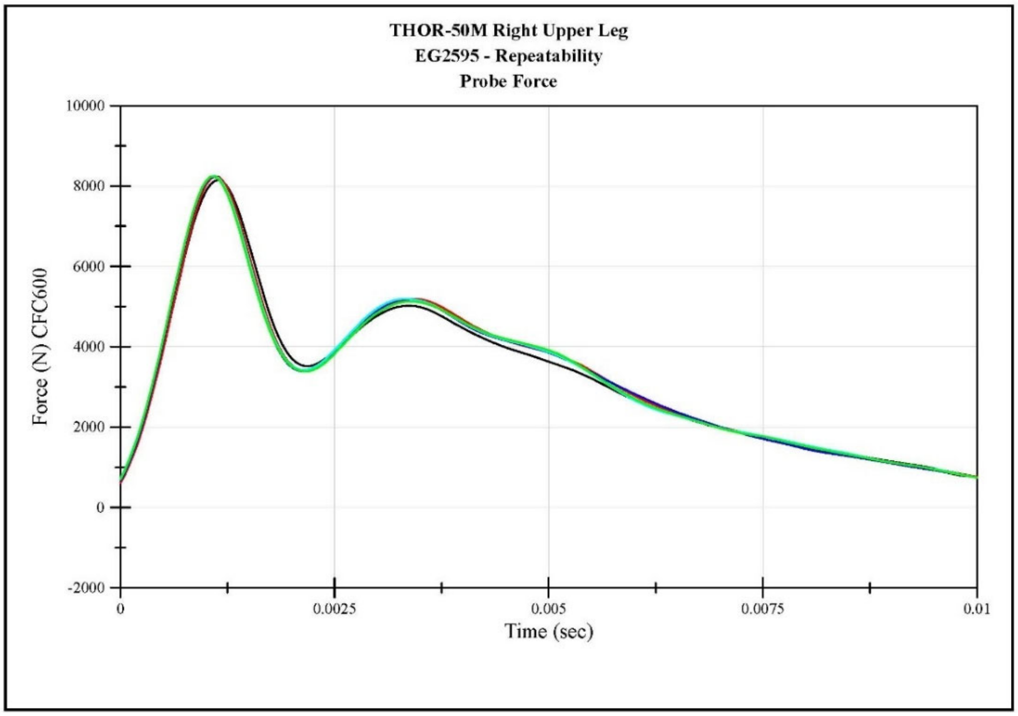

Figure 14-11. VRTC probe force for right upper leg impact repeatability tests for EG2595

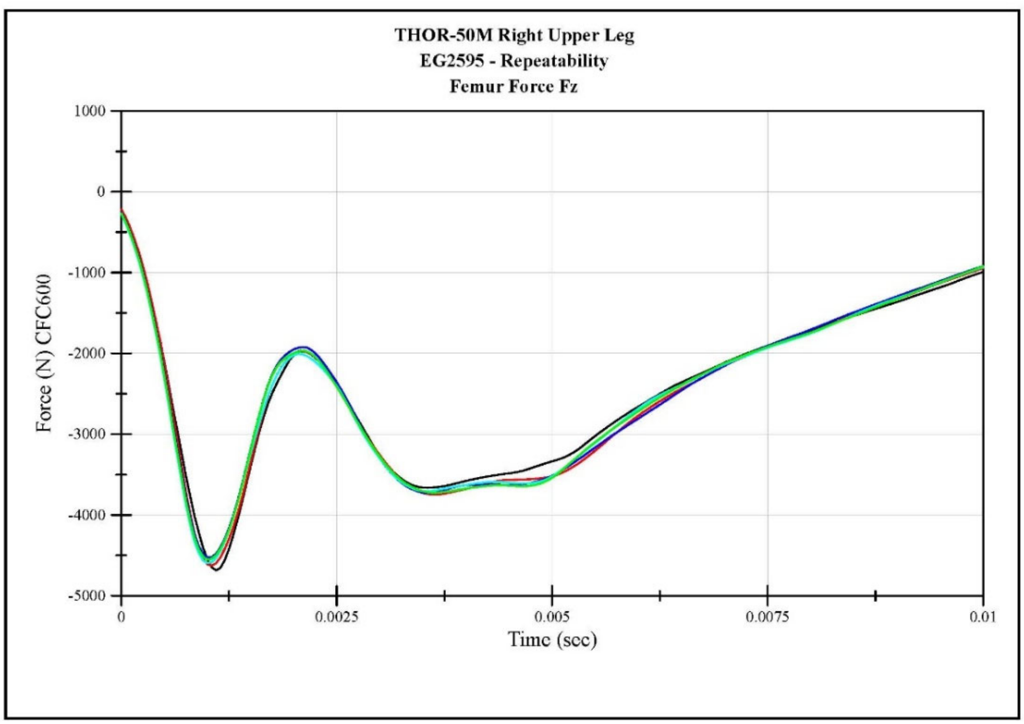

Figure 14-12. VRTC femur force Fz for right upper leg impact repeatability tests for EG2595

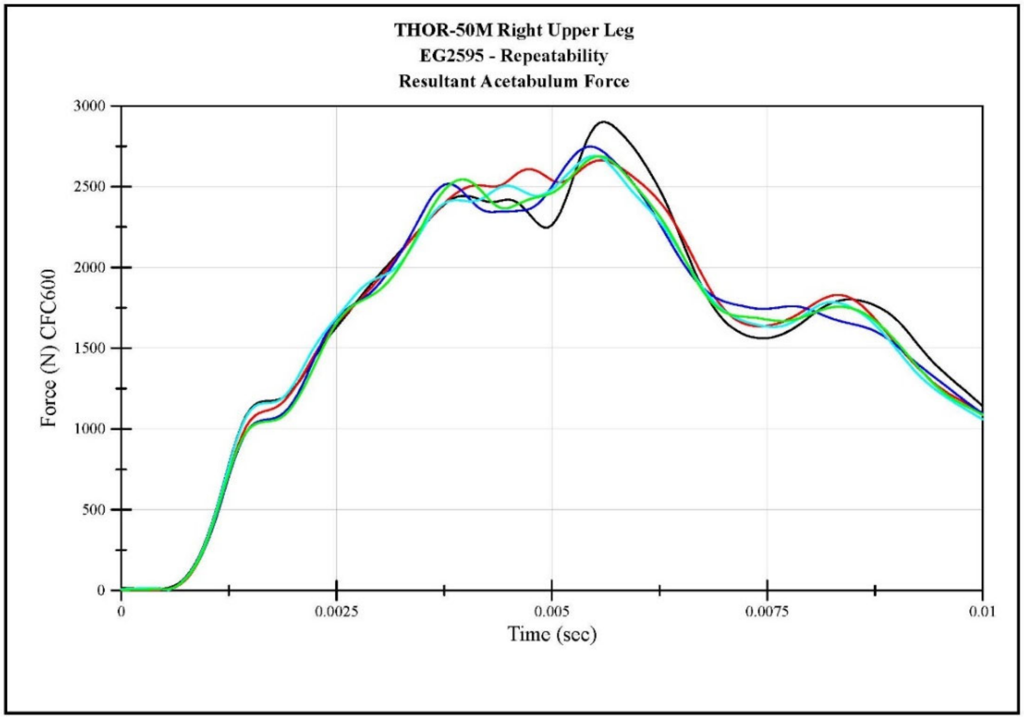

Figure 14-13. VRTC resultant acetabulum force for right upper leg impact repeatability tests for EG2595

14.2.5 THOR-50M DO9799 Left Upper Leg Testing at VRTC

Repeatability results at VRTC for the left upper leg of DO9799 yielded CV values all below 5 percent (Table 14-5, Figure 14-14 to Figure 14-16).

Table 14-5. VRTC THOR-50M DO9799 Left Upper Leg Repeatability Results

Test Number	Peak Probe Force (N)	Peak Femur Fz (N)	Peak Resultant Acetabulum Force (N)
200123-5	8651	-5028	2724
200123-6	8538	-4886	2643
200123-7	8565	-4907	2634
200123-8	8567	-4901	2653
200123-9	8558	-4909	2643
Mean	**8576**	**-4926**	**2659**
Std. Dev.	**44**	**58**	**37**
CV	**0.5%**	**1.2%**	**1.4%**

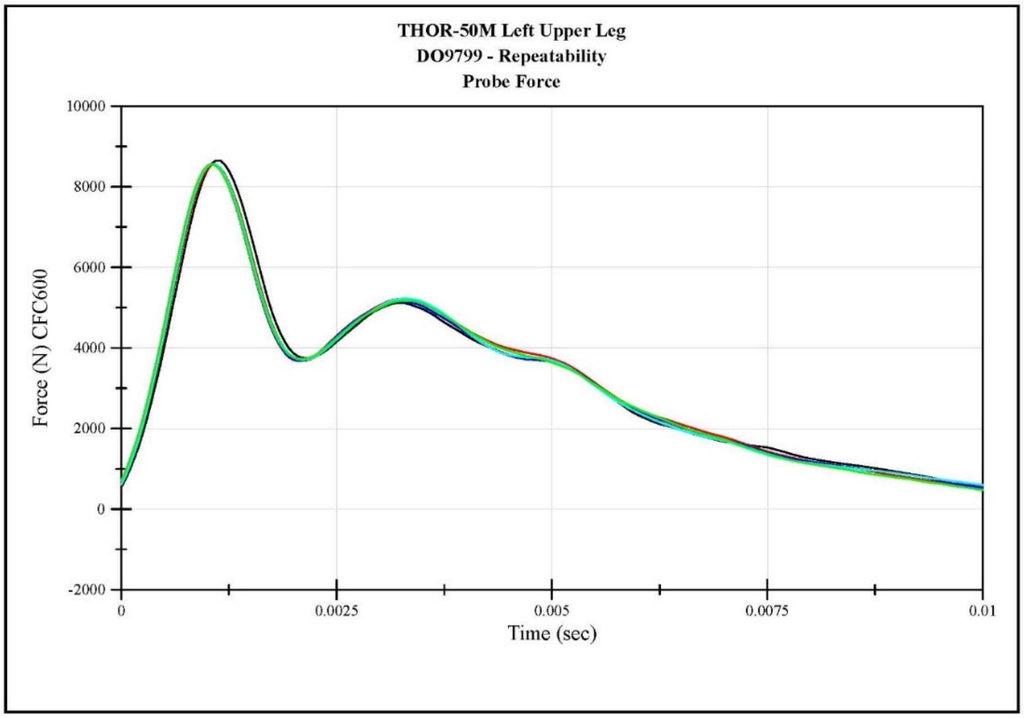

Figure 14-14. VRTC probe force for left upper leg impact repeatability tests for DO9799

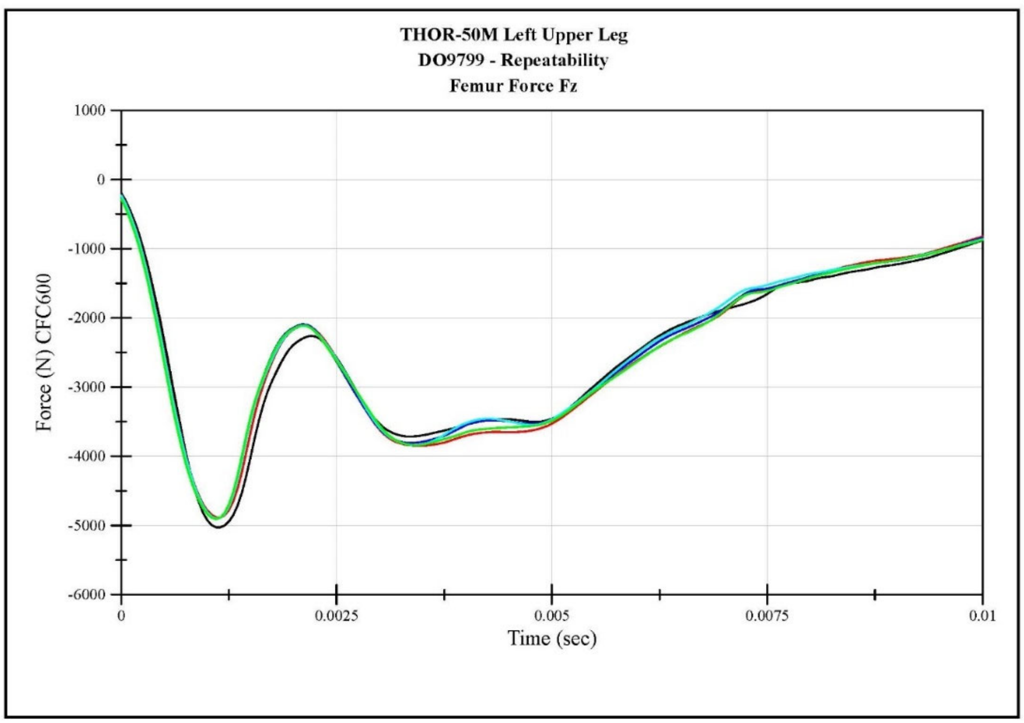

Figure 14-15. VRTC femur force Fz for left upper leg impact repeatability tests for DO9799

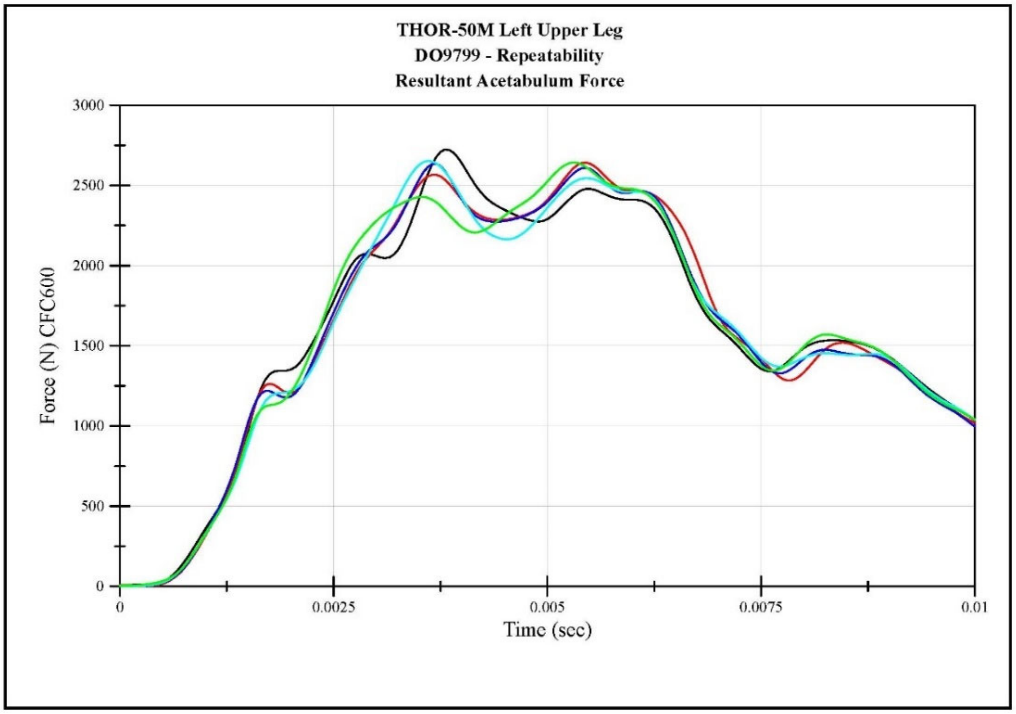

Figure 14-16. VRTC resultant acetabulum force for left upper leg impact repeatability tests for DO9799

14.2.6 THOR-50M DO9799 Right Upper Leg Testing at VRTC

Repeatability results at VRTC for the right upper leg of DO9799 yielded CV values all below 5 percent (Table 14-6, Figure 14-17 to Figure 14-19).

Table 14-6. VRTC THOR-50M D09799 Right Upper Leg Repeatability Results

Test Number	Peak Probe Force (N)	Peak Femur Fz (N)	Peak Resultant Acetabulum Force (N)
200128-3	8725	-5211	2470
200128-4	8725	-5151	2689
200128-5	8723	-5150	2447
200128-6	8631	-5098	2695
200128-7	8600	-5100	2629
Mean	**8681**	**-5142**	**2586**
Std. Dev.	**61**	**46**	**119**
CV	**0.7%**	**0.9%**	**4.6%**

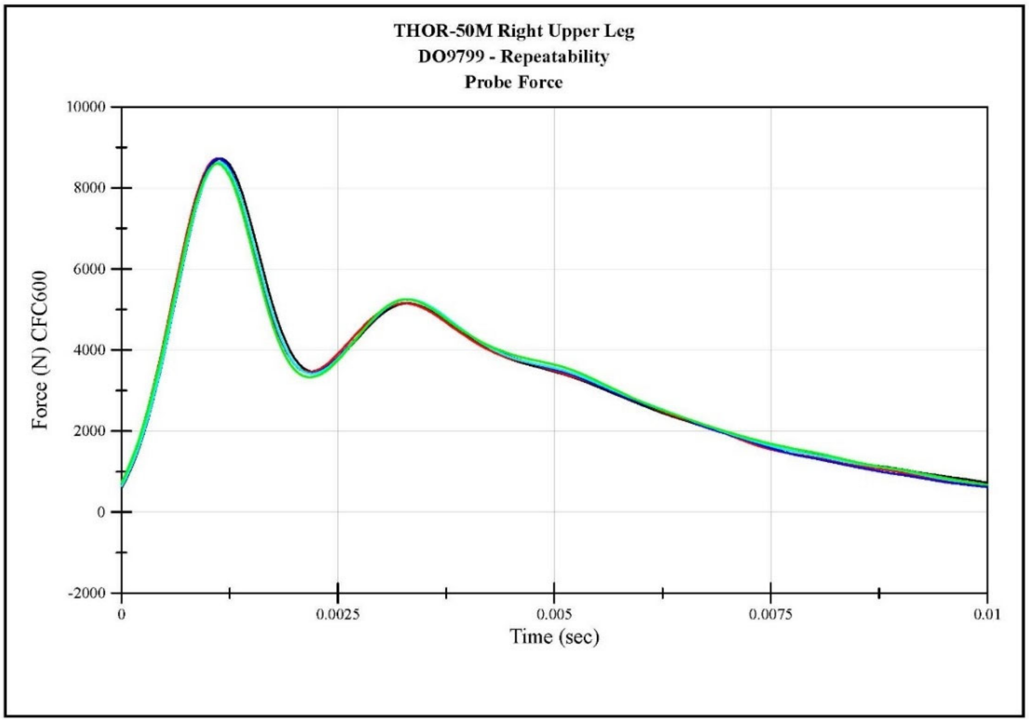

Figure 14-17. VRTC probe force for right upper leg impact repeatability tests for DO9799

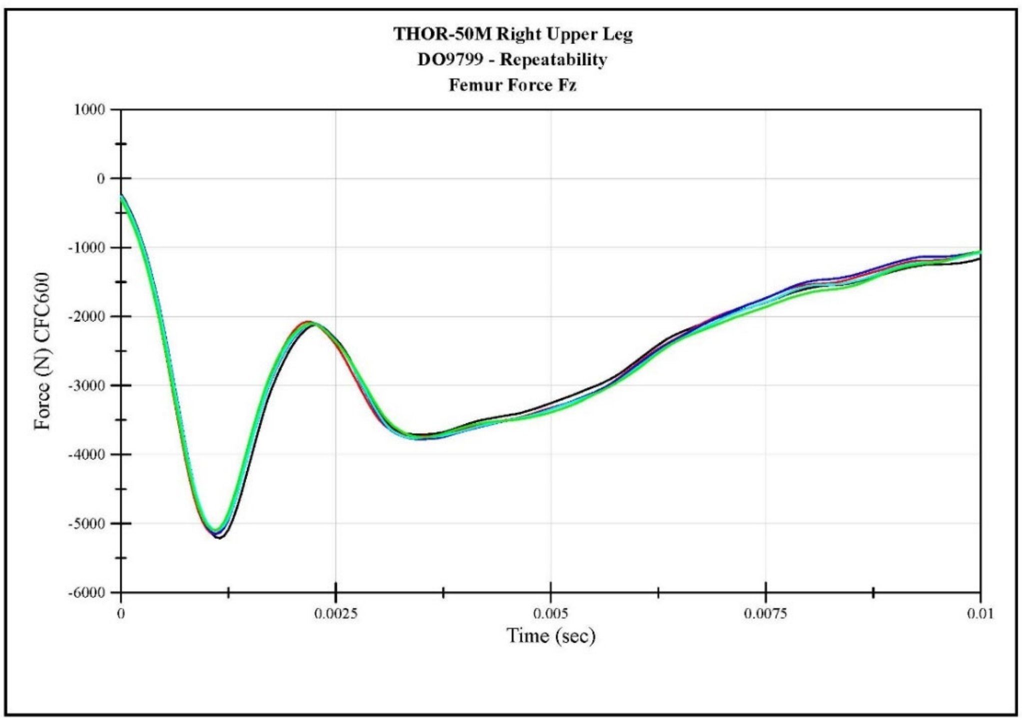

Figure 14-18. VRTC femur force Fz for right upper leg impact repeatability tests for DO9799

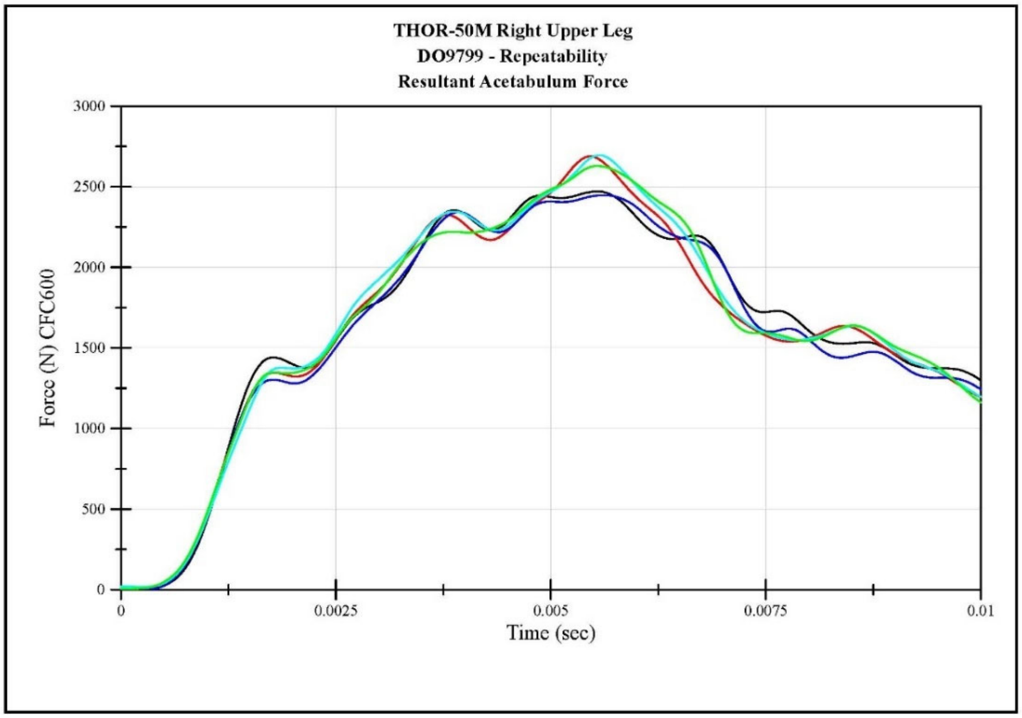

Figure 14-19. VRTC resultant acetabulum force for right upper leg impact repeatability tests for DO9799

14.2.7 THOR-50M DO9799 Left Upper Leg Testing at TRC

Repeatability results at TRC for the left upper leg of DO9799 yielded CV values all below 5 percent (Table 14-7, Figure 14-20 to Figure 14-22).

Table 14-7. TRC THOR-50M DO9799 Left Upper Leg Repeatability Results

Test Number	Peak Probe Force (N)	Peak Femur Fz (N)	Peak Resultant Acetabulum Force (N)
200715-03	7950	-4966	2973
200715-04	7971	-4809	2991
200715-05	7904	-4866	2816
200715-06	7815	-4847	2869
200715-07	7838	-4930	2899
Mean	**7895**	**-4884**	**2910**
Std. Dev.	**68**	**63**	**73**
CV	**0.9%**	**1.3%**	**2.5%**

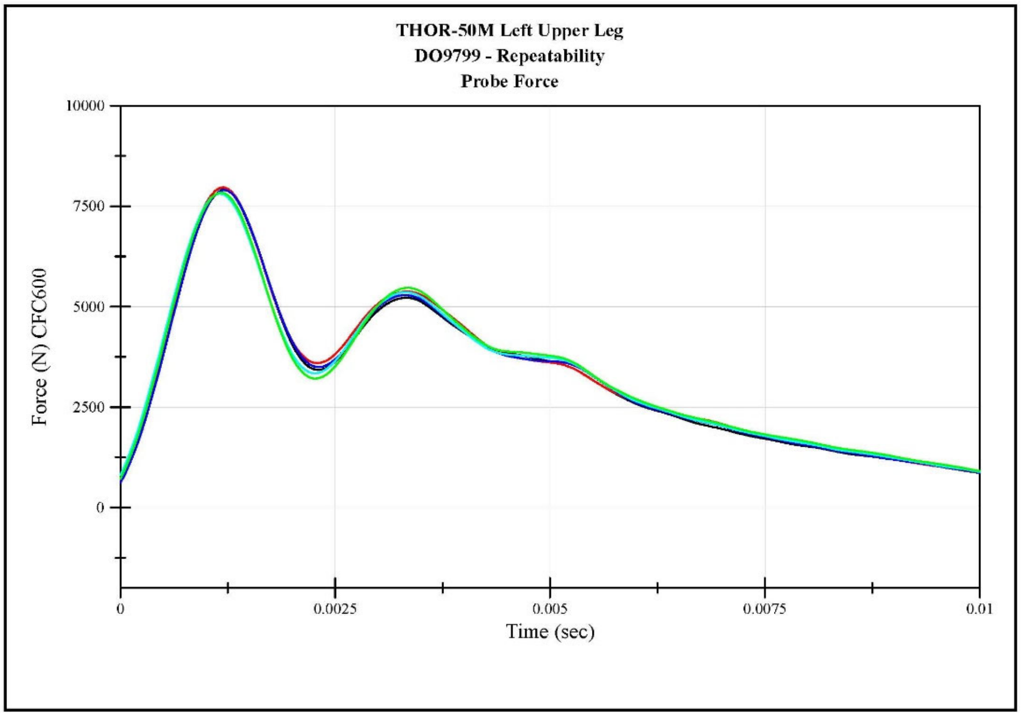

Figure 14-20. TRC probe force for left upper leg impact repeatability tests for DO9799

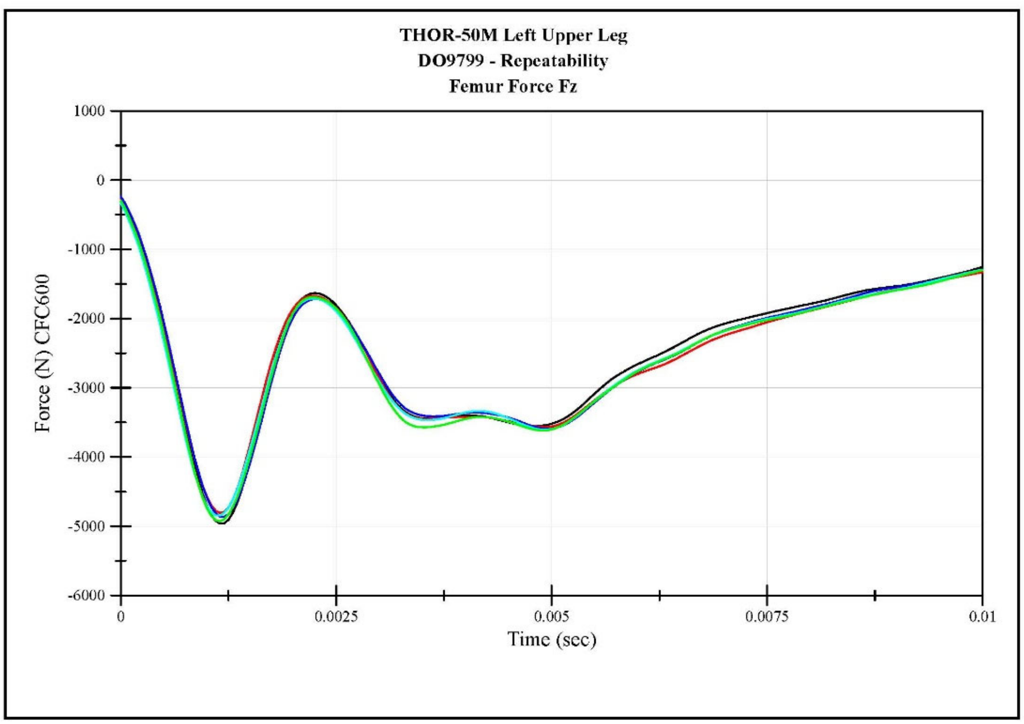

Figure 14-21. TRC femur force Fz for left upper leg impact repeatability tests for DO9799

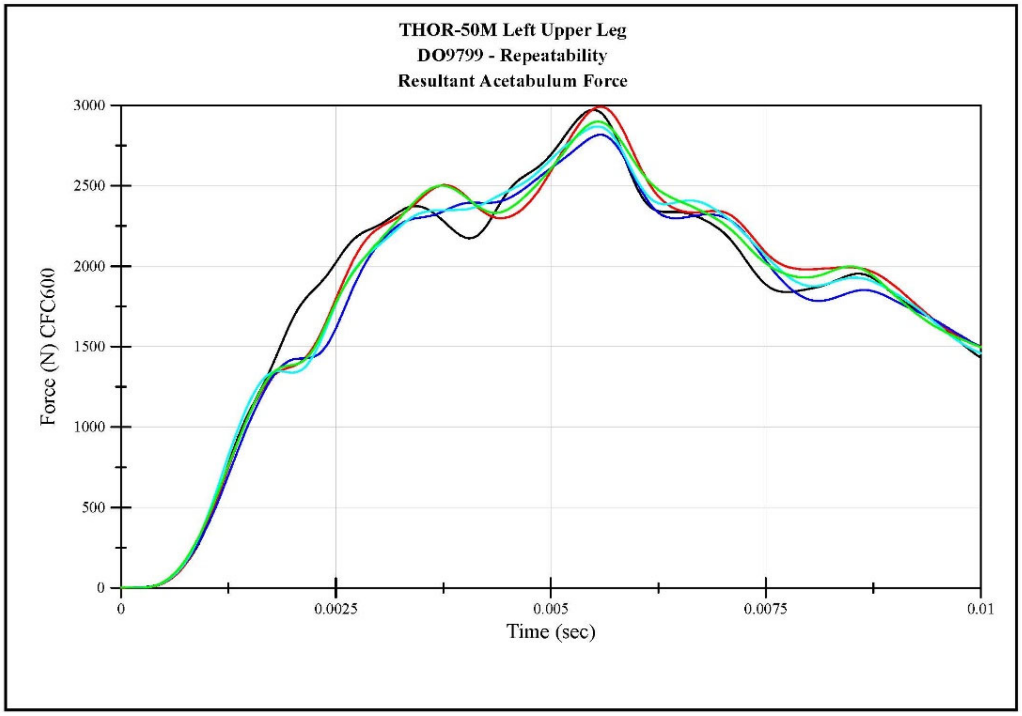

Figure 14-22. TRC resultant acetabulum force for left upper leg impact repeatability tests for DO9799

14.2.8 THOR-50M DO9799 Right Upper Leg Testing at TRC

Repeatability results at TRC for the right upper leg of DO9799 yielded CV values all below 5 percent (Table 14-8, Figure 14-23 to Figure 14-25).

Table 14-8. TRC THOR-50M D09799 Right Upper Leg Repeatability Results

Test Number	Peak Probe Force (N)	Peak Femur Fz (N)	Peak Resultant Acetabulum Force (N)
200715-06	8295	-4994	2754
200715-07	8365	-4942	2718
200715-08	8275	-4832	2697
200715-09	8278	-4850	2648
200715-10	8275	-4921	2673
Mean	**8298**	**-4908**	**2698**
Std. Dev.	**38**	**67**	**41**
CV	**0.5%**	**1.4%**	**1.5%**

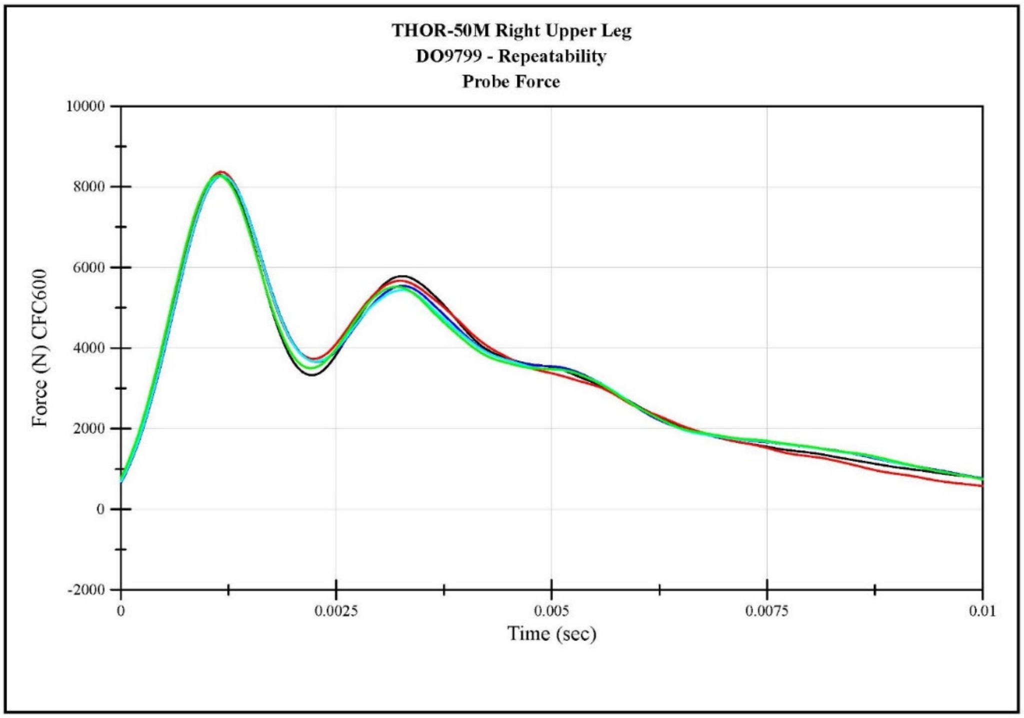

Figure 14-23. TRC probe force for right upper leg impact repeatability tests for DO9799

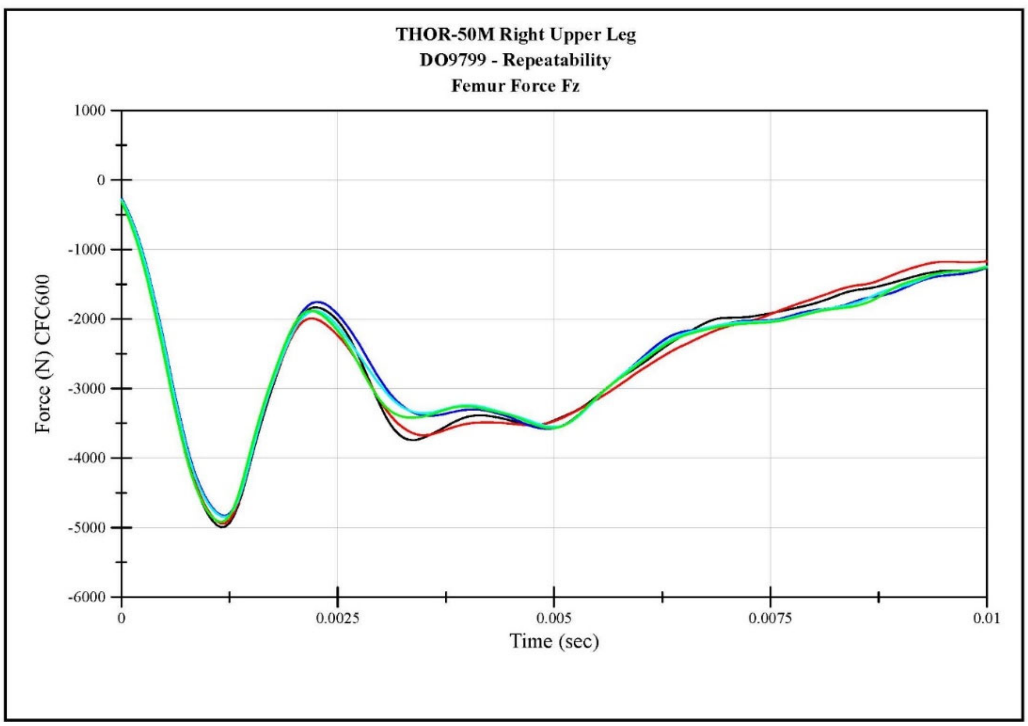

Figure 14-24. TRC femur force Fz for right upper leg impact repeatability tests for DO9799

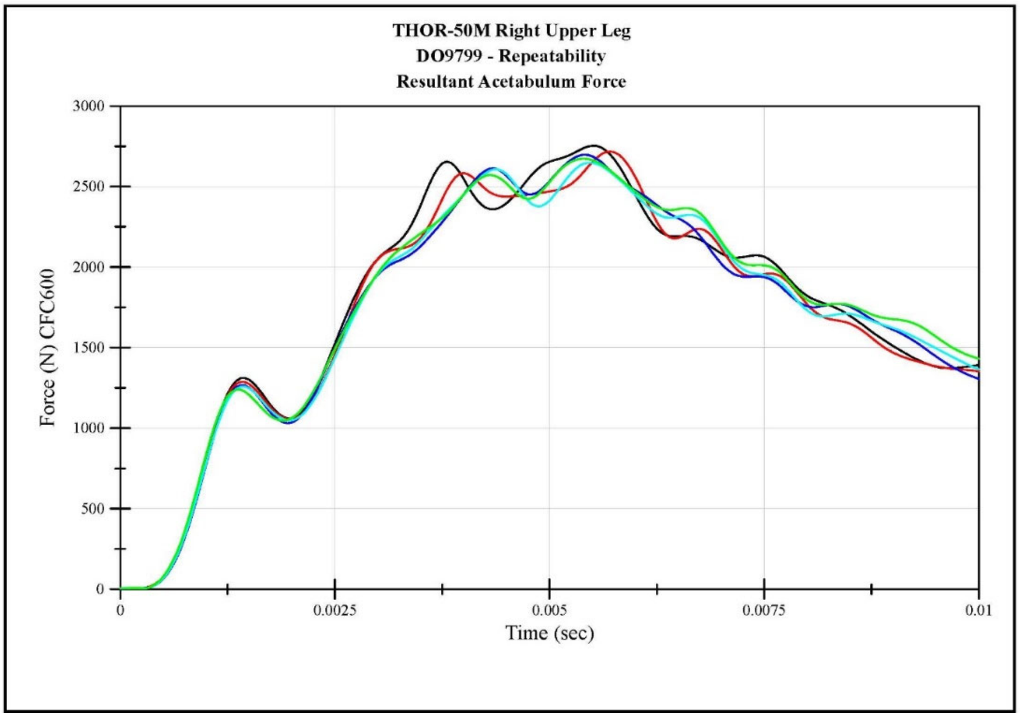

Figure 14-25. TRC resultant acetabulum force for right upper leg impact repeatability tests for DO9799

14.2.9 THOR-50M DO9799 Left Upper Leg Testing at Karco

Repeatability results at Karco for the left upper leg of DO9799 yielded CV values all below 5 percent (Table 14-9, Figure 14-26 to Figure 14-28).

Table 14-9. Karco THOR-50M DO9799 Left Upper Leg Repeatability Results

Test Number	Peak Probe Force (N)	Peak Femur Fz (N)	Peak Resultant Acetabulum Force (N)
2021-02-19 TH DO9799 Leg Left 001	8612	-5580	2941
2021-02-19 TH DO9799 Leg Left 002	8392	-5306	2911
2021-02-19 TH DO9799 Leg Left 003	8340	-5360	2926
2021-02-19 TH DO9799 Leg Left 004	8309	-5261	2838
Mean	**8413**	**-5377**	**2904**
Std. Dev.	**137**	**141**	**46**
CV	**1.6%**	**2.6%**	**1.6%**

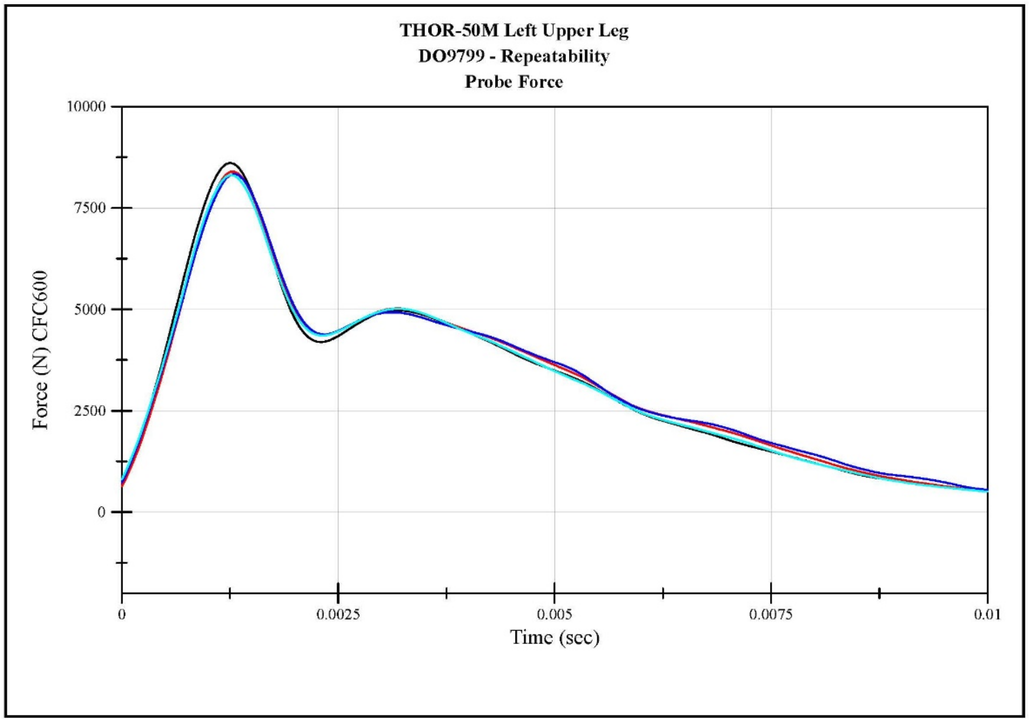

Figure 14-26. Karco probe force for left upper leg impact repeatability tests for DO9799

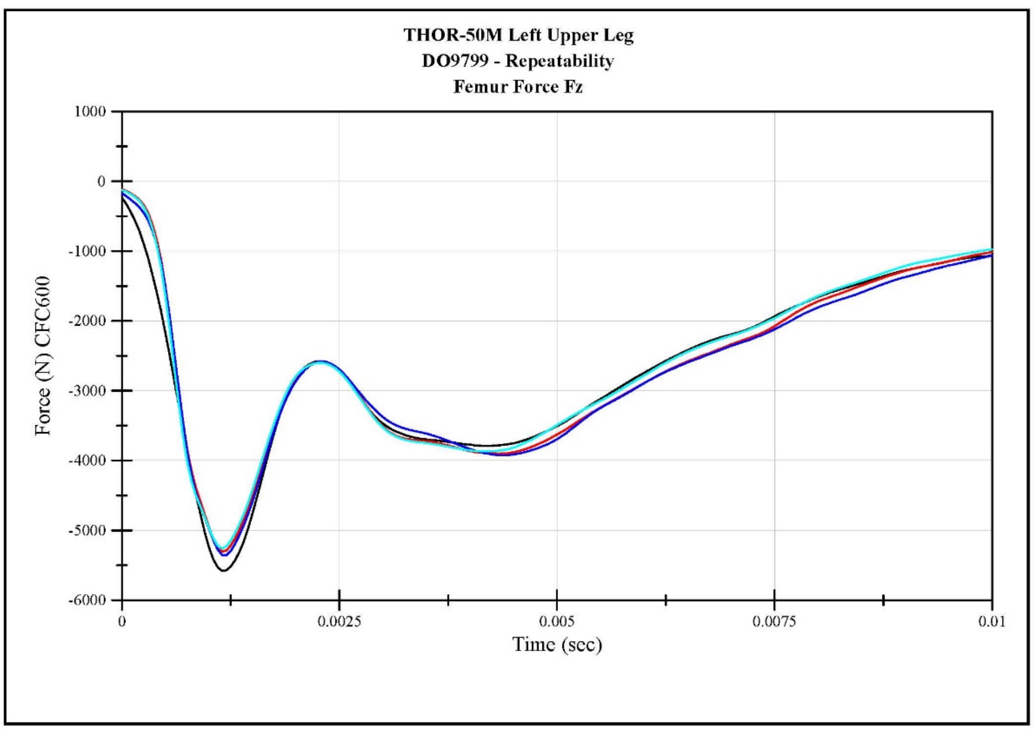

Figure 14-27. Karco femur force Fz for left upper leg impact repeatability tests for DO9799

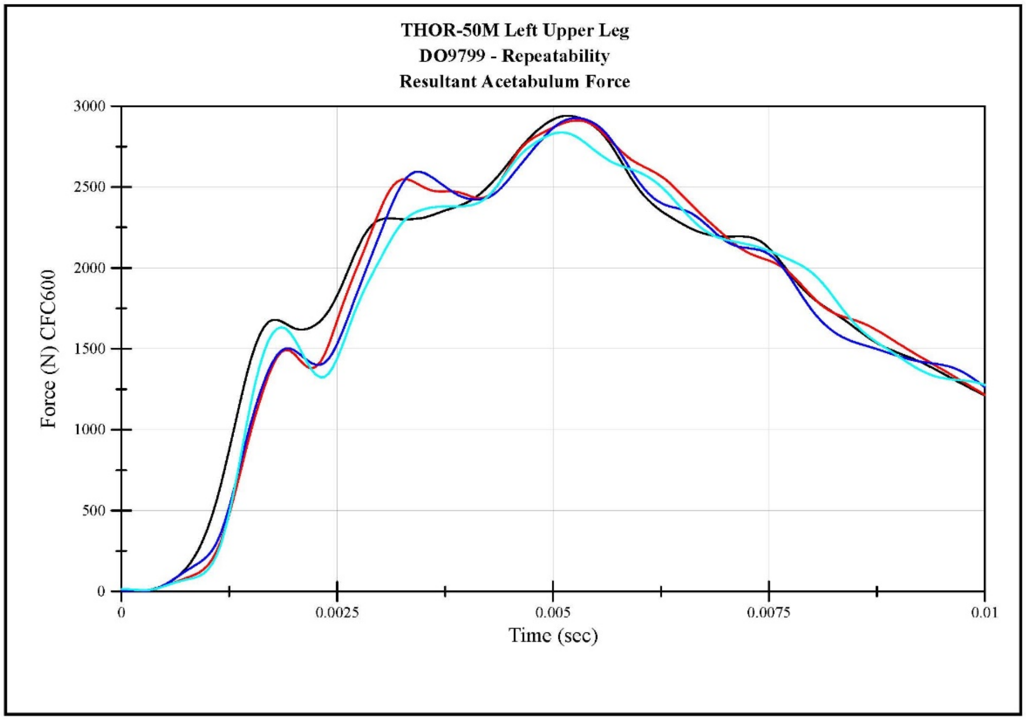

Figure 14-28. Karco resultant acetabulum force for left upper leg impact repeatability tests for DO9799

14.2.10 THOR-50M DO9799 Right Upper Leg Testing at Karco

Repeatability results at Karco for the right upper leg of DO9799 yielded CV values all below 5 percent (Table 14-10, Figure 14-29 to Figure 14-31).

Table 14-10. Karco THOR-50M D09799 Right Upper Leg Repeatability Results

Test Number	Peak Probe Force (N)	Peak Femur Fz (N)	Peak Resultant Acetabulum Force (N)
2021-02-18 TH DO9799 Leg Right 001	9073	-5279	2823
2021-02-18 TH DO9799 Leg Right 002	9013	-5174	2720
2021-02-18 TH DO9799 Leg Right 003	9011	-5248	2699
2021-02-18 TH DO9799 Leg Right 004	8973	-5269	2843
Mean	**9018**	**-5242**	**2771**
Std. Dev.	**41**	**47**	**72**
CV	**0.5%**	**0.9%**	**2.6%**

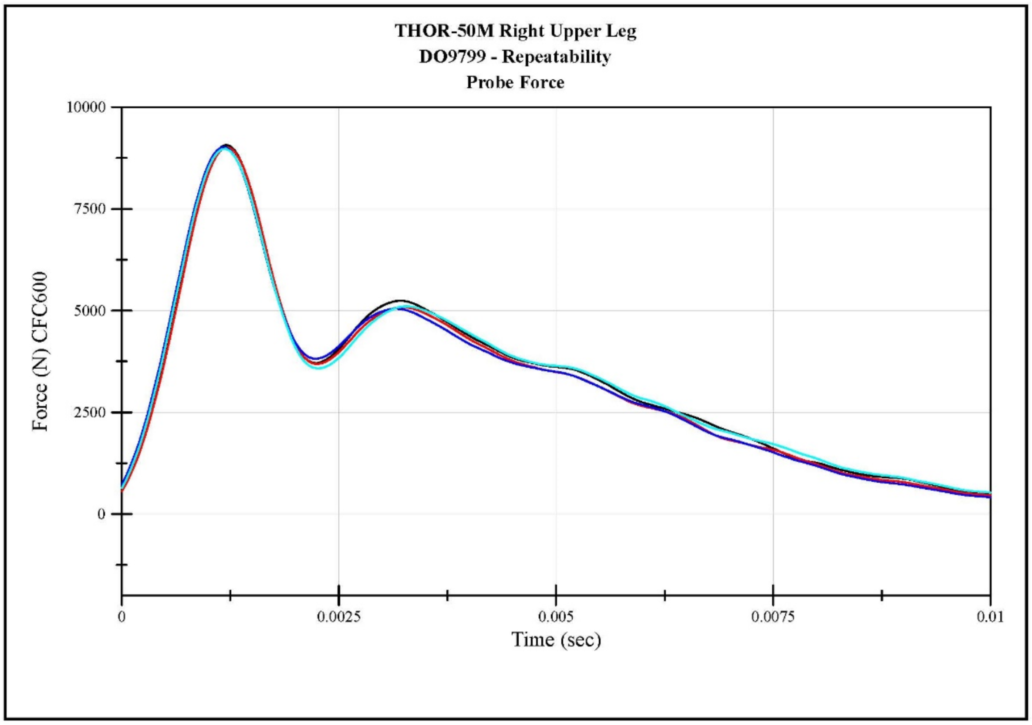

Figure 14-29. Karco probe force for right upper leg impact repeatability tests for DO9799

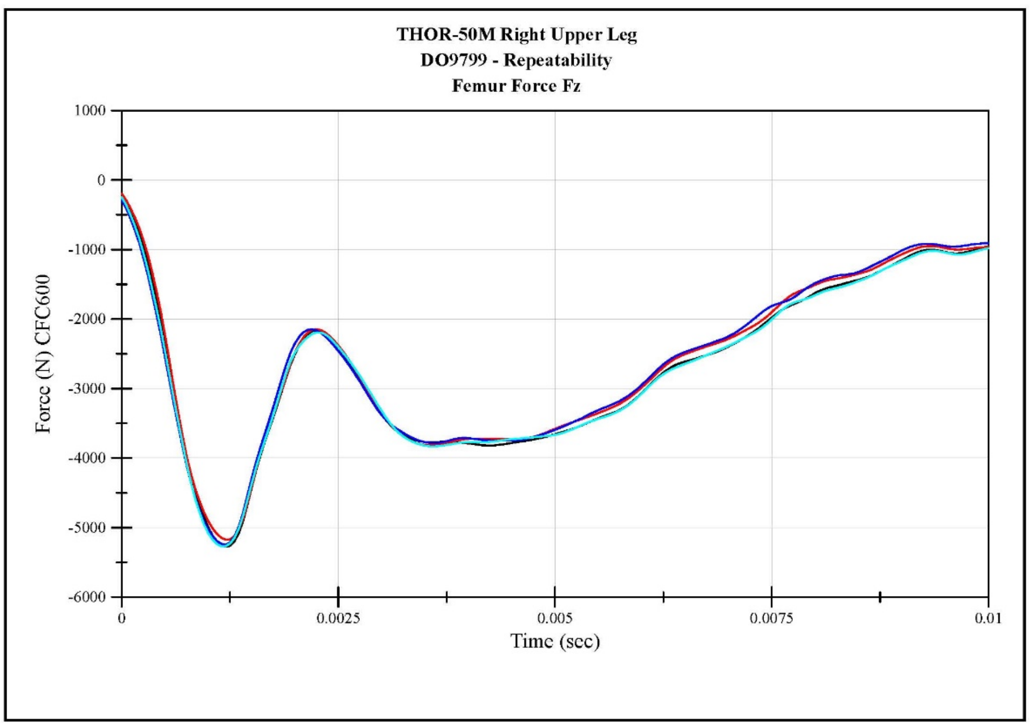

Figure 14-30. Karco femur force Fz for right upper leg impact repeatability tests for DO9799

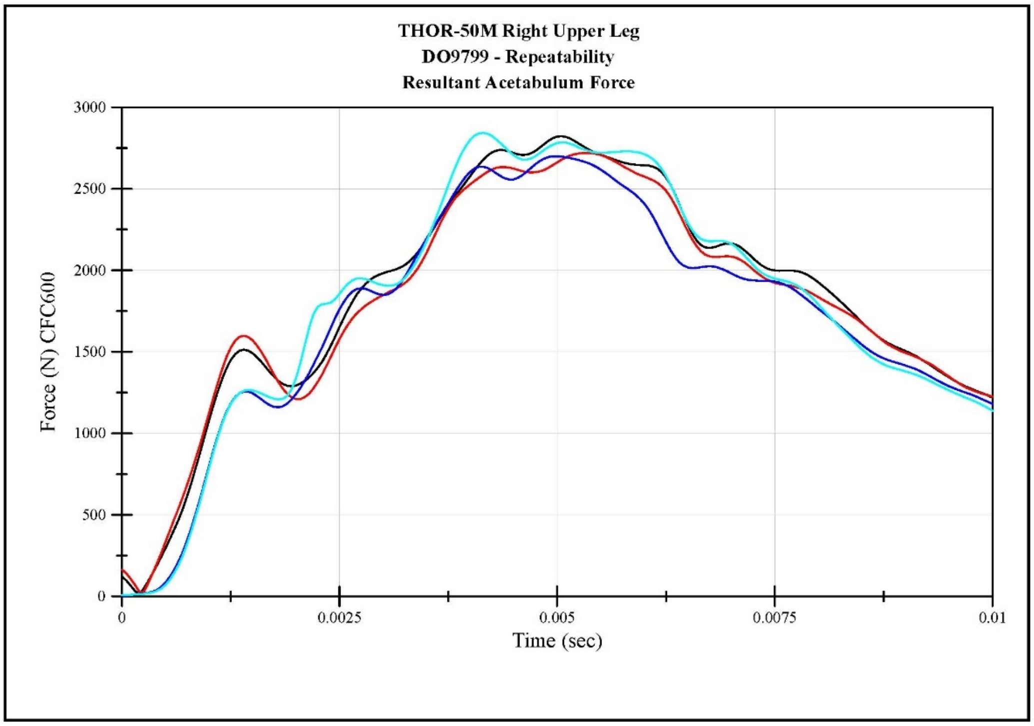

Figure 14-31. Karco resultant acetabulum force for right upper leg impact repeatability tests for DO9799

14.3 Upper Leg Dummy Reproducibility Results

Dummy Reproducibility results at VRTC displayed CVs below 5 percent for each of the measurements in the upper leg tests (Table 14-11).

Table 14-11. THOR-50M Upper Leg Dummy Reproducibility Results

Dummy Number	Test Number	Peak Probe Force (N)	Peak Femur Fz (N)	Peak Resultant Acetabulum Force (N)
VRTC DL9207 Left	**200716-15**	7856	-4525	2685
	200716-16	7727	-4524	2779
	200716-17	7630	-4563	2699
	200716-18	7625	-4516	2829
	200716-19	7718	-4531	2818
VRTC DL9207 Right	**200716-3**	7963	-4769	2836
	200716-6	7907	-4716	2770
	200716-7	7954	-4775	2713
	200716-9	7897	-4682	2542
	200716-10	8021	-4707	2567
VRTC EG2595 Left	**200206-3**	8680	-5098	2990
	200206-4	8742	-5027	2604
	200206-5	8680	-4990	2688
	200206-6	8725	-4988	2643
	200206-7	8759	-4974	2620
VRTC EG2595 Right	**200206-13**	8151	-4686	2902
	200206-14	8245	-4627	2663
	200206-15	8232	-4528	2748
	200210-1	8251	-4598	2691
	200210-2	8242	-4554	2688

Dummy Number	Test Number	Peak Probe Force (N)	Peak Femur Fz (N)	Peak Resultant Acetabulum Force (N)
VRTC DO9799 Left	**200123-5**	8651	-5028	2724
	200123-6	8538	-4886	2643
	200123-7	8565	-4907	2634
	200123-8	8567	-4901	2653
	200123-9	8558	-4909	2643
VRTC DO9799 Right	**200128-3**	8725	-5211	2470
	200128-4	8725	-5151	2689
	200128-5	8723	-5150	2447
	200128-6	8631	-5098	2695
	200128-7	8600	-5100	2629
Mean		**8310**	**-4824**	**2690**
Std. Dev.		**391**	**229**	**115**
CV		**4.7%**	**4.7%**	**4.3%**

14.4 Lab-to-Lab Variability Analysis

The results for the upper leg qualification tests from each lab are presented in Table 14-12 and Table 14-13.

The last four rows of each table show the *Test Reproducibility* results when data from all three labs are combined. Following the same trend as the within lab repeatability results, the *Test Reproducibility* for all forces displayed CVs below 5 percent for both the right and left legs.

Table 14-12. THOR-50M Left Upper Leg Lab-to-Lab Variability Results

Dummy Number	Peak Probe Force (N)	Peak Femur Fz (N)	Peak Resultant Acetabulum Force (N)
VRTC DO9799 Left	8651	-5028	2724
	8538	-4886	2643
	8565	-4907	2634
	8567	-4901	2653
	8558	-4909	2643
TRC DO9799 Left	7950	-4966	2973
	7971	-4809	2991
	7904	-4866	2816
	7815	-4847	2869
	7838	-4930	2899
Karco DO9799 Left	8612	-5580	2941
	8392	-5306	2911
	8340	-5360	2926
	8309	-5261	2838
Test Reproducibility DO9799 Left			
Mean	**8286**	**-5040**	**2819**
Std. Dev.	**320**	**237**	**133**
CV	**3.9%**	**4.7%**	**4.7%**

Table 14-13. THOR-50M Right Upper Leg Lab-to-Lab Variability Results

Dummy Number	Peak Probe Force (N)	Peak Femur Fz (N)	Peak Resultant Acetabulum Force (N)
VRTC DO9799 Right	8725	-5211	2470
	8725	-5151	2689
	8723	-5150	2447
	8631	-5098	2695
	8600	-5100	2629
TRC DO9799 Right	8295	-4994	2754
	8365	-4942	2718
	8275	-4832	2697
	8278	-4850	2648
	8275	-4921	2673
Karco DO9799 Right	9073	-5279	2823
	9013	-5174	2720
	9011	-5248	2699
	8973	-5269	2843
Test Reproducibility DO9799 Right			
Mean	**8640**	**-5087**	**2679**
Std. Dev.	**303**	**153**	**110**
CV	**3.5%**	**3.0%**	**4.1%**

14.5 Corridor Development

All the data used to determine the upper leg qualification corridors is shown in Table 14-14. The qualification corridors were calculated using the mean plus or minus 10 percent of the peak for the specified measured or calculated channels (Table 14-15).

Table 14-14. THOR-50M Upper Leg Qualification Corridor Results

Dummy Number	Test Number	Peak Probe Force (N)	Peak Femur Fz (N)	Peak Resultant Acetabulum Force (N)
VRTC DL9207 Left	**200716-15**	7856	-4525	2685
	200716-16	7727	-4524	2779
	200716-17	7630	-4563	2699
	200716-18	7625	-4516	2829
	200716-19	7718	-4531	2818
VRTC DL9207 Right	**200716-3**	7963	-4769	2836
	200716-6	7907	-4716	2770
	200716-7	7954	-4775	2713
	200716-9	7897	-4682	2542
	200716-10	8021	-4707	2567
VRTC EG2595 Left	**200206-3**	8680	-5098	2990
	200206-4	8742	-5027	2604
	200206-5	8680	-4990	2688
	200206-6	8725	-4988	2643
	200206-7	8759	-4974	2620
VRTC EG2595 Right	**200206-13**	8151	-4686	2902
	200206-14	8245	-4627	2663
	200206-15	8232	-4528	2748
	200210-1	8251	-4598	2691
	200210-2	8242	-4554	2688
VRTC DO9799 Left	**200123-5**	8651	-5028	2724
	200123-6	8538	-4886	2643
	200123-7	8565	-4907	2634
	200123-8	8567	-4901	2653
	200123-9	8558	-4909	2643
VRTC DO9799 Right	**200128-3**	8725	-5211	2470
	200128-4	8725	-5151	2689
	200128-5	8723	-5150	2447
	200128-6	8631	-5098	2695
	200128-7	8600	-5100	2629
TRC DO9799 Left	**200715-03**	7950	-4966	2973
	200715-04	7971	-4809	2991
	200715-05	7904	-4866	2816
	200715-06	7815	-4847	2869
	200715-07	7838	-4930	2899
TRC DO9799 Right	**200715-06**	8295	-4994	2754
	200715-07	8365	-4942	2718
	200715-08	8275	-4832	2697
	200715-09	8278	-4850	2648
	200715-10	8275	-4921	2673
Karco DO9799 Left	**2021-02-19 TH DO9799 Leg Left 001**	8613	-5580	2941
	2021-02-19 TH DO9799 Leg Left 002	8393	-5306	2911
	2021-02-19 TH DO9799 Leg Left 003	8341	-5360	2926
	2021-02-19 TH DO9799 Leg Left 004	8311	-5261	2838
Karco DO9799 Right	**2021-02-18 TH DO9799 Leg Right 001**	9075	-5279	2823
	2021-02-18 TH DO9799 Leg Right 002	9015	-5174	2720
	2021-02-18 TH DO9799 Leg Right 003	9013	-5248	2699
	2021-02-18 TH DO9799 Leg Right 004	8975	-5269	2843
Mean		**8333**	**-4920**	**2738**
Std. Dev.		**397**	**259**	**128**
CV		**4.8%**	**5.3%**	**4.7%**

Table 14-15. Upper Leg Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Impact Velocity	**m/s**	3.25	3.35	3.30	
Peak Probe Force	**N**	7500	9166	8333	10%
Peak Femur Fz	**N**	-5412	-4428	-4920	10%
Peak Resultant Acetabulum Force	**N**	2464	3012	2738	10%

Discussion. There was only one test that was outside the ± 10 percent intervals (highlighted with yellow in Table 14-14). The test occurred at Karco, due to high femur Z force on the DO9799 left leg in the first test of the series; femur Z forces on the right leg tests at Karco were all within specifications. Most of the variability is related to *Test Reproducibility*. This can be seen most clearly in Table 14-12 by examining the femur force levels for the left leg of DO9799. At each lab, the femur responses were very uniform in repeat tests (CVs below 2.6% at all three labs). However, when the results from all three labs are combined for this leg, the CV becomes 4.7%.

Thus, it appears that the unusual femur force result on 9799-L at Karco may have been caused by a test set-up or assembly issue. Though the set-up may have been consistent for the five tests on 9799-L, it may not have been consistent with the set-ups at other labs or with the setups on the other legs tested at VRTC.

Variability due to *Dummy Reproducibility* does not appear to be a factor, since the CVs for *Dummy Reproducibility* were below 5 percent for all forces, including femur force (Table 14-11). As in the knee qualification tests, six different femurs were used in this assessment (rather than three different units in other qualification tests). Thus, variability due to *Dummy Reproducibility* does not appear to be much of a factor in attaining the target response margin of ± 10 percent since uniformity in six femurs (rather than just three) has been demonstrated.

The test equipment and set-up may have contributed to the variability. Thus, the variability seen in the femur load appears to be an artifact of the test conditions, and not related to *Dummy Repeatability* or *Dummy Reproducibility*. In the future, test labs may need to experiment with set-ups and dummy positioning (within allowable tolerances) in order to better achieve the target response. Our tests appear to indicate that labs can attain a desired response characteristic by following a careful set-up protocol. Within each series of tests at each lab, the femur force time-histories of the tests are uniform. The fact that they are they are not as consistent from lab to lab (*Test Reproducibility*) may be attributable to a lack of experimental knowledge. In the future, labs may be able to improve this inconsistency. In other words, if a lab is able to produce a repeatable (and targeted) response on one leg, the lab should be able to do the same for all legs.

15 Ankle Inversion

15.1 Methodology

Repeatability and reproducibility tests were performed using the ankle inversion qualification procedures described in the *THOR-50M Qualification Procedures Manual*. The ankle inversion qualification consists of impact to a padded inversion/eversion bracket (drawing #TLX-9000-015) which is temporarily attached to the bottom of the ankle assembly (Figure 15-1). The impact surface of the bracket is covered with Ensolite padding to reduce noise transmission through the bracket into the ankle and load cell. The 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 test utilizes the NHTSA Dynamic Impactor (TLX-9000-013), as described in the *THOR-50M Drawing Package,* with an effective mass of 5.00 ± 0.02 kg. 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 pendulum impacts the inversion bracket at a velocity of 2.00 ± 0.05 m/s. During these tests, the lower tibia Z-axis force (Fz) and X-axis rotation were measured; the ankle resistive moment about the X-axis was calculated from the Y-axis force (Fy) and X-axis moment (Mx).

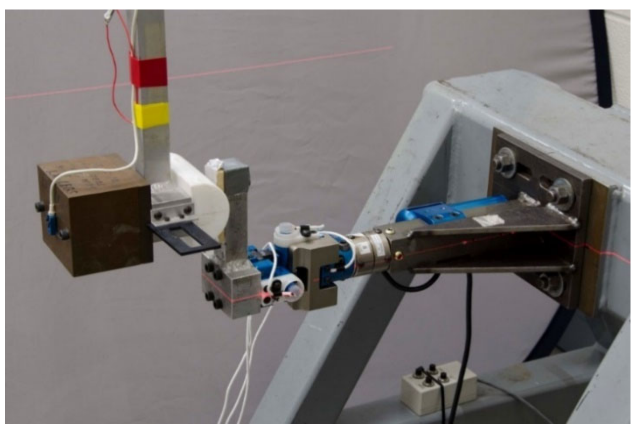

Figure 15-1. Ankle Inversion Test

15.2 Ankle Inversion Repeatability Results

Sections 15.2.1 to 15.2.7 illustrate the results of the ankle inversion repeatability tests. Each section contains a table providing the test data, followed by plot overlays of the five repeat tests conducted at all three labs. Only three legs were tested (two left and one right) in this series, rather than three legs from each side. Note that the data in the tables containing the results of each test series are listed sequentially, with the test at the top of the table beginning the test series.

15.2.1 THOR-50M Left Lower Leg DL0202 Testing at VRTC

Repeatability results at VRTC for leg DL0202 yielded CV values all below 5 percent (Table 15-1, Figure 15-2 to Figure 15-4).

Table 15-1. VRTC THOR-50M DL0202 Left Ankle Inversion Repeatability Results

Test Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle X-axis Rotation (deg)
160518-23	-466	-35.9	-33.5
160519-1	-495	-38.4	-34.2
160519-2	-502	-38.9	-34.5
160519-3	-499	-38.7	-34.5
160519-4	-499	-38.8	-34.5
Mean	**-492**	**-38.1**	**-34.2**
Std. Dev.	**15**	**1.3**	**0.4**
CV	**3.0%**	**3.3%**	**1.2%**

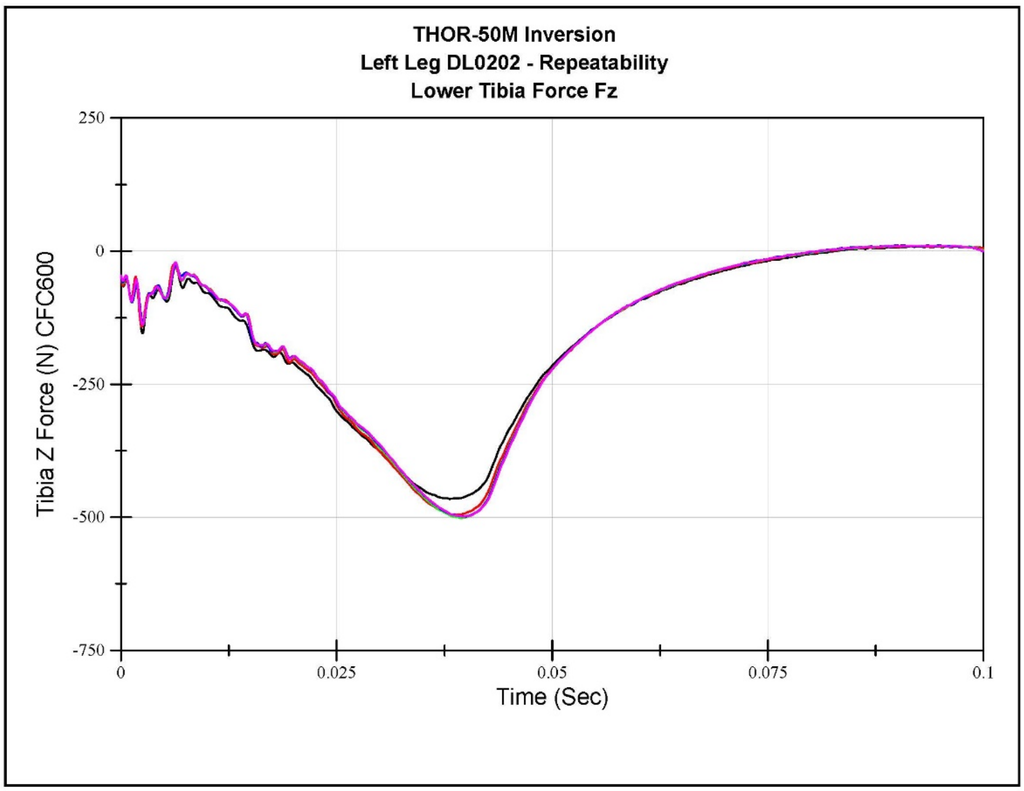

Figure 15-2. VRTC ankle inversion lower tibia Z-force repeatability for DL0202

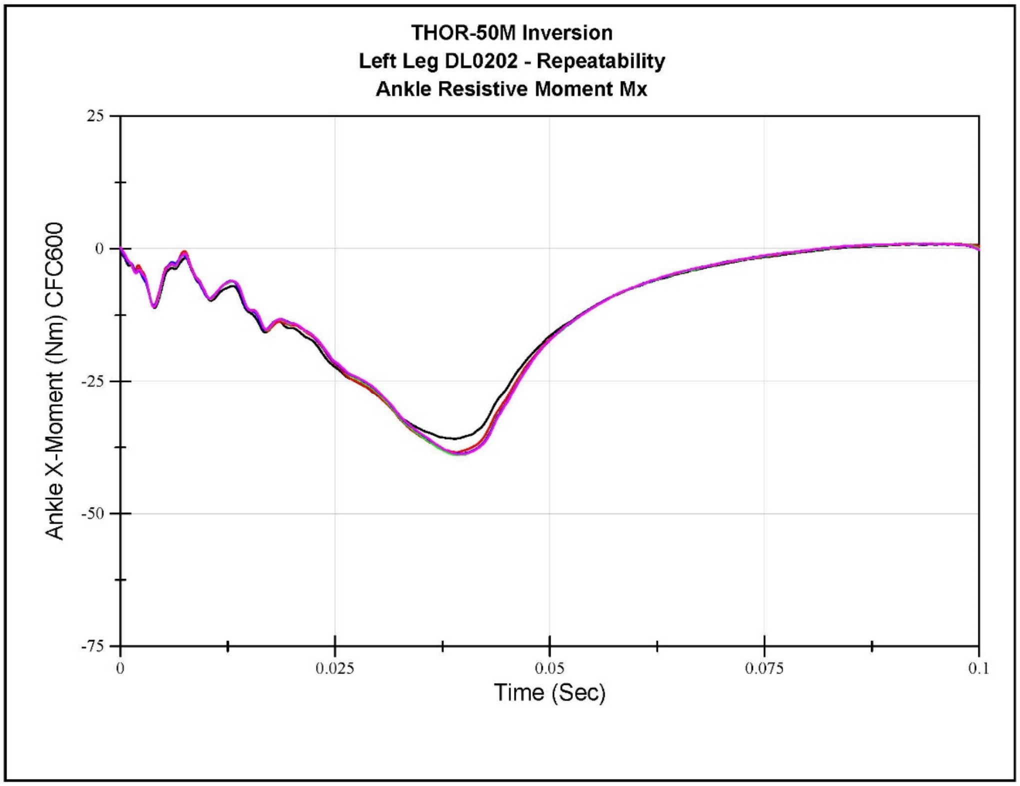

Figure 15-3. VRTC ankle inversion resistive X-moment repeatability for DL0202

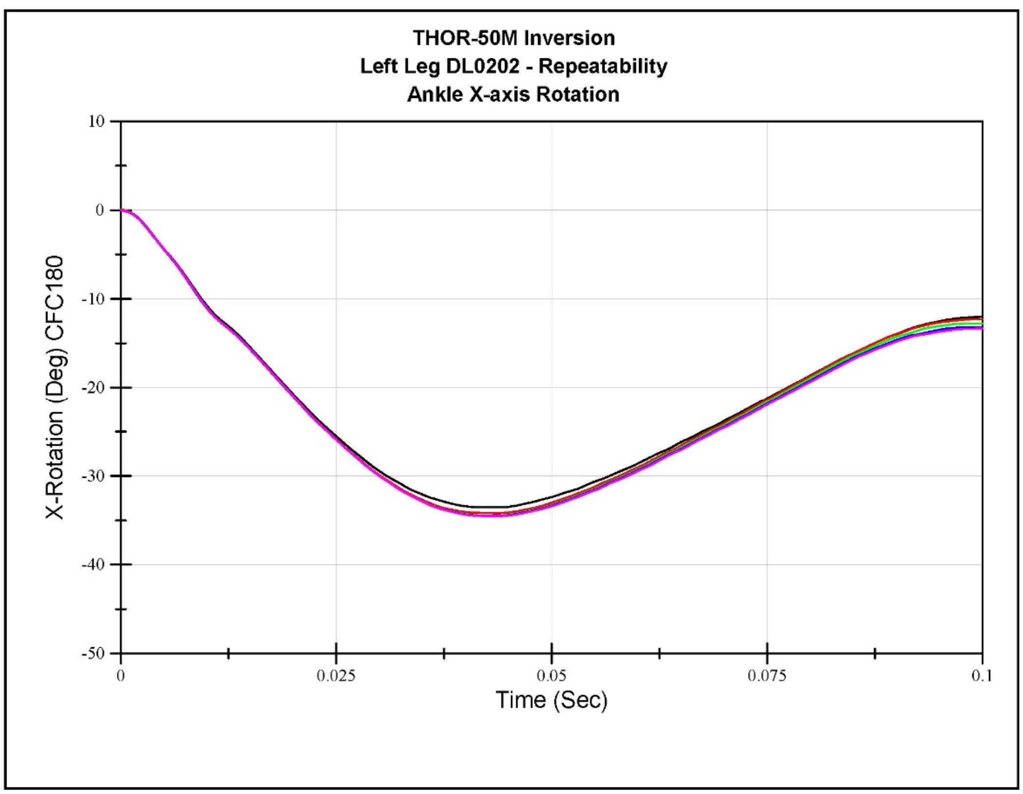

Figure 15-4. VRTC ankle inversion X-axis rotation repeatability for DL0202

15.2.2 THOR-50M Right Lower Leg DL5404 Testing at VRTC

Repeatability results at VRTC for leg DL5404 yielded CV values all below 5 percent (Table 15-2, Figure 15-5 to Figure 15-7).

Table 15-2. VRTC THOR-50M DL5404 Right Ankle Inversion Repeatability Results

Test Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle X-axis Rotation (deg)
160516-17	-451	35.9	33.9
160516-19	-481	38.6	34.5
160517-2	-493	39.7	34.8
160517-3	-503	40.4	35.0
160517-5	-492	39.6	34.9
Mean	**-484**	**38.8**	**34.6**
Std. Dev.	**20**	**1.8**	**0.4**
CV	**4.1%**	**4.6%**	**1.3%**

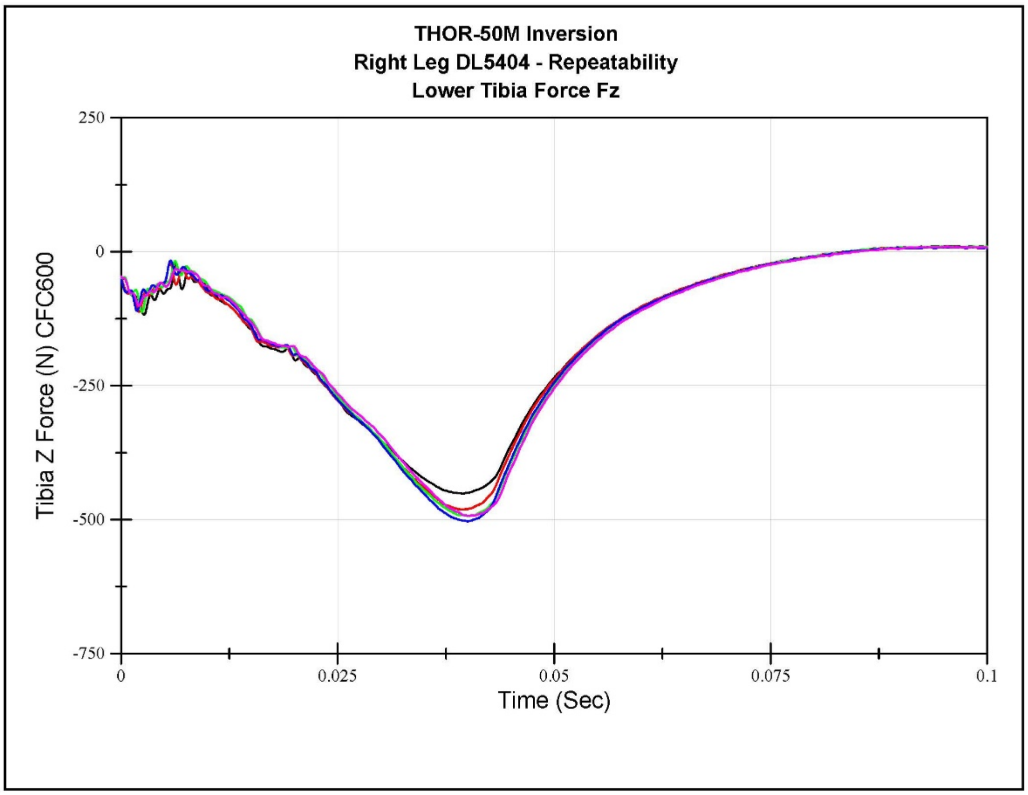

Figure 15-5. VRTC ankle inversion lower tibia Z-force repeatability for DL5404

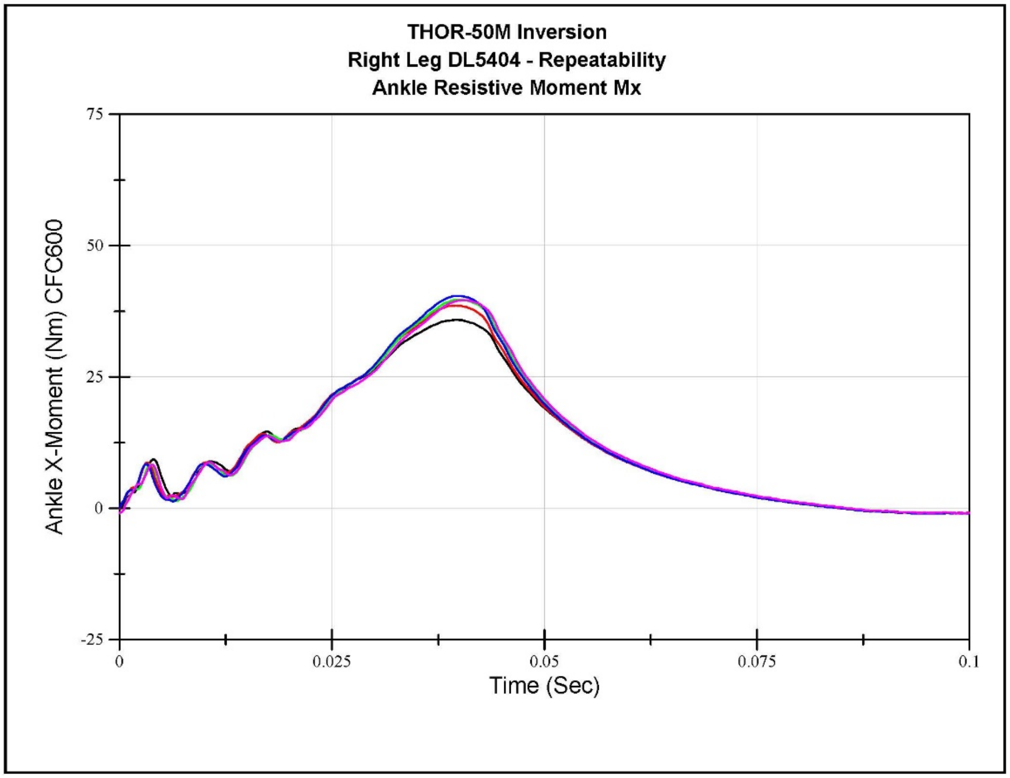

Figure 15-6. VRTC ankle inversion resistive X-moment repeatability for DL5404

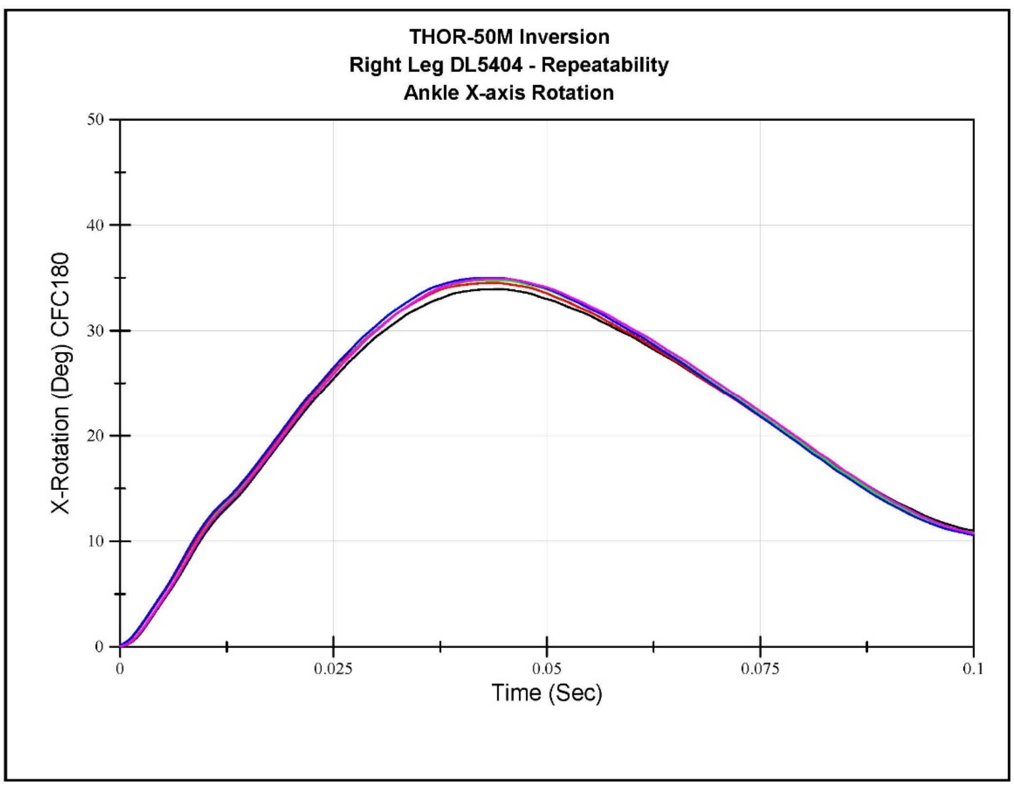

Figure 15-7. VRTC ankle inversion X-axis rotation repeatability for DL5404

15.2.3 THOR-50M Left Lower Leg 069 Testing at VRTC

Repeatability results at VRTC for leg 069 yielded CV values all below 5 percent (Table 15-3, Figure 15-8 to Figure 15-10).

Table 15-3. VRTC THOR-50M 069 Left Ankle Inversion Repeatability Results

Test Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle X-axis Rotation (deg)
160426-7	-461	-33.3	-33.0
160426-8	-503	-36.7	-34.4
160426-9	-507	-37.3	-34.7
160426-10	-506	-37.3	-34.9
160426-12	-507	-37.4	-35.1
Mean	**-497**	**-36.4**	**-34.4**
Std. Dev.	**20**	**1.7**	**0.8**
CV	**4.1%**	**4.8%**	**2.4%**

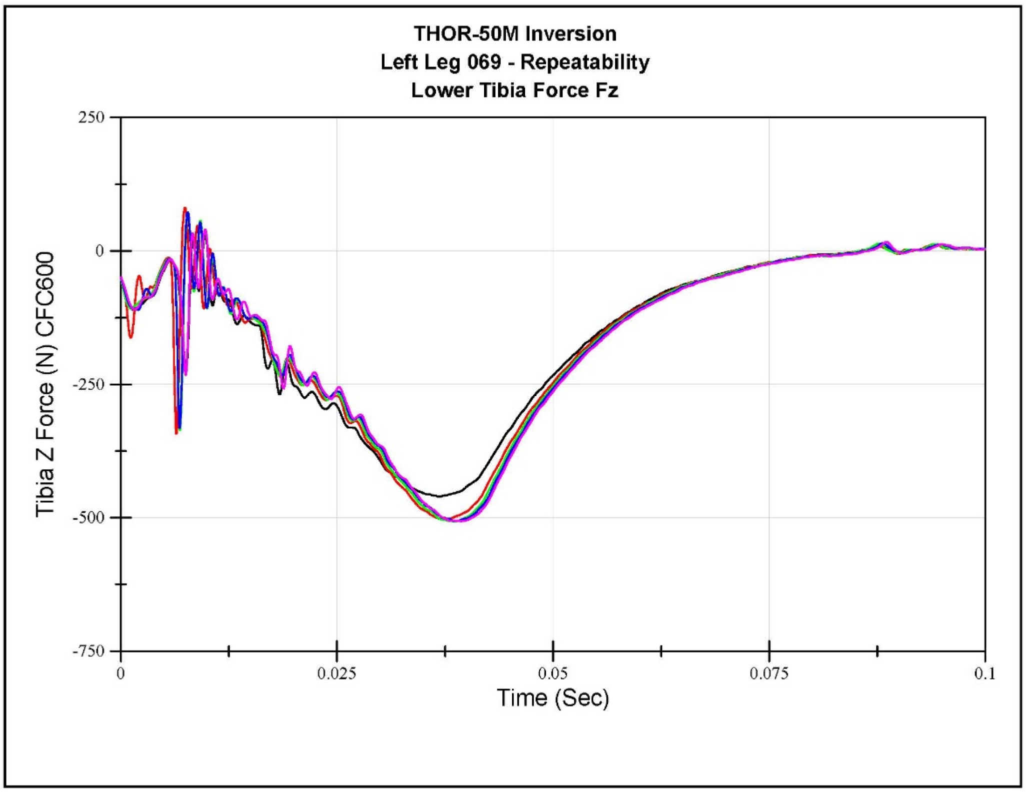

Figure 15-8. VRTC ankle inversion lower tibia Z-force repeatability for 069

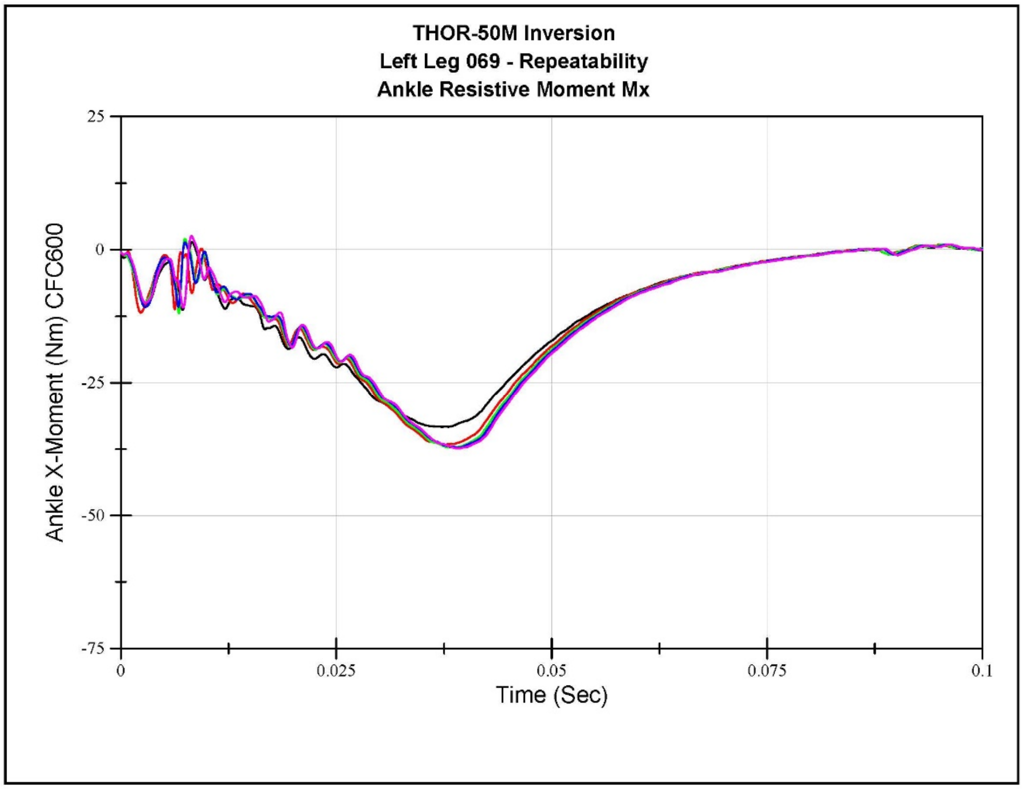

Figure 15-9. VRTC ankle inversion resistive X-moment repeatability for 069

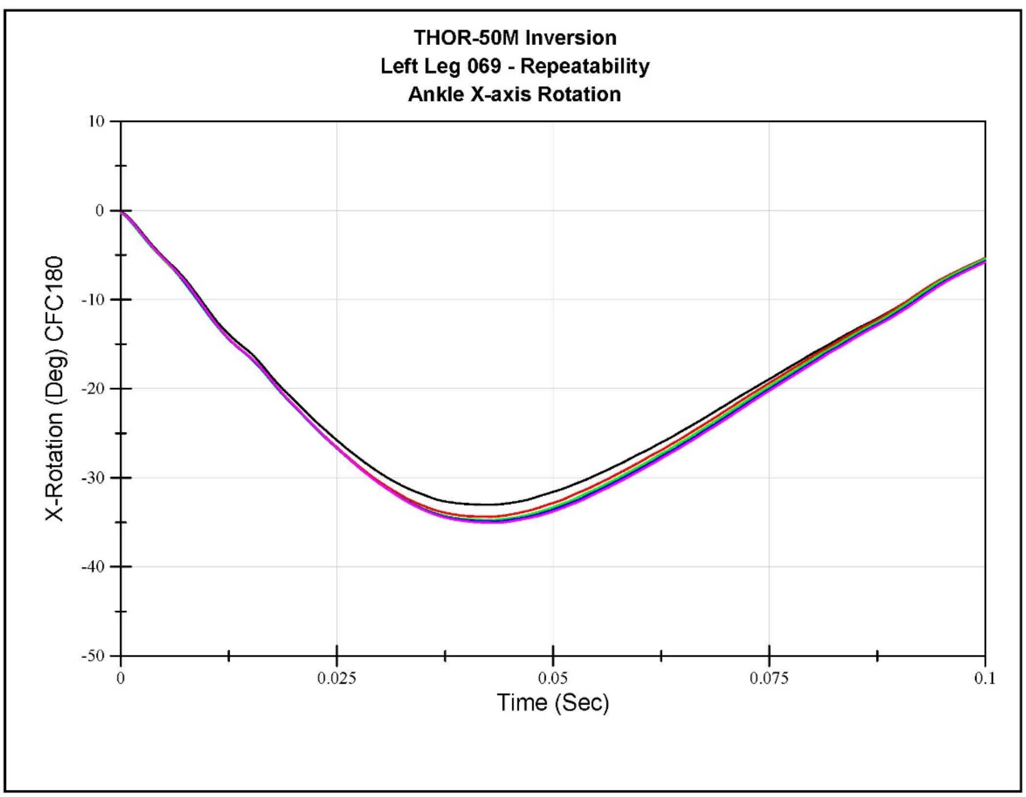

Figure 15-10. VRTC ankle inversion X-axis rotation repeatability for 069

15.2.4 THOR-50M Left Lower Leg DL0202 Testing at Humanetics

Only three tests met the input test parameters from the Humanetics tests with leg DL0202. Repeatability results with this data yielded CV values all below 5 percent (Table 15-4, Figure 15-11 to Figure 15-13).

Table 15-4. Humanetics THOR-50M DL0202 Left Ankle Inversion Repeatability Results

Test Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle X-axis Rotation (deg)
377	-535	-39.5	-34.7
379	-522	-39.1	-34.5
383	-522	-39.2	-34.6
Mean	**-527**	**-39.3**	**-34.6**
Std. Dev.	**8**	**0.2**	**0.1**
CV	**1.4%**	**0.6%**	**0.3%**

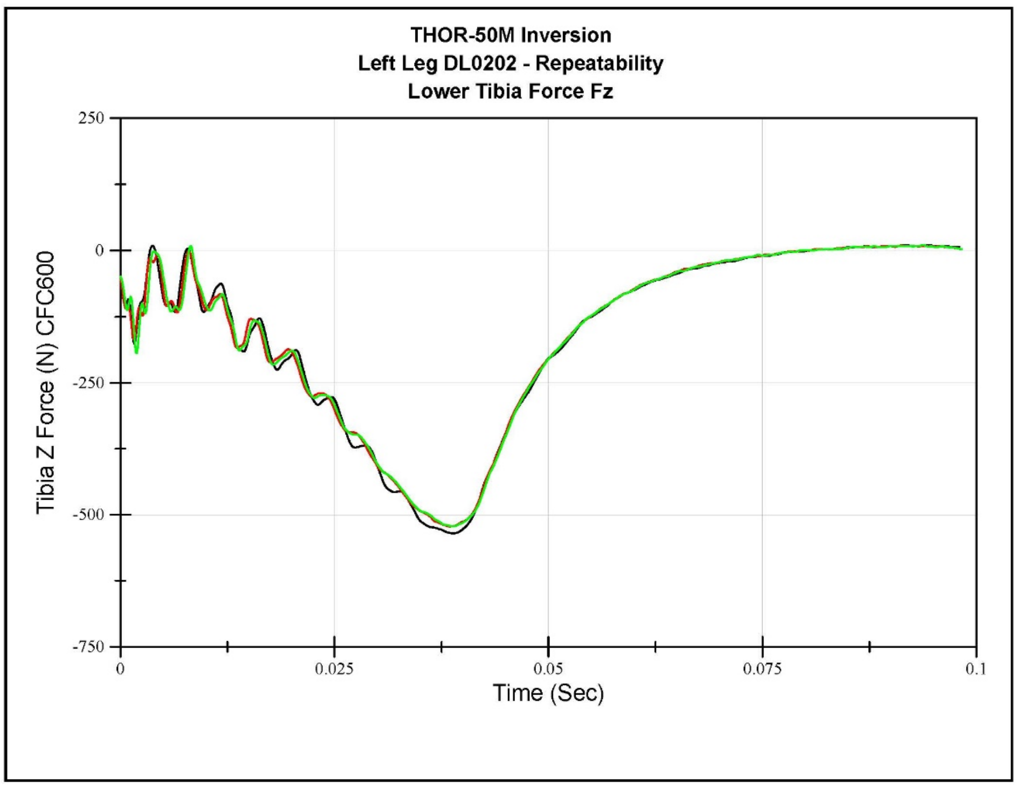

Figure 15-11. Humanetics ankle inversion lower tibia Z-force repeatability for DL0202

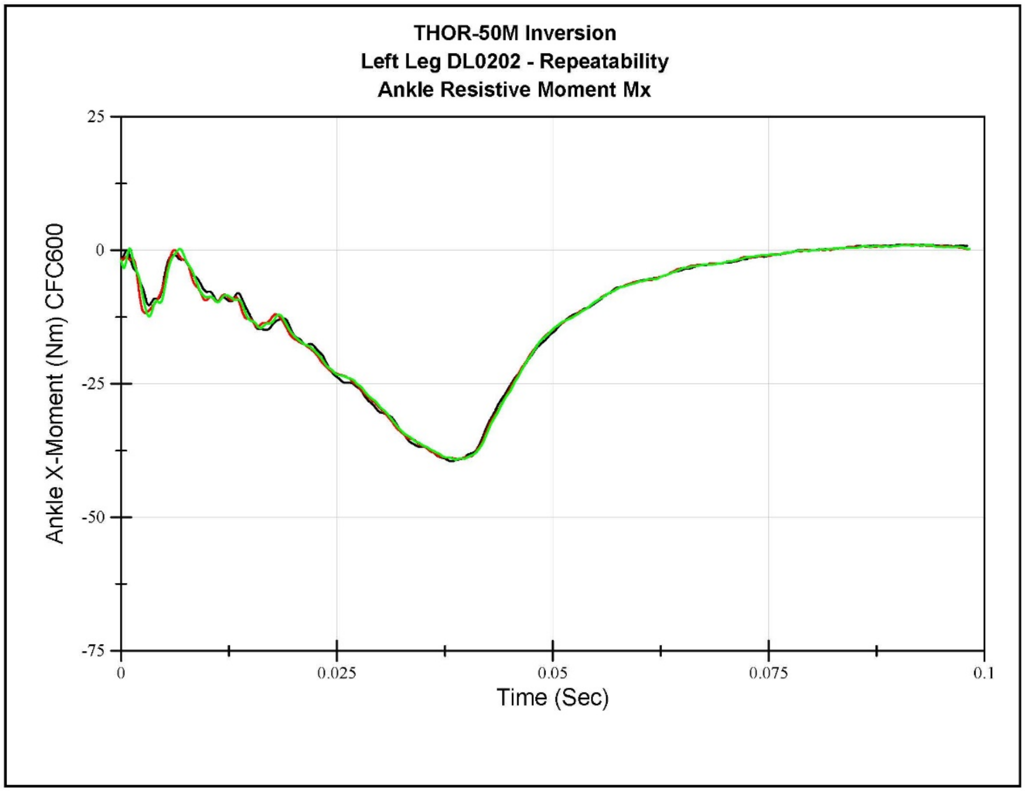

Figure 15-12. Humanetics ankle inversion resistive X-moment repeatability for DL0202

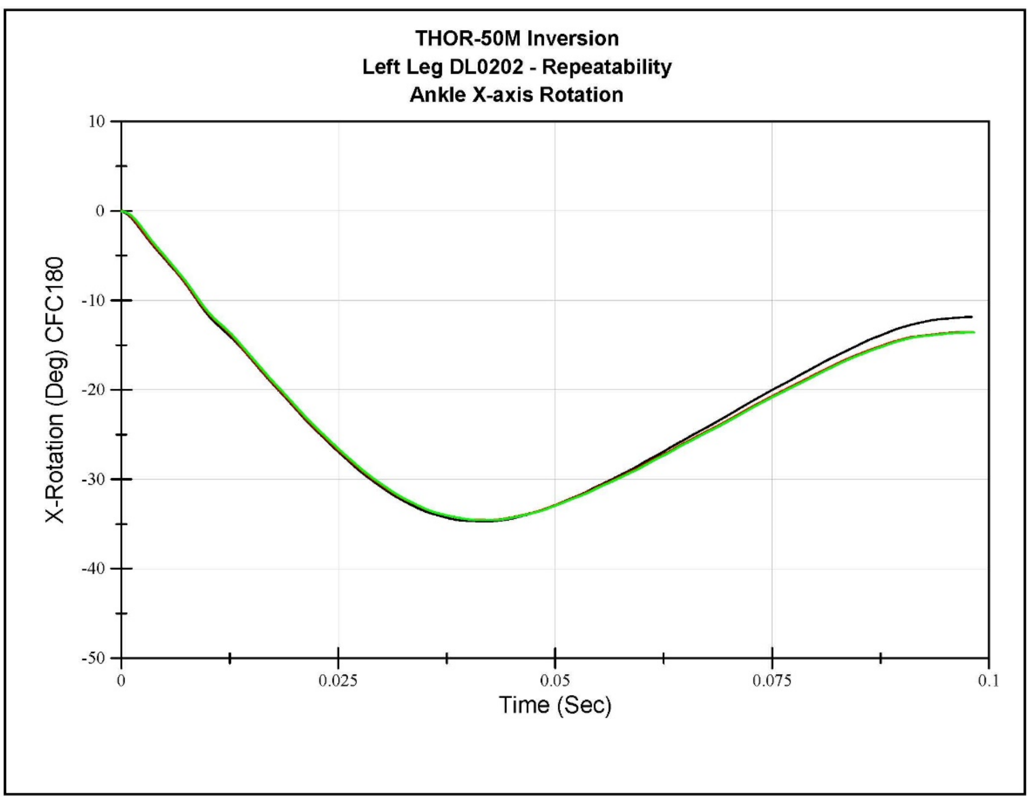

Figure 15-13. Humanetics ankle inversion X-axis rotation repeatability for DL0202

15.2.5 THOR-50M Right Lower Leg DL5404 Testing at Humanetics

Repeatability results at Humanetics for leg DL5404 yielded CV values all below 5 percent (Table 15-5, Figure 15-14 to Figure 15-16).

Table 15-5. Humanetics THOR-50M DL5404 Right Ankle Inversion Repeatability Results

Test Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle X-axis Rotation (deg)
302	-543	41.4	34.7
307	-547	42.0	34.9
308	-539	41.2	34.9
310	-542	41.4	35.0
311	-538	41.2	35.0
313	-538	40.9	35.0
Mean	**-541**	**41.3**	**34.9**
Std. Dev.	**3**	**0.4**	**0.1**
CV	**0.6%**	**0.9%**	**0.3%**

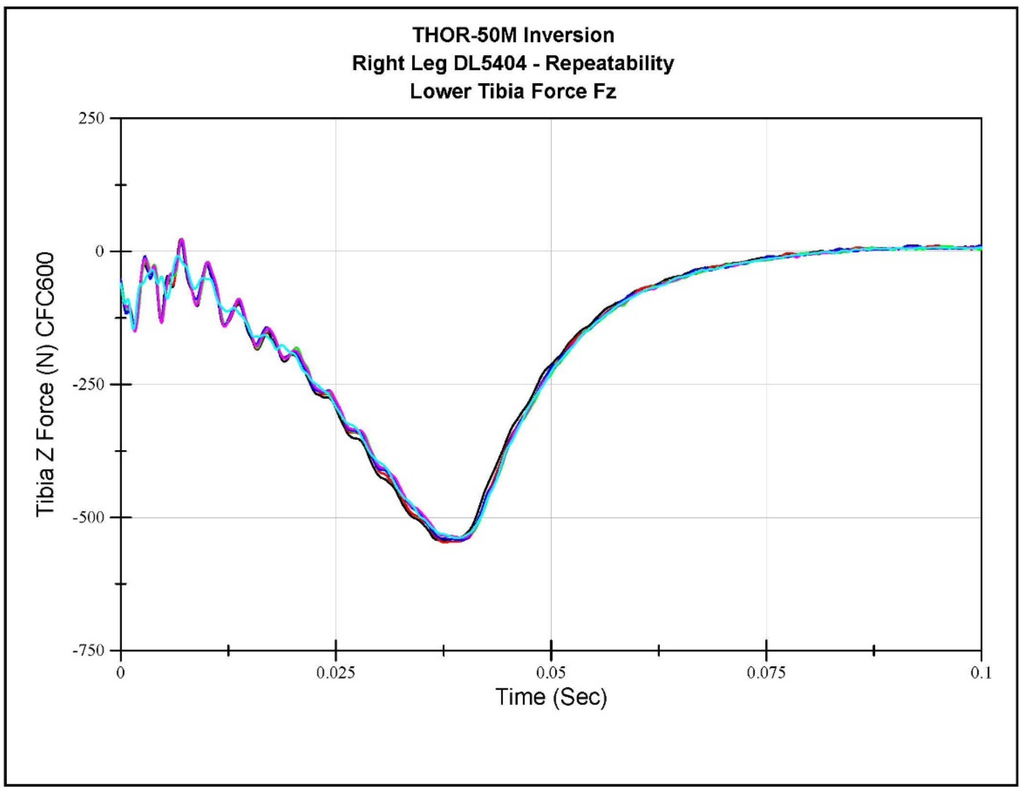

Figure 15-14. Humanetics ankle inversion lower tibia Z-force repeatability for DL5404

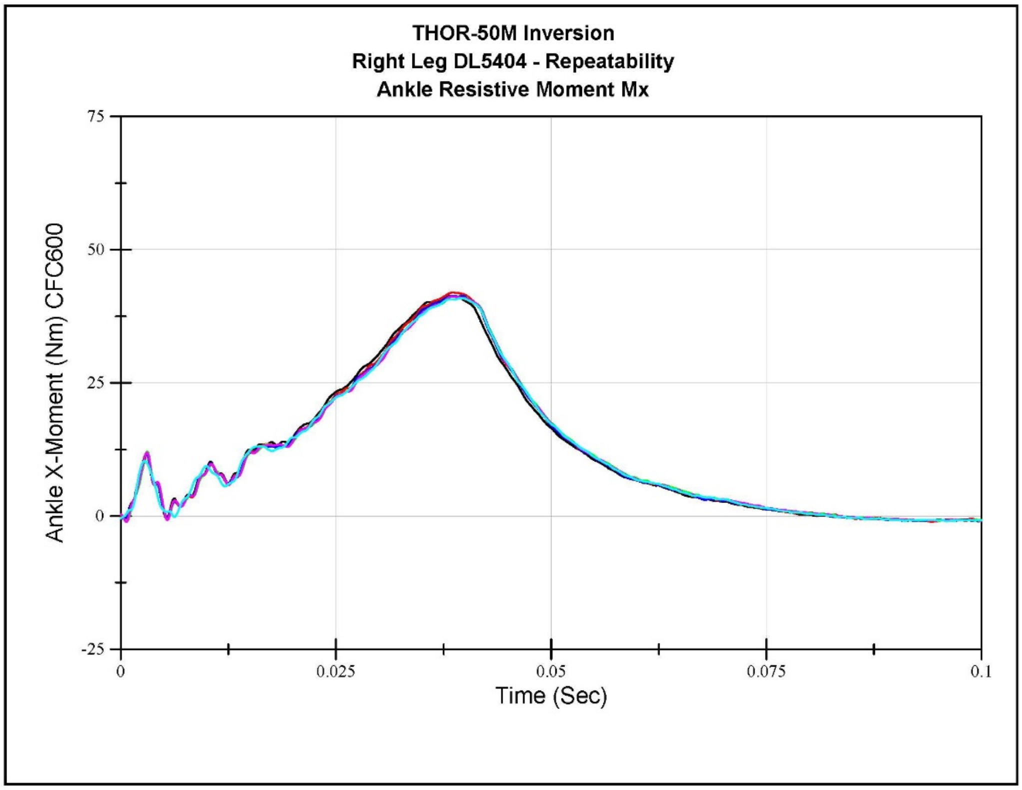

Figure 15-15. Humanetics ankle inversion resistive X-moment repeatability for DL5404

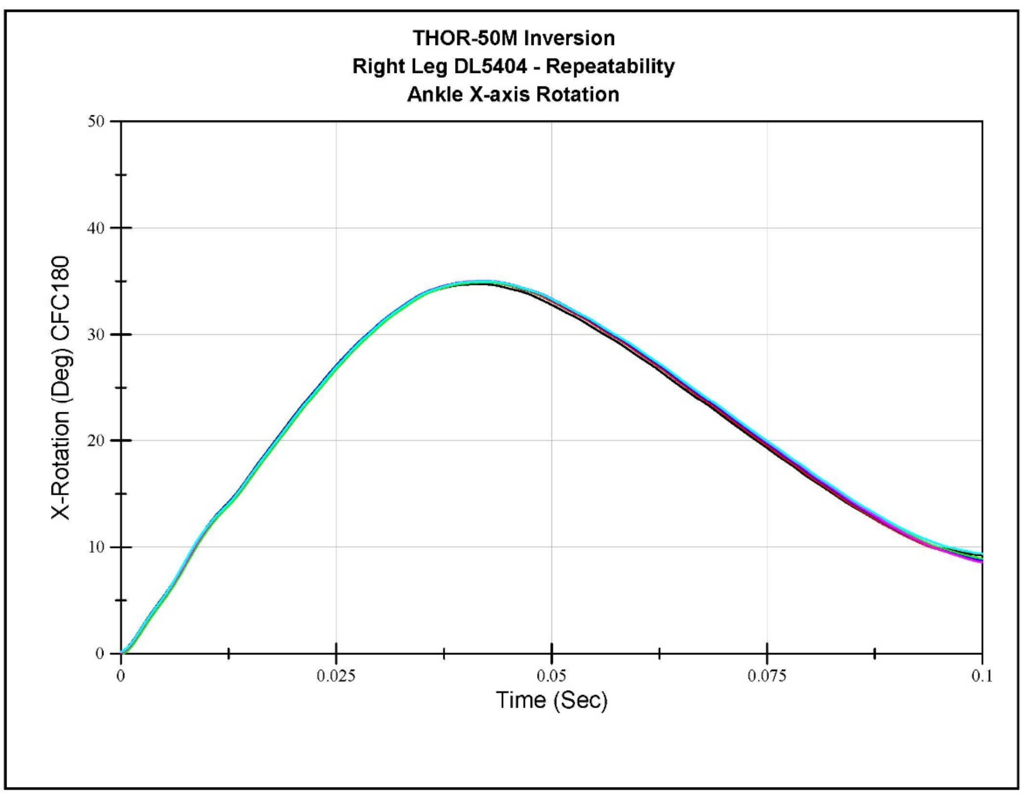

Figure 15-16. Humanetics ankle inversion X-axis rotation repeatability for DL5404

15.2.6 THOR-50M Left Lower Leg DL0202 Testing at Calspan

No repeatability results at Calspan for leg DL0202 ankle inversion qualification were available because input test parameters were out of range in all but one test. Results from the one test which met the input parameters are presented in Table 15-6, and Figure 15-17 to Figure 15-19.

Table 15-6. Calspan THOR-50M DL0202 Left Ankle Inversion Repeatability Results

Test Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle X-axis Rotation (deg)
20160623161713	-481	-37.5	-32.5

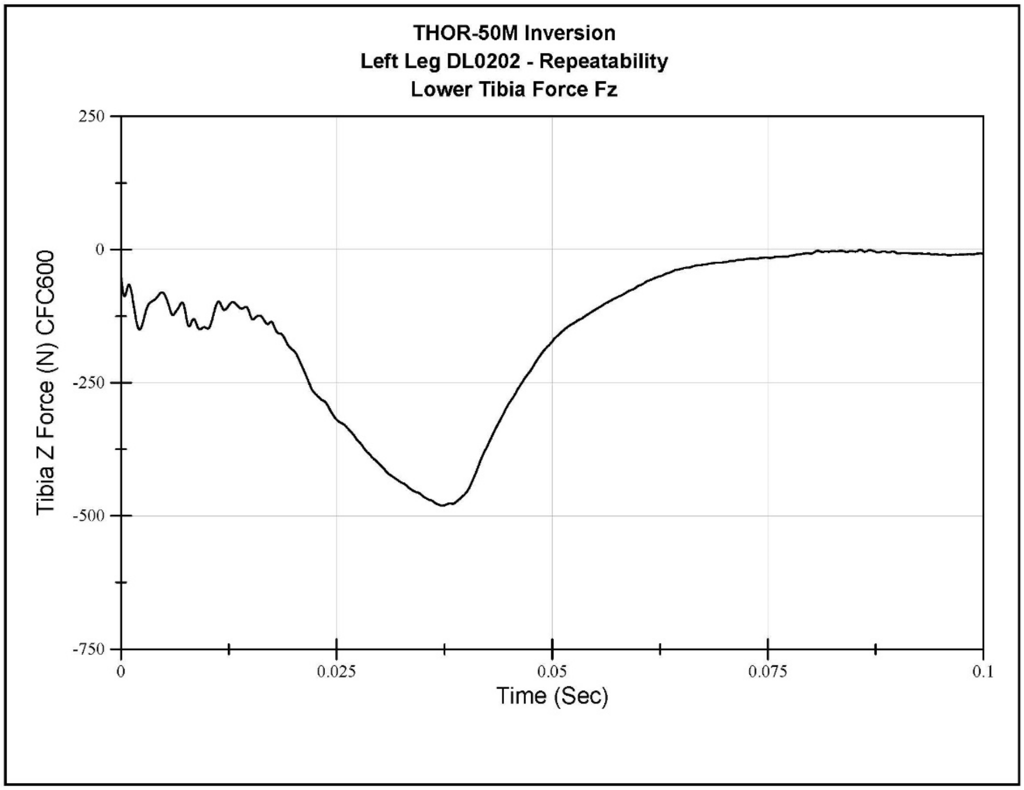

Figure 15-17. Calspan ankle inversion lower tibia Z-force repeatability for DL0202

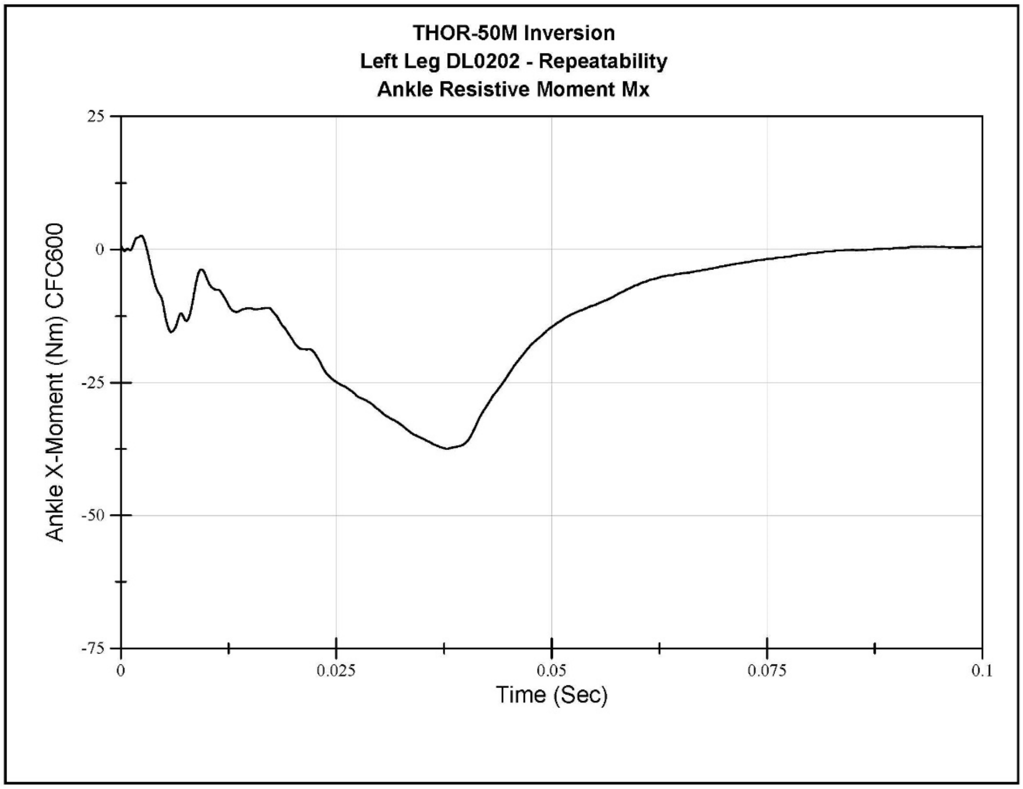

Figure 15-18. Calspan ankle inversion resistive X-moment repeatability for DL0202

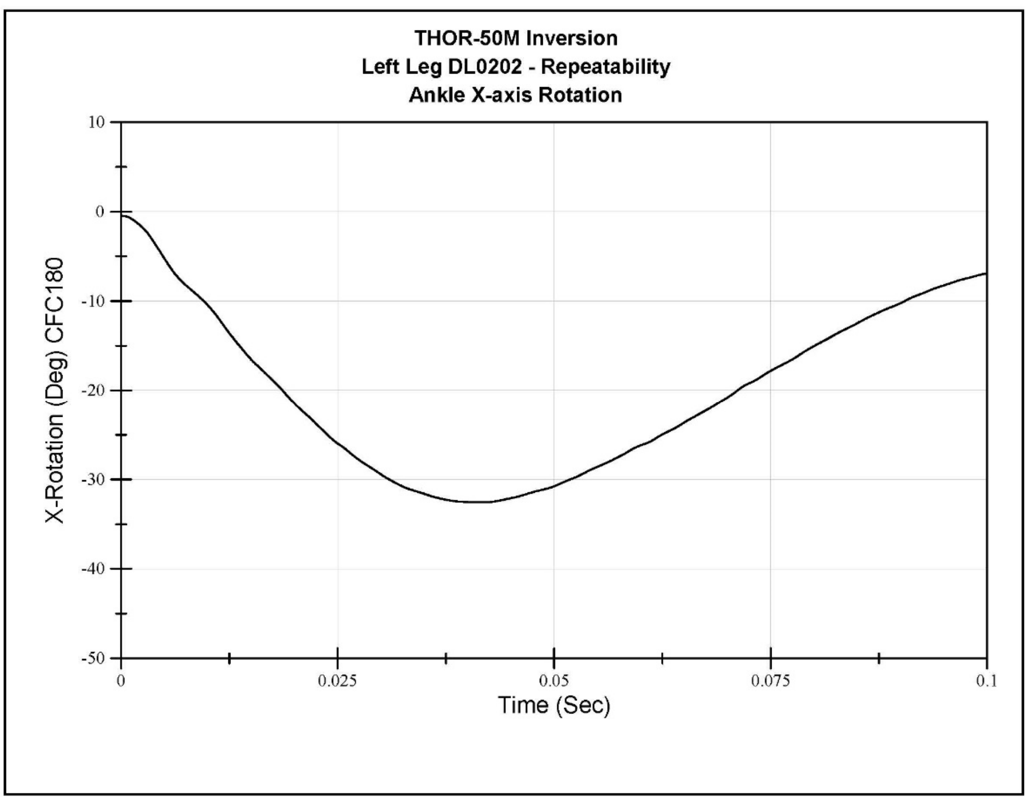

Figure 15-19. Calspan ankle inversion X-axis rotation repeatability for DL0202

15.2.7 THOR-50M Right Lower Leg DL5404 Testing at Calspan

Repeatability results at Calspan for leg DL5404 yielded CV values all below 5 percent (Table 15-7, Figure 15-20 to Figure 15-22).

Table 15-7. Calspan THOR-50M DL5404 Right Ankle Inversion Repeatability Results

Test Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle X-axis Rotation (deg)
20160629161425	-463	37.6	33.5
20160629164844	-500	41.4	34.4
20160629172326	-501	41.3	34.4
20160630073807	-491	40.7	34.4
20160630081451	-515	42.1	34.7
Mean	**-494**	**40.6**	**34.3**
Std. Dev.	**19**	**1.7**	**0.4**
CV	**3.9%**	**4.3%**	**1.3%**

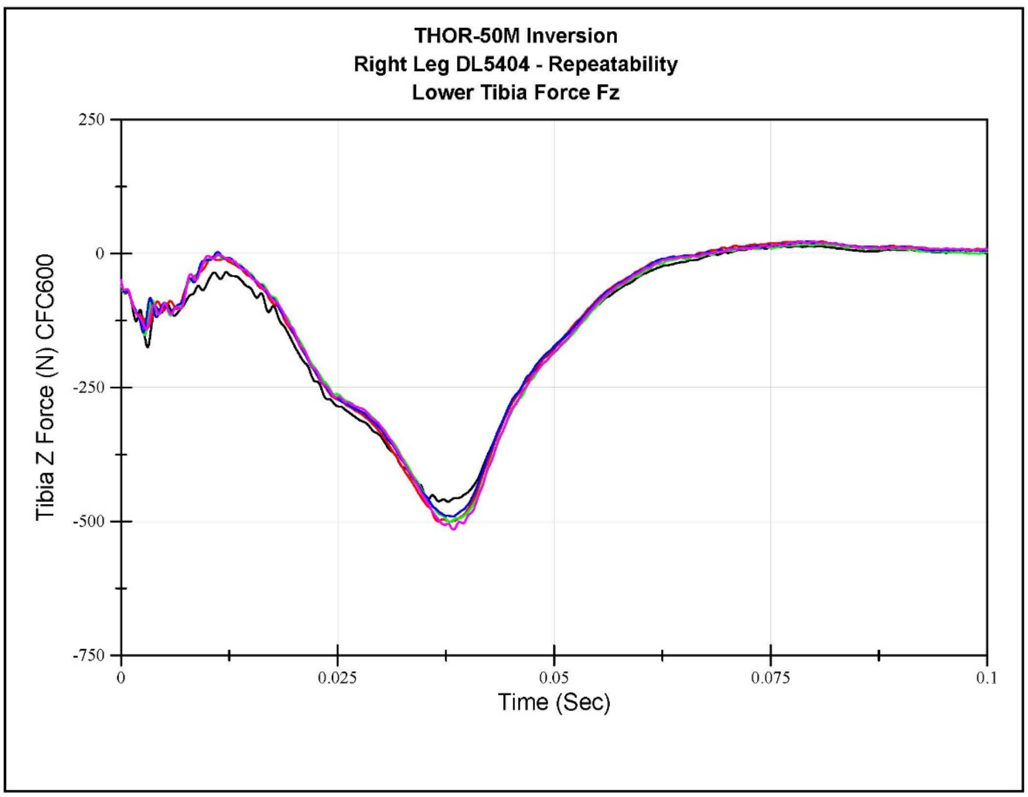

Figure 15-20. Calspan ankle inversion lower tibia Z-force repeatability for DL5404

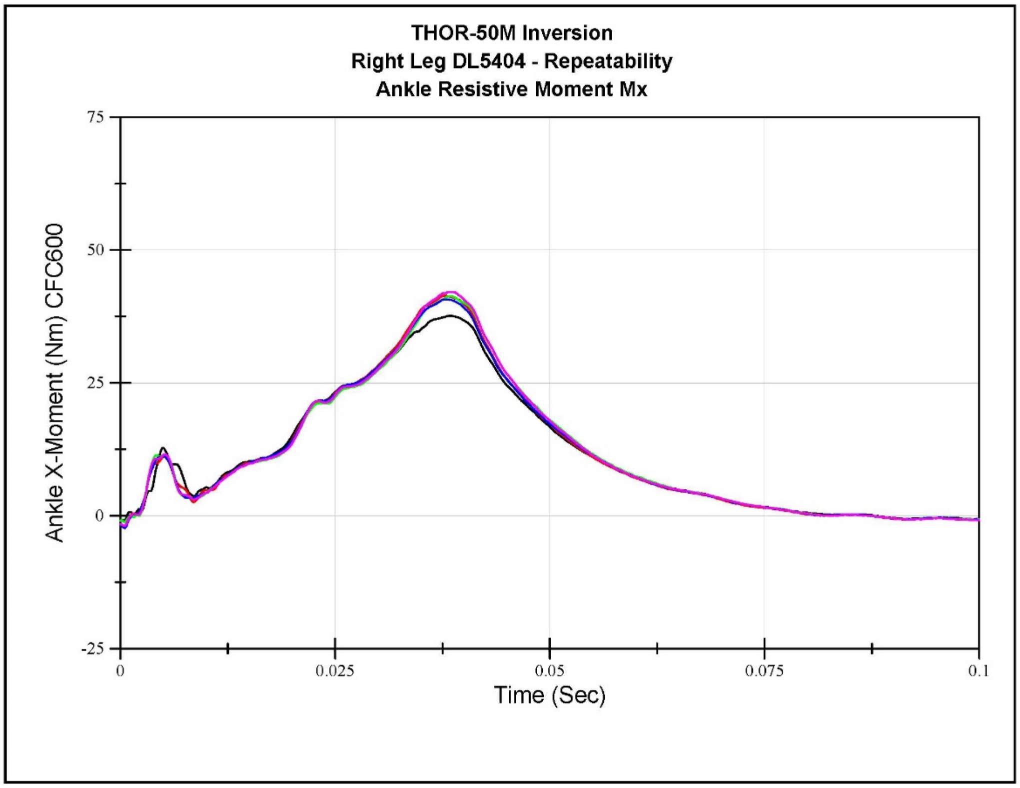

Figure 15-21. Calspan ankle inversion resistive X-moment repeatability for DL5404

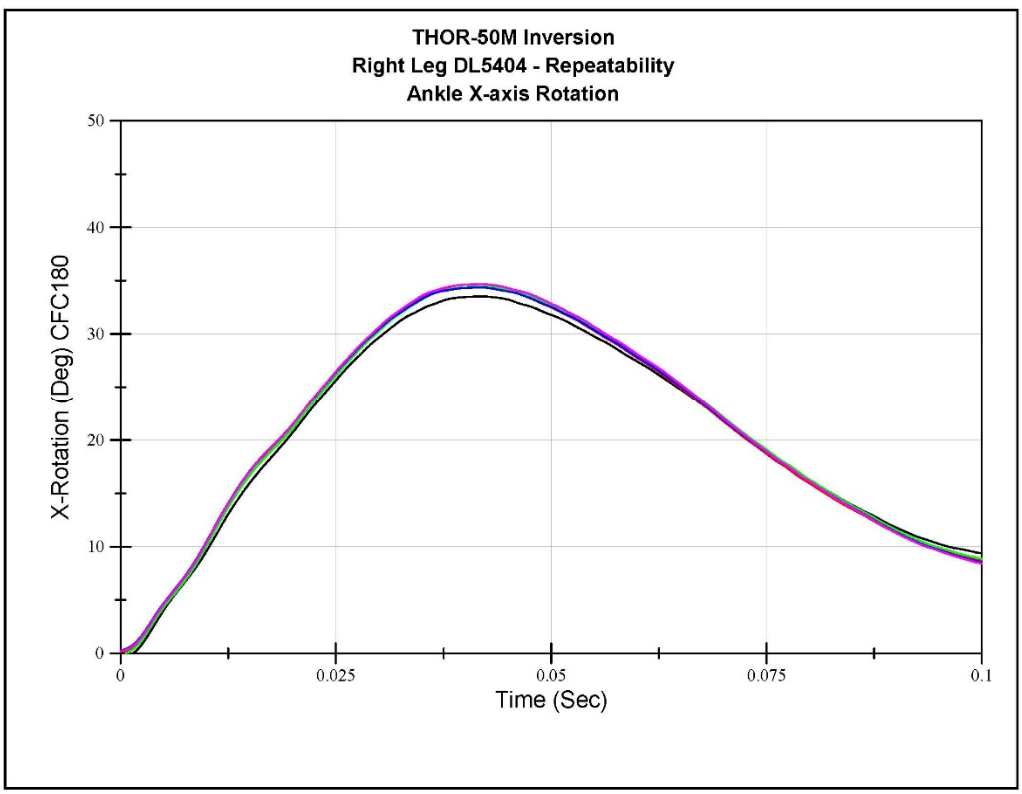

Figure 15-22. Calspan ankle inversion X-axis rotation repeatability for DL5404

15.3 Ankle Inversion Dummy Reproducibility Results

Reproducibility results at VRTC for the ankle inversion qualification yielded CV values all below 5 percent (Table 15-8). When combining left and right data, the absolute values of peak moment and peak rotation were used.

Table 15-8. THOR-50M Ankle Inversion Reproducibility Results

Leg Number	Test Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle X-axis Rotation (deg)
VRTC DL0202 Left Shoe: DO9799 VRTC DW2433/DV0872 (A)	**160518-23**	-466	-35.9	-33.5
	160519-1	-495	-38.4	-34.2
	160519-2	-502	-38.9	-34.5
	160519-3	-499	-38.7	-34.5
	160519-4	-499	-38.8	-34.5
VRTC DL5404 Right Shoe: DO9799 VRTC DV0860/DV0874 (B)	**160516-17**	-451	35.9	33.9
	160516-19	-481	38.6	34.5
	160517-2	-493	39.7	34.8
	160517-3	-503	40.4	35.0
	160517-5	-492	39.6	34.9
VRTC 069 Left Shoe: VRTC DV0855/DW2435 (D)	**160426-7**	-461	-33.3	-33.0
	160426-8	-503	-36.7	-34.4
	160426-9	-507	-37.3	-34.7
	160426-10	-506	-37.3	-34.9
	160426-12	-507	-37.4	-35.1
Mean		**-491**	**37.8**	**34.4**
Std. Dev.		**18**	**1.8**	**0.6**
CV		**3.7%**	**4.9%**	**1.6%**

15.4 Lab-to-Lab Variability Analysis

The results for the ankle inversion tests from each lab are presented in Table 15-9 and Table 15-10. For the left ankle inversion, the last four rows of Table 15-9 show the *Test Reproducibility* results when data from all three labs are combined, where all CVs are below 5 percent. Note that only one test in the Calspan data set was within the velocity tolerance, so no statistical analysis is available for the Calspan data set.

For the right ankle inversion, the last four rows of Table 15-10 show *Test Reproducibility* results when data from all three labs are combined. The CV values for moment and rotation are below 5 percent, and the tibia force produced a CV above 5 percent but less than 10 percent.

Table 15-9. THOR-50M Left Ankle Inversion Lab-to-Lab Variability Results

Leg Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle X-axis Rotation (deg)
VRTC DL0202 Left	-466	-35.9	-33.5
	-495	-38.4	-34.2
	-502	-38.9	-34.5
	-499	-38.7	-34.5
	-499	-38.8	-34.5
Humanetics DL0202 Left Shoe: DO9799 VRTC DW2433/DV0872 (A)	-535	-39.5	-34.7
	-522	-39.1	-34.5
	-522	-39.2	-34.6
Calspan DL0202 Left Shoe: DO9799 VRTC DW2433/DV0872 (A)	-481	-37.5	-32.5
Test Reproducibility DL0202 Left			
Mean	**-502**	**-38.5**	**-34.2**
Std. Dev.	**22**	**1.1**	**0.7**
CV	**4.3%**	**2.9%**	**2.1%**

Table 15-10. THOR-50M Right Ankle Inversion Lab-to-Lab Variability Results

Leg Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle X-axis Rotation (deg)
VRTC DL5404 Right Shoe: DO9799 VRTC DV0860/DV0874 (B)	-451	35.9	33.9
	-481	38.6	34.5
	-493	39.7	34.8
	-503	40.4	35.0
	-492	39.6	34.9
Humanetics DL5404 Right Shoe: DO9799 VRTC DV0860/DV0874 (B)	-543	41.4	34.7
	-547	42.0	34.9
	-539	41.2	34.9
	-542	41.4	35.0
	-538	41.2	35.0
	-538	40.9	35.0
Calspan DL5404 Right Shoe: DO9799 VRTC DV0860/DV0874 (B)	-463	37.6	33.5
	-500	41.4	34.4
	-501	41.3	34.4
	-491	40.7	34.4
	-515	42.1	34.7
Test Reproducibility DL5404 Right			
Mean	**-509**	**40.3**	**34.6**
Std. Dev.	**30**	**1.7**	**0.4**
CV	**5.9%**	**4.2%**	**1.2%**

15.5 Corridor Development

All the data used to determine the ankle inversion qualification corridors is shown in Table 15-11. The qualification corridors were calculated using the mean plus or minus 10 percent of the peak for the specified measured or calculated channels (Table 15-12 and Table 15-13). When combining left and right data, the absolute values of peak moment and peak rotation were used.

Table 15-11. THOR-50M Ankle Inversion Qualification Corridor Results

Leg Number	Test Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle X-axis Rotation (deg)
VRTC DL0202 Left Shoe: DO9799 VRTC DW2433/DV0872 (A)	160518-23	-466	-35.9	-33.5
	160519-1	-495	-38.4	-34.2
	160519-2	-502	-38.9	-34.5
	160519-3	-499	-38.7	-34.5
	160519-4	-499	-38.8	-34.5
VRTC DL5404 Right Shoe: DO9799 VRTC DV0860/DV0874 (B)	160516-17	-451	35.9	33.9
	160516-19	-481	38.6	34.5
	160517-2	-493	39.7	34.8
	160517-3	-503	40.4	35.0
	160517-5	-492	39.6	34.9
VRTC 069 Left Shoe: VRTC DV0855/DW2435 (D)	160426-7	-461	-33.3	-33.0
	160426-8	-503	-36.7	-34.4
	160426-9	-507	-37.3	-34.7
	160426-10	-506	-37.3	-34.9
	160426-12	-507	-37.4	-35.1
Humanetics DL0202 Left Shoe: DO9799 VRTC DW2433/DV0872 (A)	377	-535	-39.5	-34.7
	379	-522	-39.1	-34.5
	383	-522	-39.2	-34.6
Humanetics DL5404 Right Shoe: DO9799 VRTC DV0860/DV0874 (B)	302	-543	41.4	34.7
	307	-547	42.0	34.9
	308	-539	41.2	34.9
	310	-542	41.4	35.0
	311	-538	41.2	35.0
	313	-538	40.9	35.0
Calspan DL0202 Left Shoe: DO9799 VRTC DW2433/DV0872 (A)	20160623161713	-481	-37.5	-32.5
Calspan DL5404 Right Shoe: DO9799 VRTC DV0860/DV0874 (B)	20160629161425	-463	37.6	33.5
	20160629164844	-500	41.4	34.4
	20160629172326	-501	41.3	34.4
	20160630073807	-491	40.7	34.4
	20160630081451	-515	42.1	34.7
Mean		**-505**	**39.1**	**34.5**
Std. Dev.		**26**	**2.12**	**0.61**
CV		**5.1%**	**5.4%**	**1.8%**

Table 15-12. Left Ankle Inversion Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Impact Velocity	**m/s**	1.95	2.05	2.00	
Peak Lower Tibia Fz	**N**	-555	-454	-505	10%
Peak Ankle Resistive Moment	**Nm**	-43.0	-35.2	-39.1	10%
Peak Ankle X-axis Rotation	**deg**	-37.9	-31.0	-34.5	10%

Table 15-13. Right Ankle Inversion Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Impact Velocity	**m/s**	1.95	2.05	2.00	
Peak Lower Tibia Fz	**N**	-555	-454	-505	10%
Peak Ankle Resistive Moment	**Nm**	35.2	43.0	39.1	10%
Peak Ankle X-axis Rotation	**deg**	31.0	37.9	34.5	10%

Discussion. At VRTC and Calspan, the first trial resulted in a response wherein the ankle moment, tibia Fz, and ankle rotation were slightly lower than subsequent tests. However, only two initial tests (both at VRTC) had responses below 10 percent of the target, so we did not investigate this effect any further. All other tests (at all labs) were within 10 percent of the target.

The initial test effect may be related to the Ensolite pad used to reduce shock (see engineering drawing TLX-9000-027), newness of the components within the ankle assembly, or caused by the fact that the ankles were assembled immediately prior to the test series. Since the initial test effect was seen only in tests that made use of the pad (inversion and eversion), it is suspected that the pad is most likely the cause of the initial test effect. The pad, which covers the impact arm (not part of the dummy), is made of a closed-cell sponge. Only the initial test is affected. Since Ensolite does not exhibit the same breakdown as the open-celled Confor foam used for the face, subsequent tests in a given test series are highly uniform,

We regard the initial test effect as a *Test Repeatability* issue because it is thought to be associated mostly with the foam, which is part of the text fixture. However, the effect represents only a minor impediment to achieving the qualification targets (i.e., qualification is achieved by simply repeating the test).

With regard to assuring ankle uniformity (i.e., *Dummy Reproducibility*), the effect is only a concern if an initial qualification test produces responses that are just below the upper qualification limits. In this case, the ankle might be too stiff in a subsequent crash test. (This situation did not arise in our testing.) Here again, this may be confirmed by simply running an additional test. *Dummy Reproducibility* does not otherwise appear to be a factor in attaining the target responses.

Variability due to *Test Reproducibility* might pose a minor obstacle, as the CV for the tibia force was above 5 percent but less than 10 percent. Higher forces were seen at Humanetics relative to those at Calspan and VRTC (though all were within 10 percent of the target). Thus, in the future labs should be aware that they may need to adjust their test set-ups slightly (within given tolerances) to attain the desired response.

16 Ankle Eversion

16.1 Methodology

Repeatability and reproducibility 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 inversion/eversion bracket (drawing #TLX-9000-015) which is temporarily attached to the bottom of the ankle assembly (Figure 16-1). The impact surface of the bracket is covered with Ensolite padding to reduce noise transmission through the bracket into the ankle and load cell. The 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 test utilizes the NHTSA Dynamic Impactor (TLX-9000-013), as described in the *THOR-50M Drawing Package*, with an effective mass of 5.00 ± 0.02 kg. 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 pendulum impacts the eversion bracket at a velocity of 2.00 ± 0.05 m/s. During these tests, the lower tibia Z-axis force (Fz) and X-axis rotation were measured; the ankle resistive moment about the X-axis was calculated from the Y-axis force (Fy) and X-axis moment (Mx).

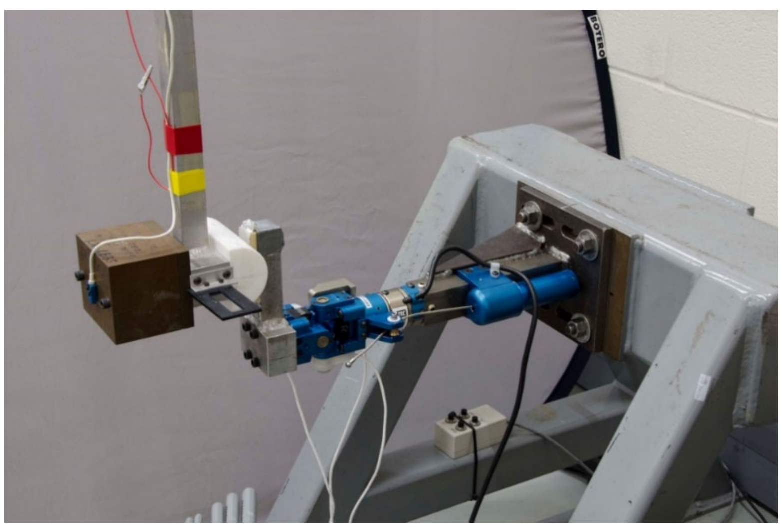

Figure 16-1. Ankle Eversion Test

16.2 Ankle Eversion Repeatability Results

Sections 16.2.1 to 16.2.7 illustrate the results of the ankle eversion repeatability tests. Each section contains a table providing the test data, followed by plot overlays of the five repeat tests conducted at all three labs. Only three legs were tested (two left and one right) in this series, rather than three legs from each side, since the left and right legs are symmetrical. Note that the data in the tables containing the results of each test series are listed sequentially, with the test at the top of the table beginning the test series.

16.2.1 THOR-50M Left Lower Leg DL0202 Testing at VRTC

Repeatability results at VRTC for leg DL0202 yielded CV values all below 5 percent (Table 16-1, Figure 16-2 to Figure 16-4).

Table 16-1. VRTC THOR-50M DL0202 Left Ankle Eversion Repeatability Results

Test Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle X-axis Rotation (deg)
160519-5	-512	38.9	28.6
160519-6	-555	42.3	29.5
160519-7	-554	42.4	29.5
160519-9	-560	42.7	29.6
160519-10	-563	43.0	29.6
Mean	**-549**	**41.9**	**29.4**
Std. Dev.	**21**	**1.7**	**0.4**
CV	**3.8%**	**4.1%**	**1.4%**

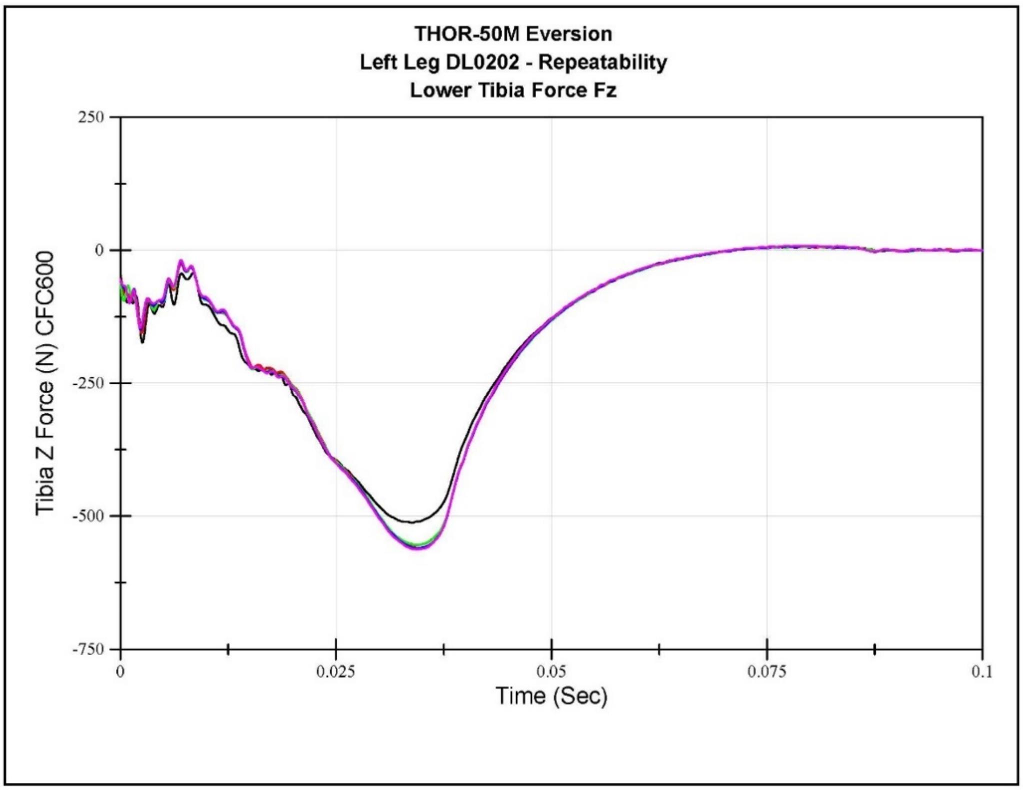

Figure 16-2. VRTC ankle eversion lower tibia Z-force repeatability for DL0202

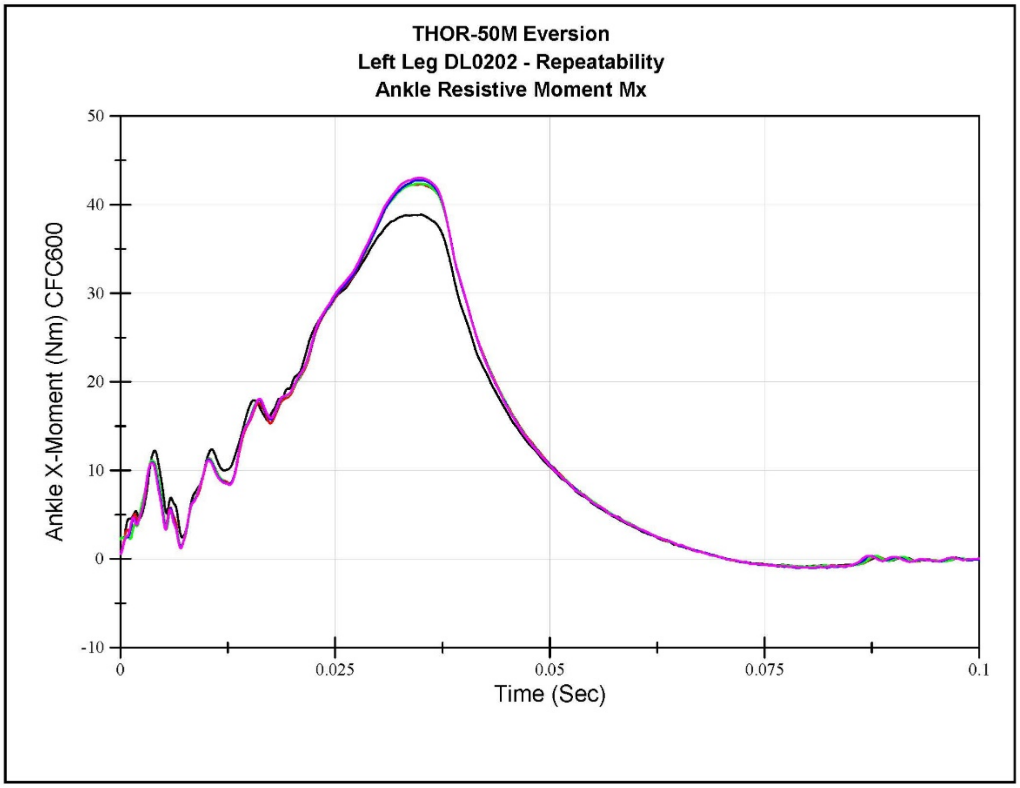

Figure 16-3. VRTC ankle eversion resistive X-moment repeatability for DL0202

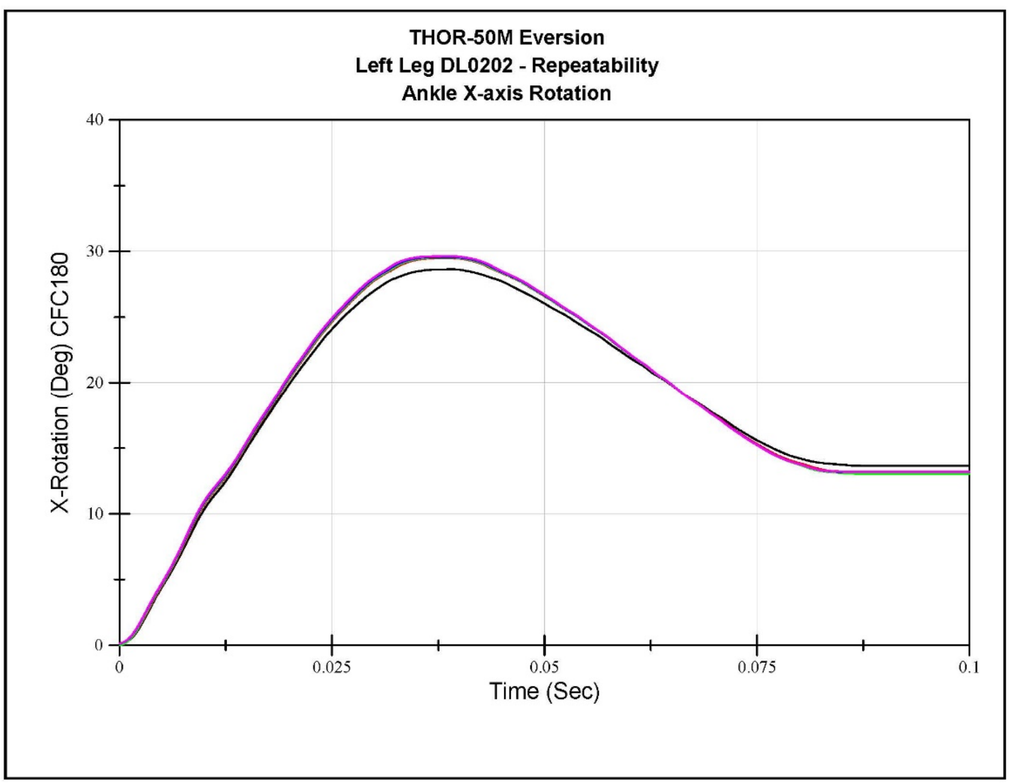

Figure 16-4. VRTC ankle eversion X-axis rotation repeatability for DL0202

16.2.2 THOR-50M Right Lower Leg DL5404 Testing at VRTC

Repeatability results at VRTC for leg DL5404 yielded CV values all below 5 percent (Table 16-2, Figure 16-5 to Figure 16-7).

Table 16-2. VRTC THOR-50M DL5404 Right Ankle Eversion Repeatability Results

Test Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle X-axis Rotation (deg)
160517-7	-530	-39.9	-29.5
160517-9	-571	-43.4	-30.3
160517-10	-573	-43.5	-30.4
160517-11	-574	-43.7	-30.4
160517-12	-573	-43.6	-30.5
Mean	**-564**	**-42.8**	**-30.2**
Std. Dev.	**19**	**1.6**	**0.4**
CV	**3.4%**	**3.8%**	**1.3%**

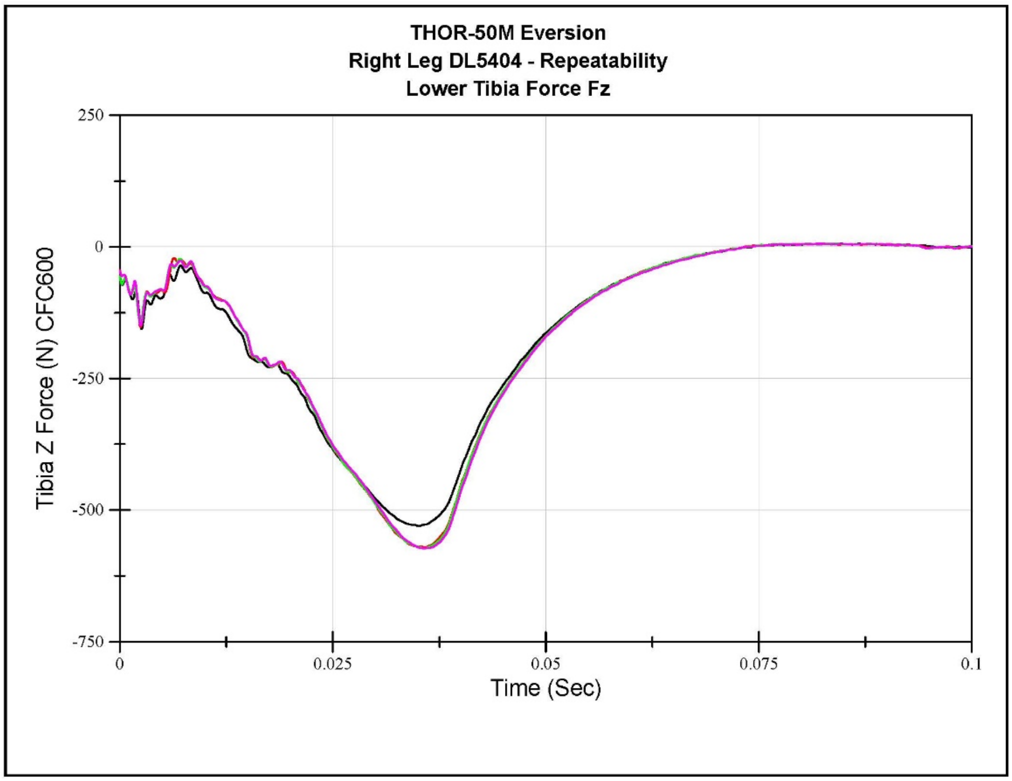

Figure 16-5. VRTC ankle eversion lower tibia Z-force repeatability for DL5404

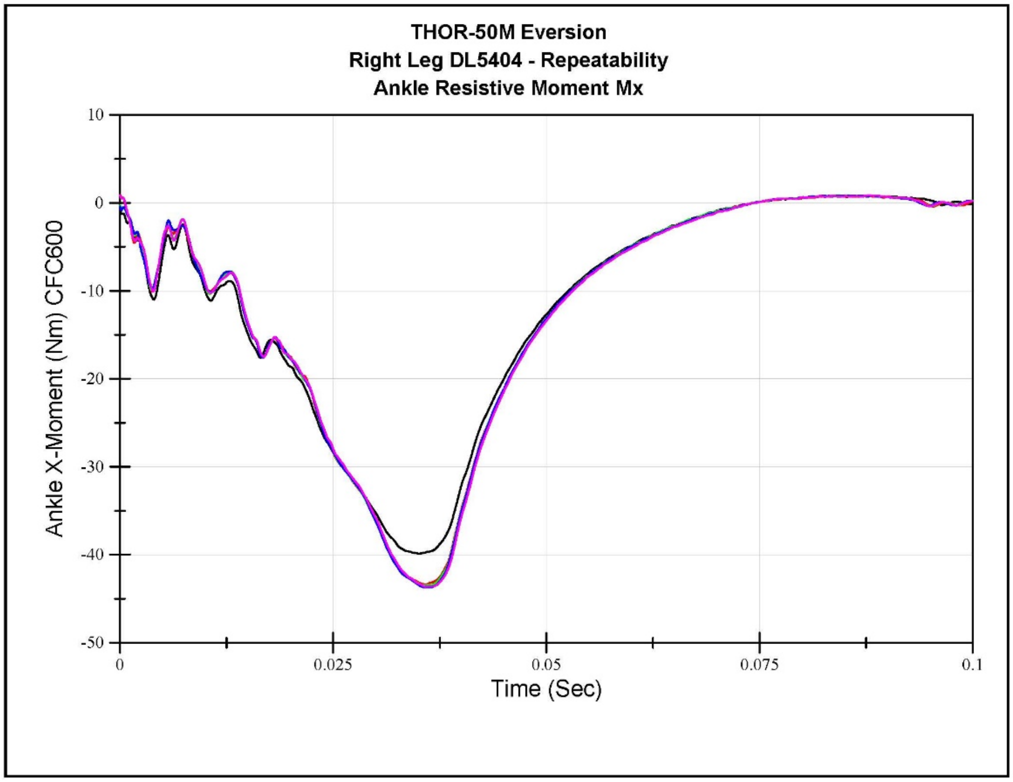

Figure 16-6. VRTC ankle eversion resistive X-moment repeatability for DL5404

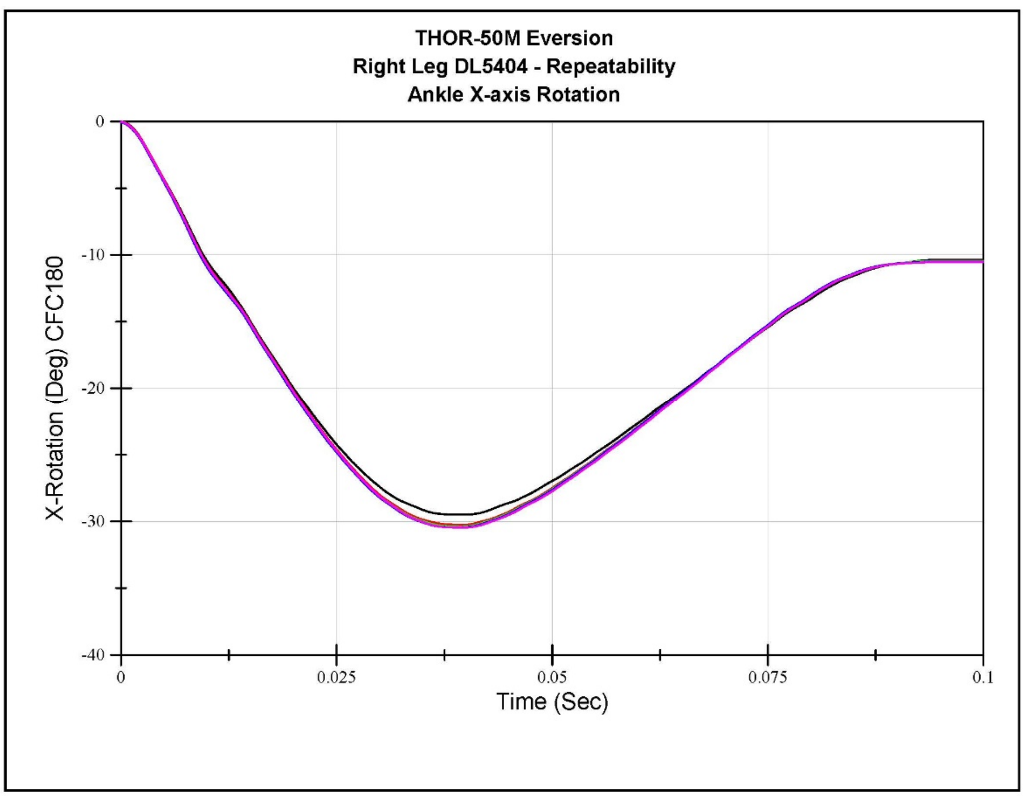

Figure 16-7. VRTC ankle eversion X-axis rotation repeatability for DL5404

16.2.3 THOR-50M Left Lower Leg 069 Testing at VRTC

Repeatability results for leg 069 yielded CV values all below 5 percent (Table 16-3, Figure 16-8 to Figure 16-10).

Table 16-3. VRTC THOR-50M 069 Left Ankle Eversion Repeatability Results

Test Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle X-axis Rotation (deg)
160425-5	-614	44.6	28.8
160425-9	-614	44.8	29.1
160425-11	-614	44.5	29.2
160425-13	-619	45.1	29.4
Mean	**-615**	**44.8**	**29.1**
Std. Dev.	**2**	**0.3**	**0.2**
CV	**0.4%**	**0.6%**	**0.8%**

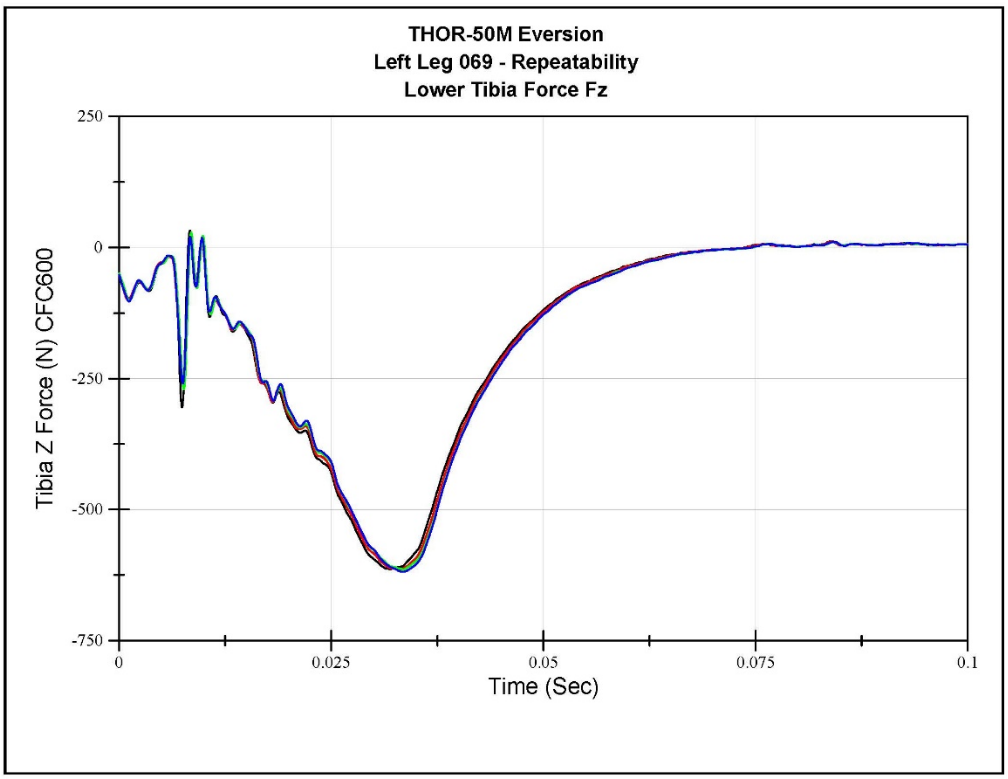

Figure 16-8. VRTC ankle eversion lower tibia Z-force repeatability for 069

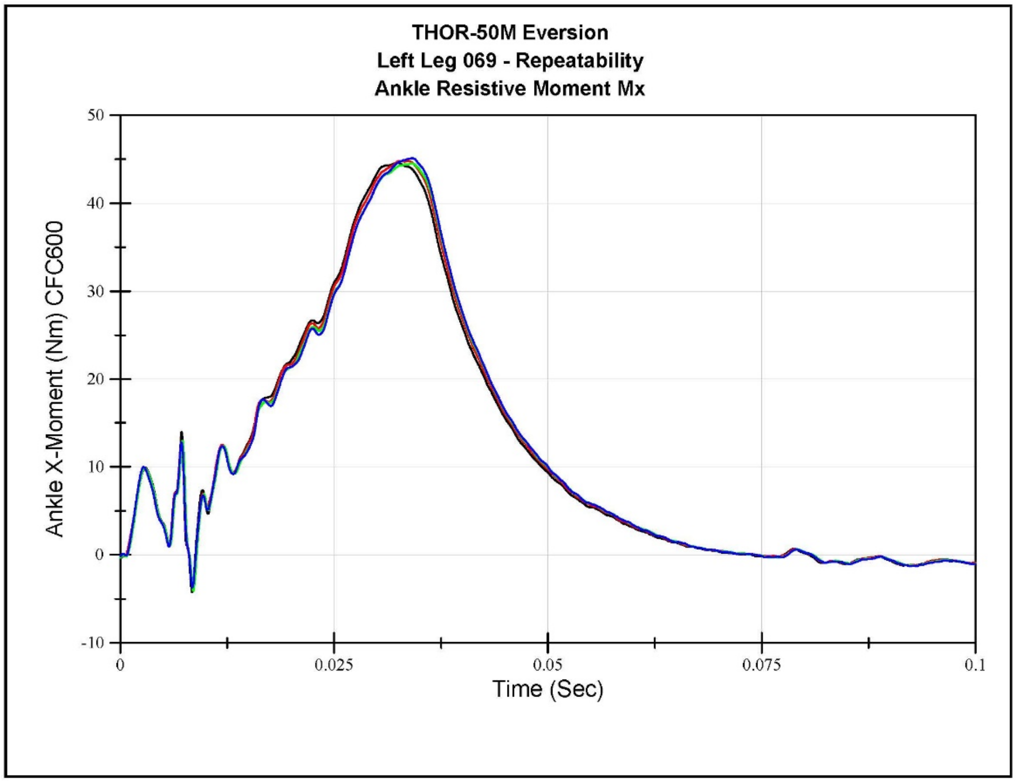

Figure 16-9. VRTC ankle eversion resistive X-moment repeatability for 069

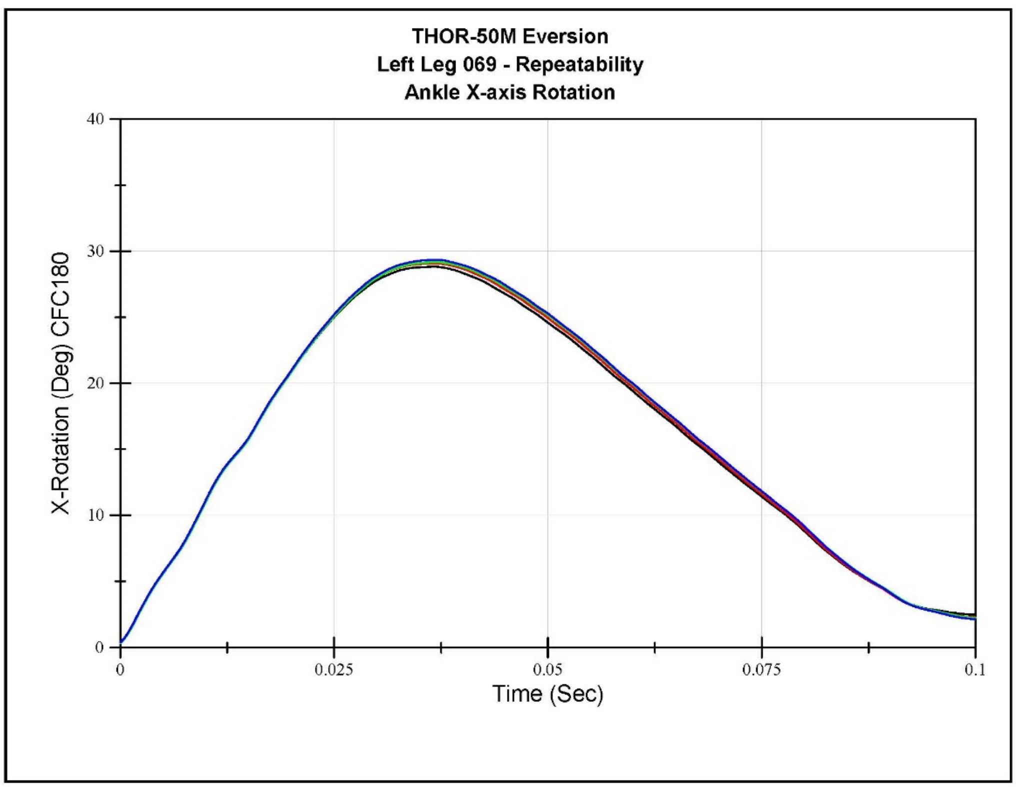

Figure 16-10. VRTC ankle eversion X-axis rotation repeatability for 069

16.2.4 THOR-50M Left Lower Leg DL0202 Testing at Humanetics

Repeatability results at Humanetics for leg DL0202 yielded CV values all below 5 percent (Table 16-4. Figure 16-11 to Figure 16-13).

Table 16-4. Humanetics THOR-50M DL0202 Left Ankle Eversion Repeatability Results

Test Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle X-axis Rotation (deg)
389	-565	42.0	29.5
392	-573	42.3	29.5
393	-573	42.3	29.5
395	-570	42.0	29.5
396	-569	41.9	29.5
Mean	**-570**	**42.1**	**29.5**
Std. Dev.	**3**	**0.2**	**0.0**
CV	**0.6%**	**0.4%**	**0.1%**

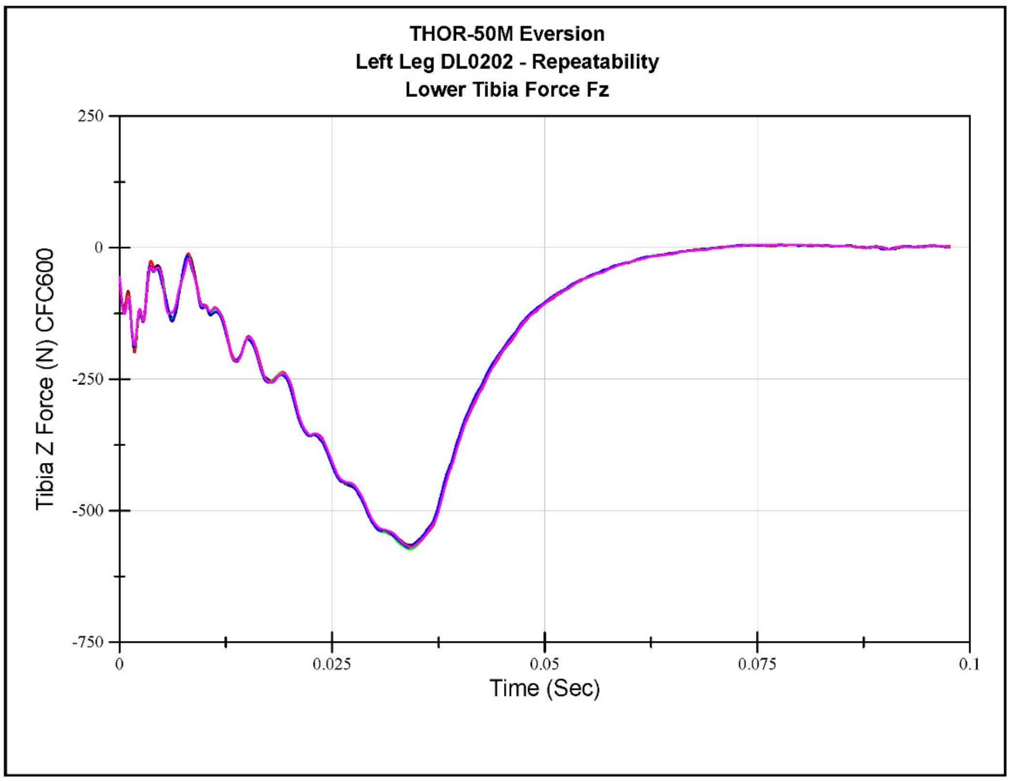

Figure 16-11. Humanetics ankle eversion lower tibia Z-force repeatability for DL0202

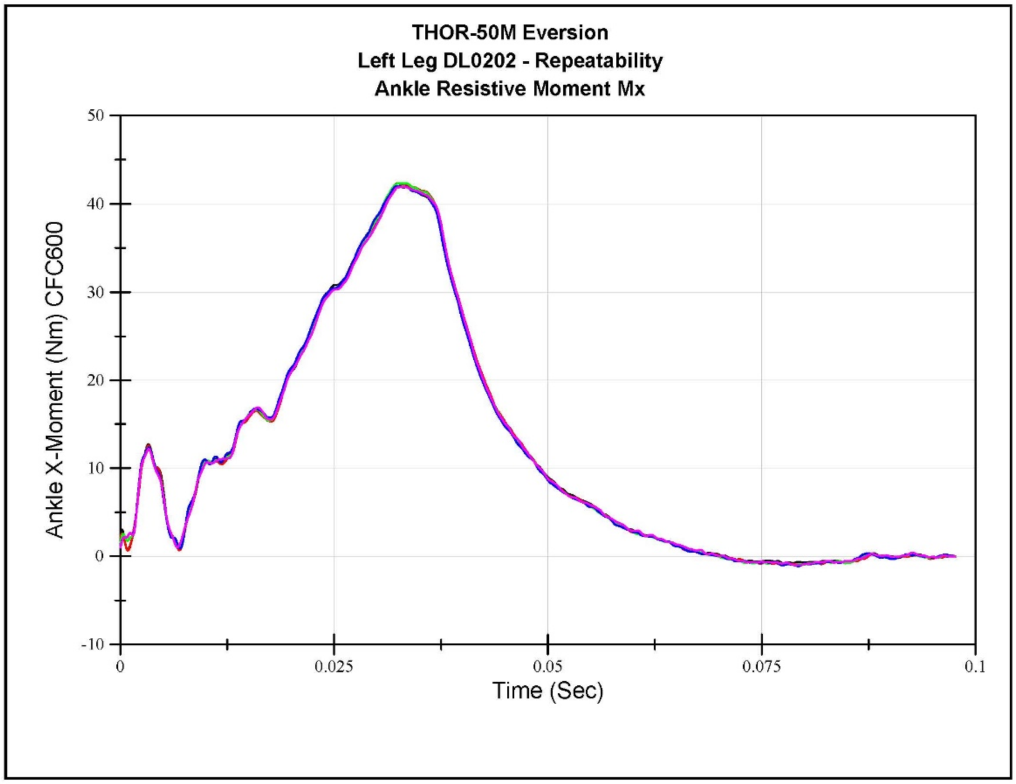

Figure 16-12. Humanetics ankle eversion resistive X-moment repeatability for DL0202

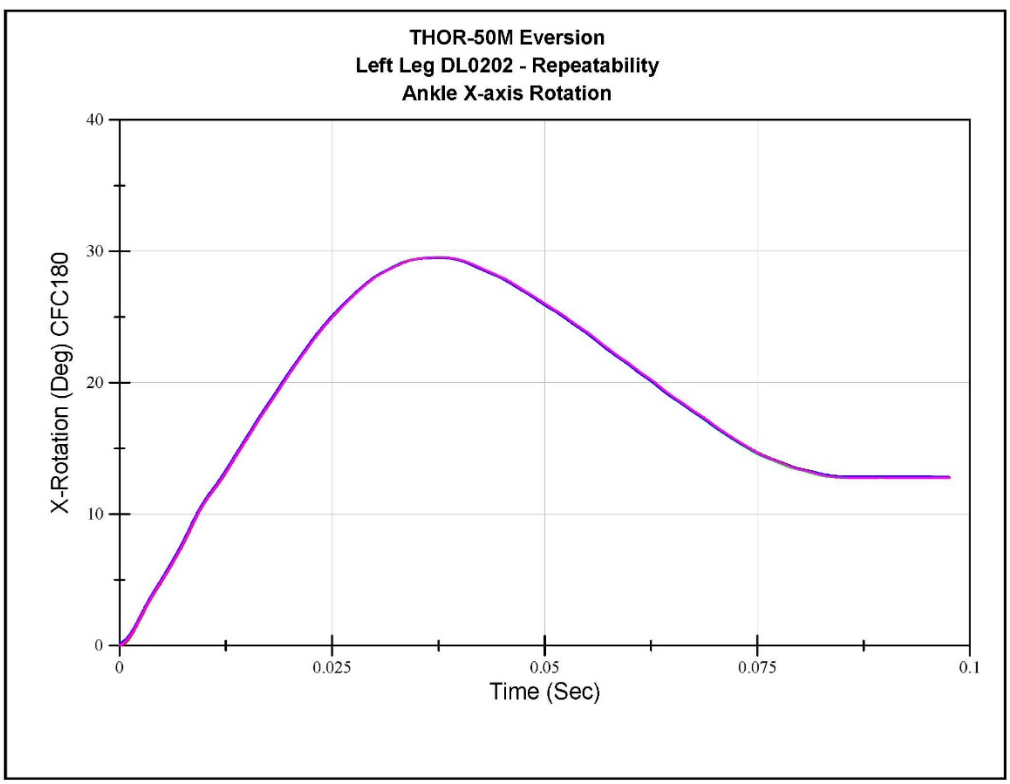

Figure 16-13. Humanetics ankle eversion X-axis rotation repeatability for DL0202

16.2.5 THOR-50M Right Lower Leg DL5404 Testing at Humanetics

Repeatability results at Humanetics for leg DL5404 yielded CV values all below 5 percent (Table 16-5 and Figure 16-14 to Figure 16-16).

Table 16-5. Humanetics THOR-50M DL5404 Right Ankle Eversion Repeatability Results

Test Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle X-axis Rotation (deg)
321	-568	-41.6	-29.6
325	-617	-45.1	-30.5
328	-608	-44.6	-30.5
332	-613	-45.0	-30.7
333	-613	-45.1	-30.8
335	-614	-44.9	-30.8
Mean	**-606**	**-44.4**	**-30.5**
Std. Dev.	**19**	**1.4**	**0.5**
CV	**3.1%**	**3.1%**	**1.5%**

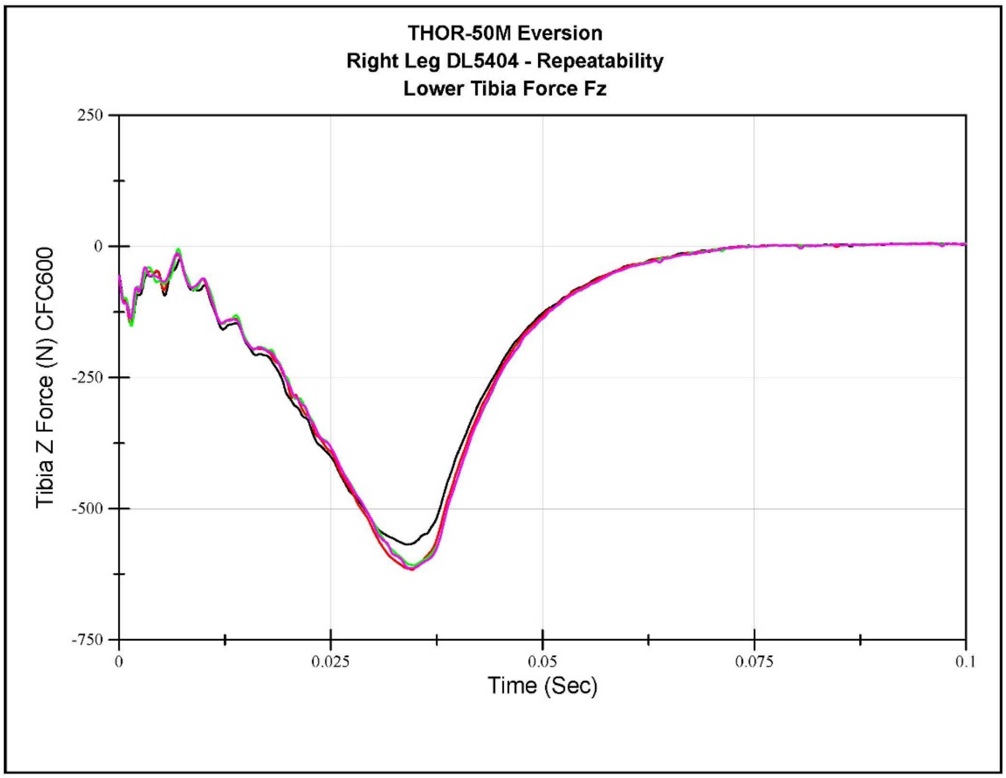

Figure 16-14. Humanetics ankle eversion lower tibia Z-force repeatability for DL5404

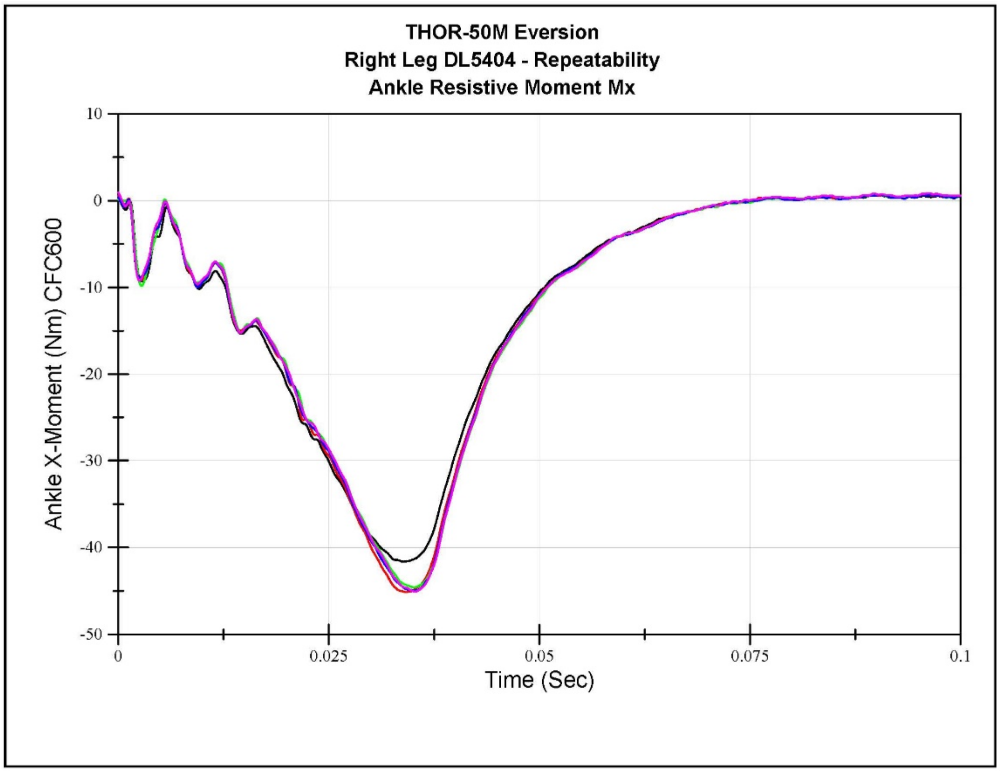

Figure 16-15. Humanetics ankle eversion resistive X-moment repeatability for DL5404

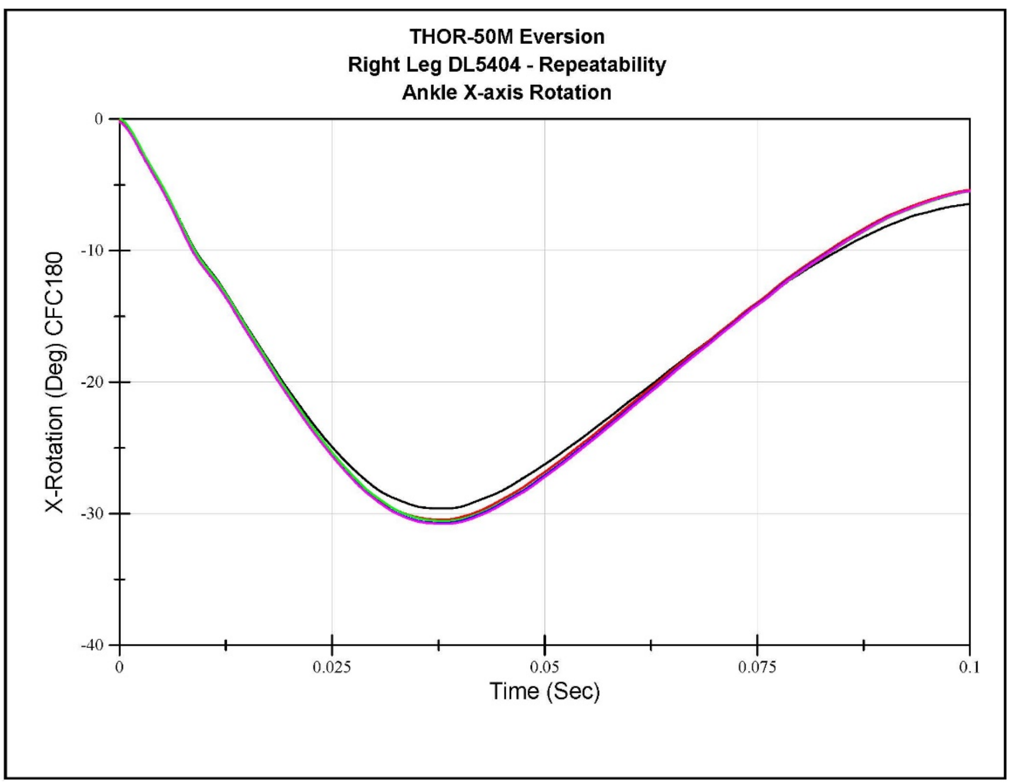

Figure 16-16. Humanetics ankle eversion X-axis rotation repeatability for DL5404

16.2.6 THOR-50M Left Lower Leg DL0202 Testing at Calspan

Repeatability results at Calspan for leg DL0202 yielded CV values below 5 percent for the peak X-axis rotation, and the peak lower tibia Fz, and peak resistive moment were above 5 percent but less than 10 percent (Table 16-6, Figure 16-17 to Figure 16-19). The elevated CV values were due to the low values in the first test.

Table 16-6. Calspan THOR-50M DL0202 Left Ankle Eversion Repeatability Results

Test Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle X-axis Rotation (deg)
20160623133759	-454	35.6	26.9
20160623140737	-530	41.5	27.0
20160623143850	-561	43.9	28.7
20160623153954	-549	43.2	27.6
Mean	**-523**	**41.0**	**27.6**
Std. Dev.	**48**	**3.8**	**0.8**
CV	**9.2%**	**9.2%**	**2.9%**

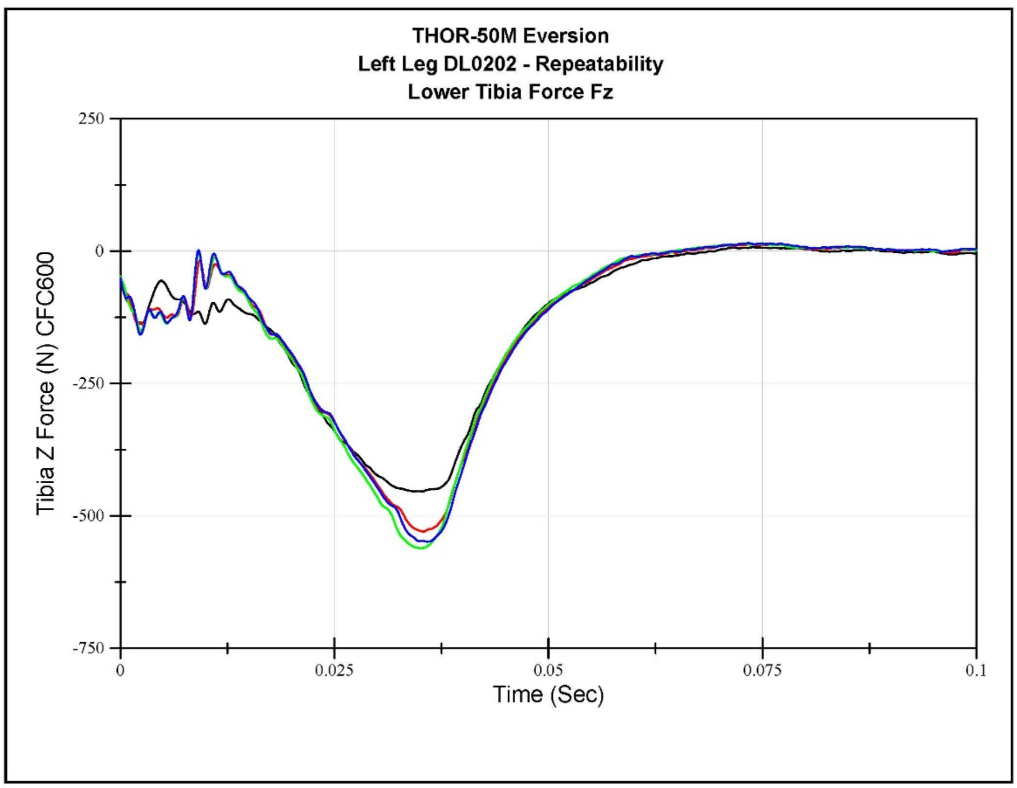

Figure 16-17. Calspan ankle eversion lower tibia Z-force repeatability for DL0202

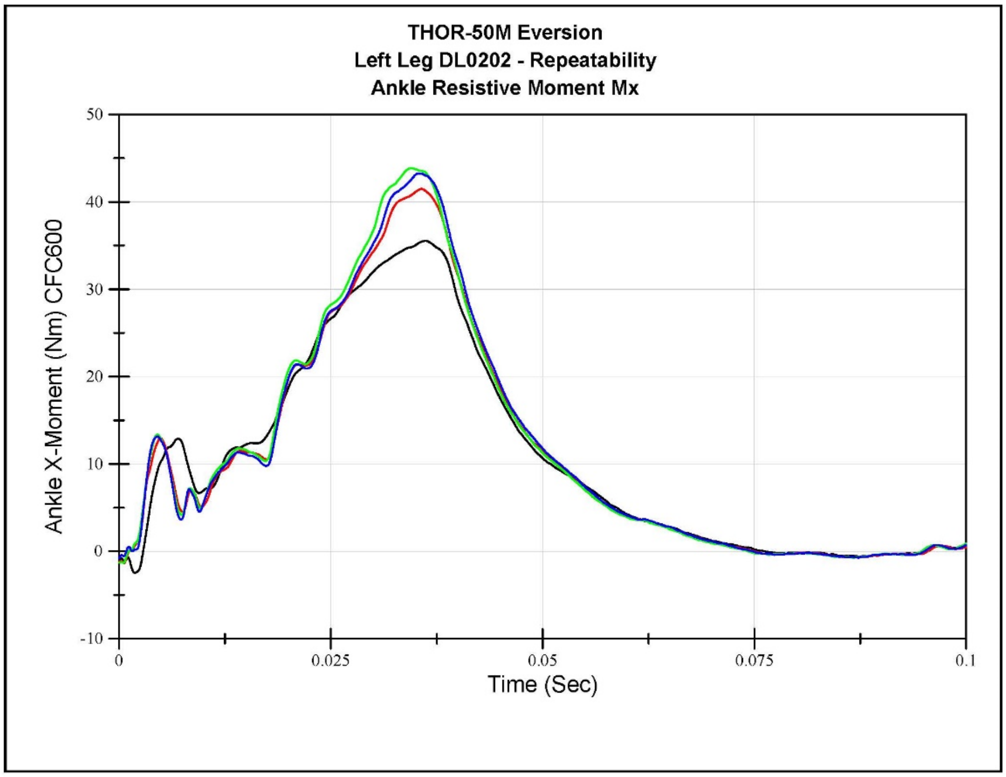

Figure 16-18. Calspan ankle eversion resistive X-moment repeatability for DL0202

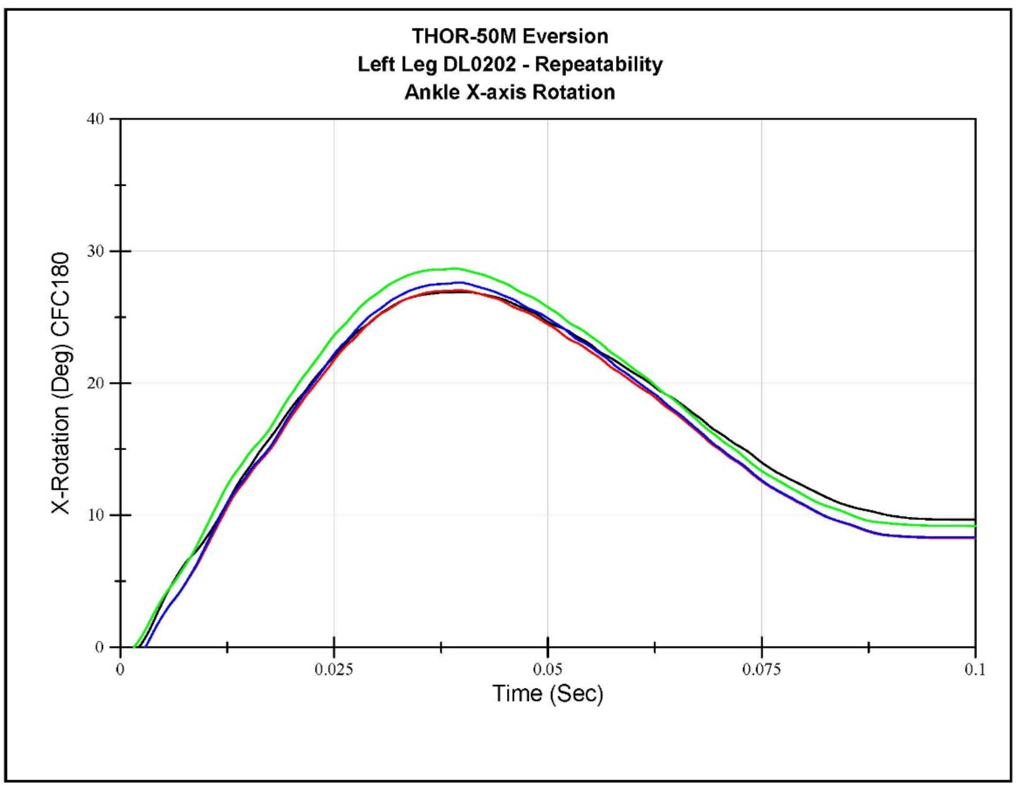

Figure 16-19. Calspan ankle eversion X-axis rotation repeatability for DL0202

16.2.7 THOR-50M Right Lower Leg DL5404 Testing at Calspan

Repeatability results at Calspan for leg DL5404 yielded CV values below 5 percent for the peak X-axis rotation and the peak lower tibia Fz, and peak resistive moment was above 5 percent but less than 10 percent (Table 16-7, Figure 16-20 to Figure 16-22).

Table 16-7. Calspan THOR-50M DL5404 Right Ankle Eversion Repeatability Results

Test Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle X-axis Rotation (deg)
20160629133518	-519	-39.6	-29.2
20160629140556	-573	-44.6	-30.2
20160629143642	-569	-44.4	-30.2
20160629150832	-578	-45.1	-30.4
20160629154307	-587	-45.4	-30.5
Mean	**-565**	**-43.8**	**-30.1**
Std. Dev.	**27**	**2.4**	**0.5**
CV	**4.8%**	**5.5%**	**1.7%**

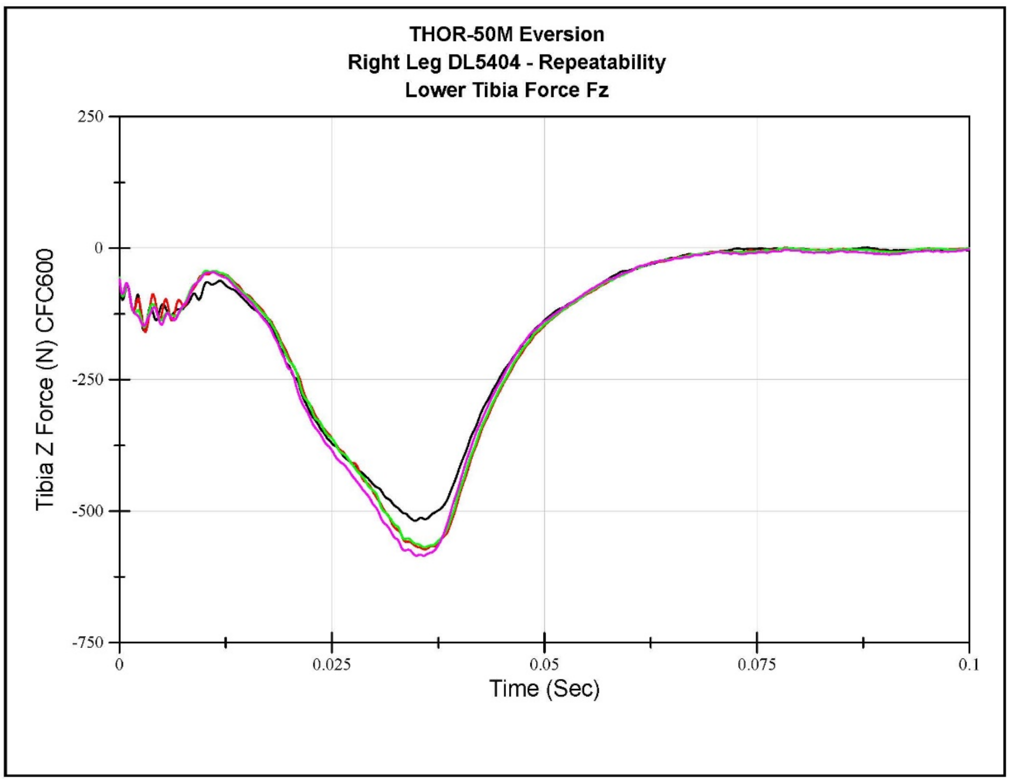

Figure 16-20. Calspan ankle eversion lower tibia Z-force repeatability for DL5404

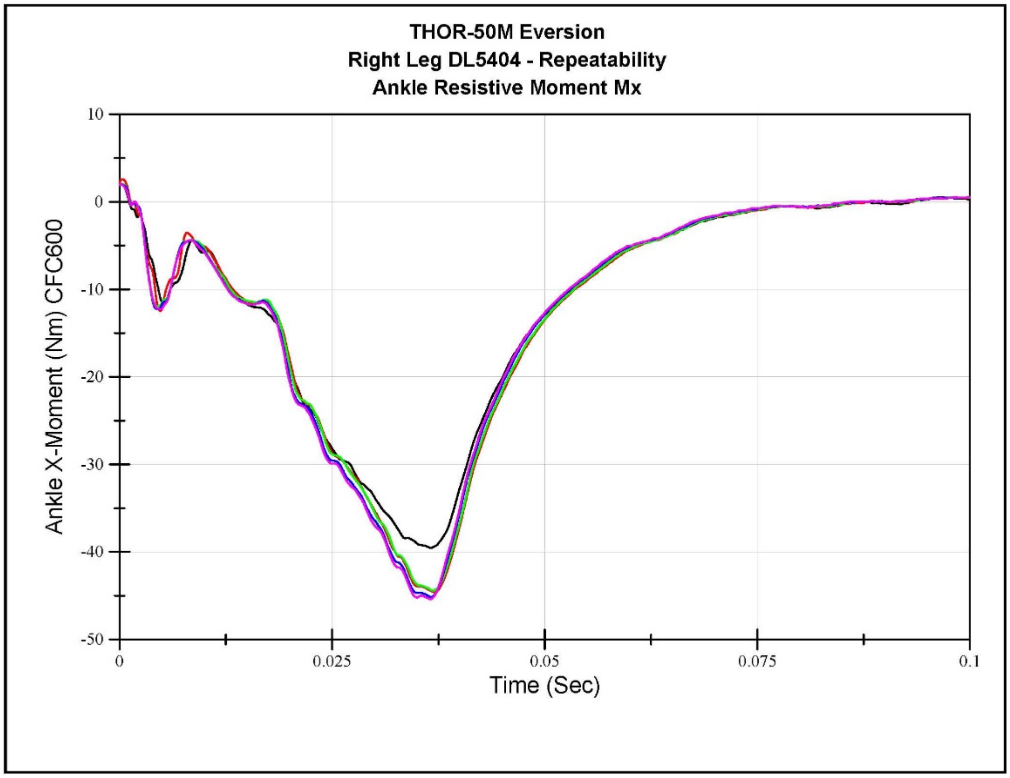

Figure 16-21. Calspan ankle eversion resistive X-moment repeatability for DL5404

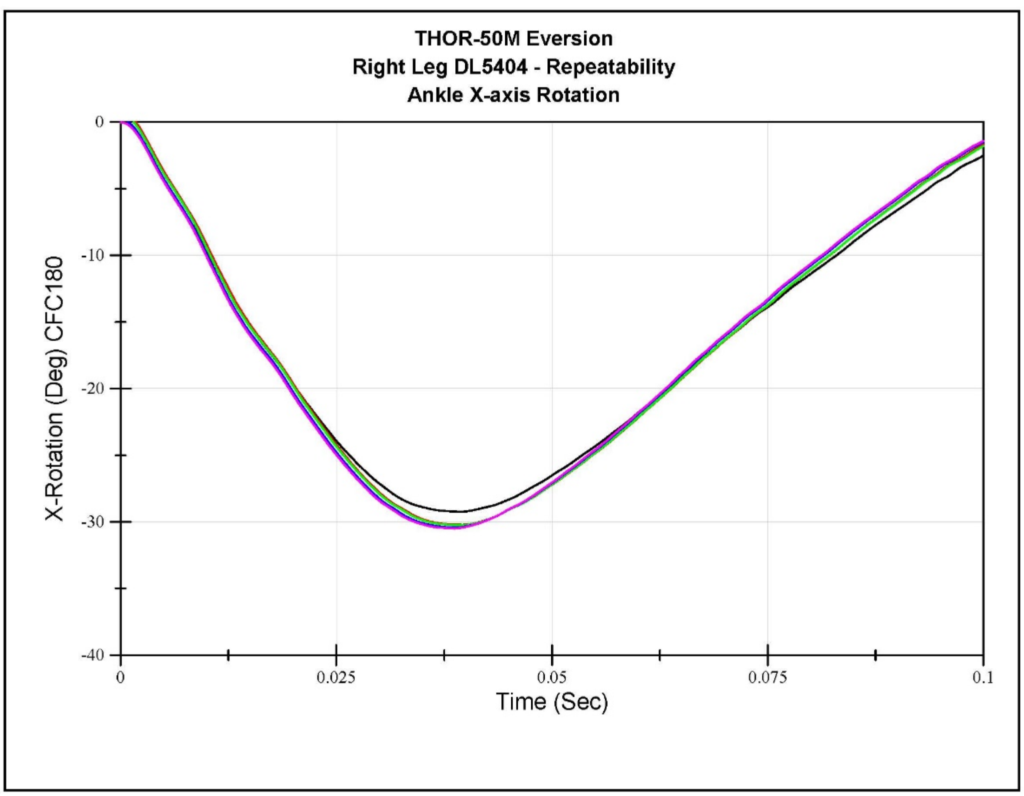

Figure 16-22. Calspan ankle eversion X-axis rotation repeatability for DL5404

16.3 Ankle Eversion Dummy Reproducibility Results

Dummy Reproducibility results at VRTC for the ankle eversion qualification yielded CV values below 5 percent for the peak X-axis rotation and the peak resistive moment, and the peak lower tibia Fz, was above 5 percent but less than 10 percent (Table 16-8). When combining left and right data, the absolute values of peak moment and peak rotation were used.

Table 16-8. THOR-50M Ankle Eversion Dummy Reproducibility Results

Leg Number	Test Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle X-axis Rotation (deg)
VRTC DL0202 Left	**160519-5**	-512	38.9	28.6
	160519-6	-555	42.3	29.5
	160519-7	-554	42.4	29.5
	160519-9	-560	42.7	29.6
	160519-10	-563	43.0	29.6
VRTC DL5404 Right	**160517-7**	-530	-39.9	-29.5
	160517-9	-571	-43.4	-30.3
	160517-10	-573	-43.5	-30.4
	160517-11	-574	-43.7	-30.4
	160517-12	-573	-43.6	-30.5
VRTC 069 Left	**160425-5**	-614	44.6	28.8
	160425-9	-614	44.8	29.1
	160425-11	-614	44.5	29.2
	160425-13	-619	45.1	29.4
Mean		**-573**	**43.0**	**29.6**
Std. Dev.		**32**	**1.79**	**0.6**
CV		**5.6%**	**4.2%**	**2.0%**

16.4 Lab-to-Lab Variability Analysis

The results for the ankle eversion tests from each lab are presented in Table 16-9 and Table 16-10. For the left ankle eversion, the last four rows of Table 16-9 show the *Test Reproducibility* results when data from all three labs are combined. The results for the left leg at Calspan yielded a CV below 5 percent for the peak X-axis rotation, and the peak lower tibia Fz and peak resistive moment were above 5 percent but less than 10 percent.

For the right ankle eversion, the last four rows of Table 16-10 show *Test Reproducibility* results when data from all three labs are combined. The results for the right leg yielded CV values all below 5 percent.

Table 16-9. THOR-50M Left Ankle Eversion Lab-to-Lab Variability Results

Leg Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle X-axis Rotation (deg)
VRTC DL0202 Left	-512	38.9	28.6
	-555	42.3	29.5
	-554	42.4	29.5
	-560	42.7	29.6
	-563	43.0	29.6
Humanetics DL0202 Left	-565	42.0	29.5
	-573	42.3	29.5
	-573	42.3	29.5
	-570	42.0	29.5
	-569	41.9	29.5
Calspan DL0202 Left	-454	35.6	26.9
	-530	41.5	27.0
	-561	43.9	28.7
	-549	43.2	27.6
Test Reproducibility DL0202 Left			
Mean	**-549**	**41.7**	**28.9**
Std. Dev.	**32**	**2.1**	**1.0**
CV	**5.9%**	**5.0%**	**3.4%**

Table 16-10. THOR-50M Right Ankle Eversion Lab-to-Lab Variability Results

Leg Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle X-axis Rotation (deg)
VRTC DL5404 Right	-530	-39.9	-29.5
	-571	-43.4	-30.3
	-573	-43.5	-30.4
	-574	-43.7	-30.4
	-573	-43.6	-30.5
Humanetics DL5404 Right	-568	-41.6	-29.6
	-617	-45.1	-30.5
	-608	-44.6	-30.5
	-613	-45.0	-30.7
	-613	-45.1	-30.8
Calspan DL5404 Right	-519	-39.6	-29.2
	-573	-44.6	-30.2
	-569	-44.4	-30.2
	-578	-45.1	-30.4
	-587	-45.4	-30.5
Test Reproducibility DL5404 Right			
Mean	**-578**	**43.6**	**30.2**
Std. Dev.	**28**	**1.9**	**0.4**
CV	**4.9%**	**4.3%**	**1.5%**

16.5 Corridor Development

All the data used to determine the ankle eversion qualification corridors is shown in Table 16-11. Data where the velocity exceeded the ± 0.05 m/s tolerance were excluded from the corridor development. The qualification corridors were calculated using the mean plus or minus 10 percent of the peak for the specified measured or calculated channels (Table 16-12 and Table 16-13).

Table 16-11. THOR-50M Ankle Eversion Qualification Corridor Results

Leg Number	Test Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle X-axis Rotation (deg)
VRTC DL0202 Left	**160519-5**	-512	38.9	28.6
	160519-6	-555	42.3	29.5
	160519-7	-554	42.4	29.5
	160519-9	-560	42.7	29.6
	160519-10	-563	43.0	29.6
VRTC DL5404 Right	**160517-7**	-530	-39.9	-29.5
	160517-9	-571	-43.4	-30.3
	160517-10	-573	-43.5	-30.4
	160517-11	-574	-43.7	-30.4
	160517-12	-573	-43.6	-30.5
VRTC 069 Left	**160425-5**	-614	44.6	28.8
	160425-9	-614	44.8	29.1
	160425-11	-614	44.5	29.2
	160425-13	-619	45.1	29.4
Humanetics DL0202 Left	**389**	-565	42.0	29.5
	392	-573	42.3	29.5
	393	-573	42.3	29.5
	395	-570	42.0	29.5
	396	-569	41.9	29.5
Humanetics DL5404 Right	**321**	-568	-41.6	-29.6
	325	-617	-45.1	-30.5
	328	-608	-44.6	-30.5
	332	-613	-45.0	-30.7
	333	-613	-45.1	-30.8
	335	-614	-44.9	-30.8
Calspan DL0202 Left	**20160623133759**	-454	35.6	26.9
	20160623140737	-530	41.5	27.0
	20160623143850	-561	43.9	28.7
	20160623153954	-549	43.2	27.6
Calspan DL5404 Right	**20160629133518**	-519	-39.6	-29.2
Calspan DL5404 Right	**20160629140556**	-573	-44.6	-30.2
	20160629143642	-569	-44.4	-30.2
	20160629150832	-578	-45.1	-30.4
	20160629154307	-587	-45.4	-30.5
Mean		**-571**	**43.0**	**29.6**
Std. Dev.		**36**	**2.1**	**1.0**
CV		**6.2%**	**5.0%**	**3.3%**

Table 16-12. Left Ankle Eversion Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Impact Velocity	**m/s**	1.95	2.05	2.00	
Peak Lower Tibia Fz	**N**	-629	-514	-571	10%
Peak Ankle Resistive Moment	**Nm**	38.7	47.3	43.0	10%
Peak Ankle X-axis Rotation	**deg**	26.6	32.5	29.6	10%

Table 16-13. Right Ankle Eversion Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Impact Velocity	**m/s**	1.95	2.05	2.00	
Peak Lower Tibia Fz	**N**	-629	-514	-571	10%
Peak Ankle Resistive Moment	**Nm**	-47.3	-38.7	-43.0	10%
Peak Ankle X-axis Rotation	**deg**	-32.5	-26.6	-29.6	10%

Discussion. Similar to what was observed in the ankle inversion test, the initial trial in a test series exhibited a peak ankle moment, peak lower tibia Fz, and peak ankle rotation that were slightly lower than subsequent tests. This is also thought to be related to the Ensolite pad, a *Test Repeatability* issue. The initial test effect was particularly prominent at Calspan. When those tests are ignored, the CV values of all metrics are significantly improved.

As with the inversion tests, initial test effect is only a minor impediment in qualifying the ankle (simply repeat the test). Only two initial tests (one at VRTC, one at Calspan) had responses below 10 percent of the target response (Table 16-11, yellow cells). All other tests were within 10 percent of the target.

Dummy Reproducibility does not appear to be a concern in the relevant tests (Section 16.3) run at VRTC (same lab, three different legs). In those tests, we did note that the CV for tibia force was slightly elevated (5.6%). However, this CV was influenced by low forces in the initial tests, which is related to *Test Repeatability* as discussed above. The CVs for ankle moment and rotation were both low: 4.2% and 2.0%, respectively.

Test Reproducibility did not pose an obstacle to demonstrating the uniformity of the dummy, as tests at the three different labs on the same ankle produced similar responses.

17 Ball of Foot

17.1 Methodology

Repeatability and reproducibility 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. In these tests, the molded shoe was utilized, as described in the *THOR-50M Drawing Package*, while the leg is held rigidly with the tibia horizontal (Figure 17-1). The test utilizes the NHTSA Dynamic Impactor (TLX-9000-013), as described in the *THOR-50M Drawing Package,* with an effective mass of 5.00 ± 0.02 kg. 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 pendulum impacts the ball of the foot at a velocity of 5.00 ± 0.05 m/s. During these tests, the lower tibia Z-axis force (Fz) and Y-axis rotation were measured; the ankle resistive moment about the Y-axis was calculated from the X-axis force (Fx) and Y-axis moment (My).

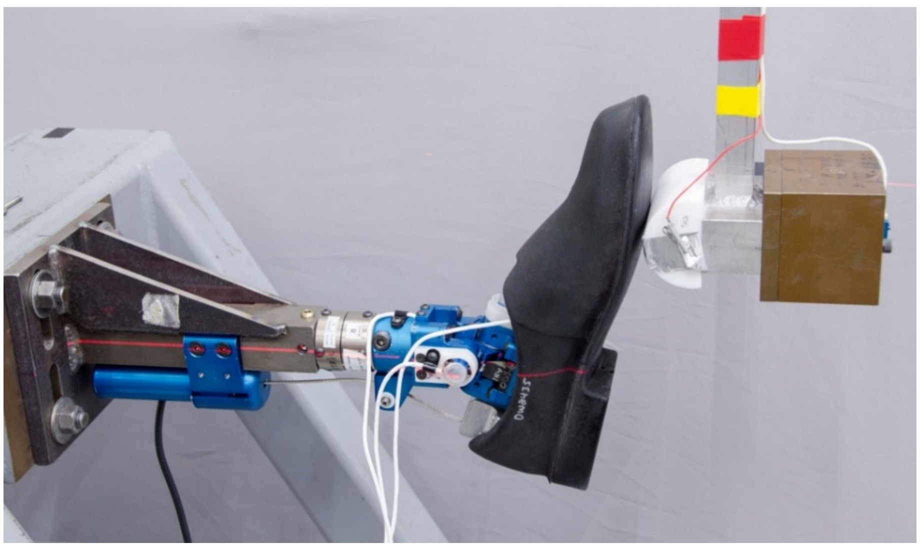

Figure 17-1. Ball of Foot Test

17.2 Ball of Foot Impact Repeatability Results

Sections 17.2.1 to 17.2.7 illustrate the results of the ball of foot impact repeatability tests. Each section contains a table providing the test data, followed by plot overlays of the five repeat tests conducted at all three labs. Note that the data in the tables containing the results of each test series are listed sequentially, with the test at the top of the table beginning the test series.

17.2.1 THOR-50M Left Lower Leg DL0202 Testing at VRTC

Repeatability results at VRTC for leg DL0202 yielded CV values all below 5 percent (Table 17-1, Figure 17-2 to Figure 17-4).

Table 17-1. VRTC THOR-50M Leg DL0202 Left Ball of Foot Repeatability Results

Leg Number Shoe Number	Test Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle Y-axis Rotation (in dorsiflexion) (deg)
DL0202 Left Leg DW2433/DV0872 (A) Shoe	**160518-5**	-3106	53.5	34.1
	160518-6	-3024	54.6	34.8
	160518-7	-3008	54.5	34.9
	160518-8	-3002	54.5	35.0
	160518-9	-3000	54.5	35.1
Mean		**-3028**	**54.3**	**34.8**
Std. Dev.		**45**	**0.5**	**0.4**
CV		**1.5%**	**0.9%**	**1.1%**

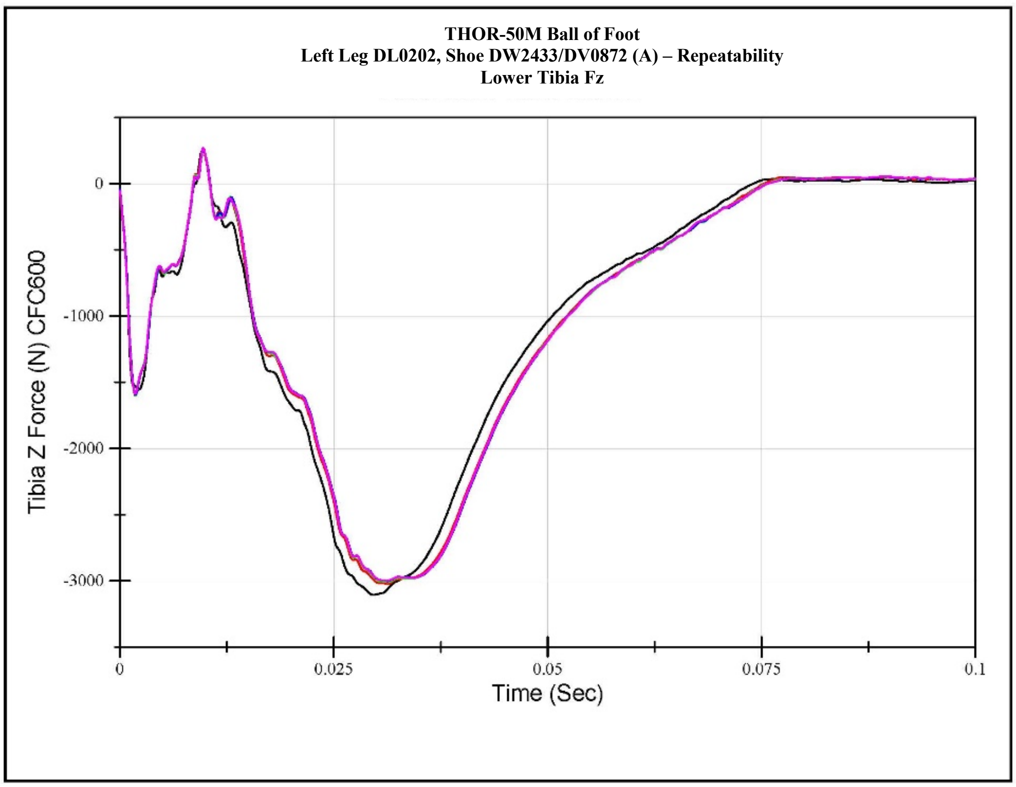

Figure 17-2. VRTC ball of foot lower tibia Z-force repeatability for DL0202

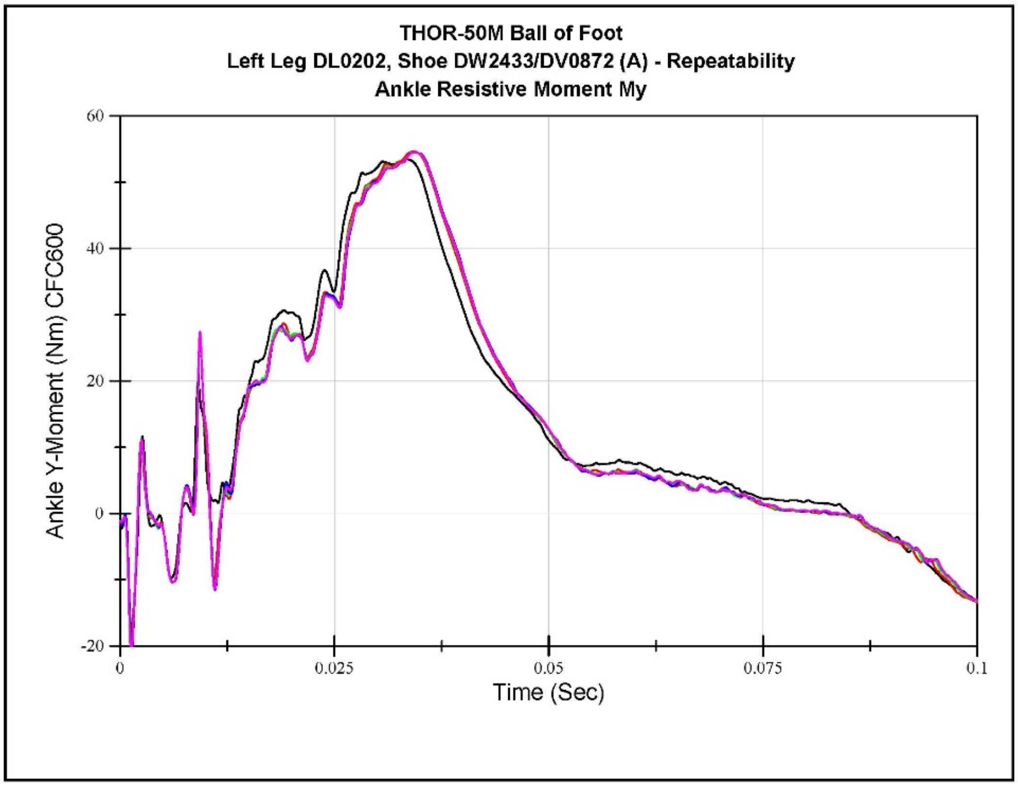

Figure 17-3. VRTC ball of foot ankle resistive Y-moment repeatability for DL0202

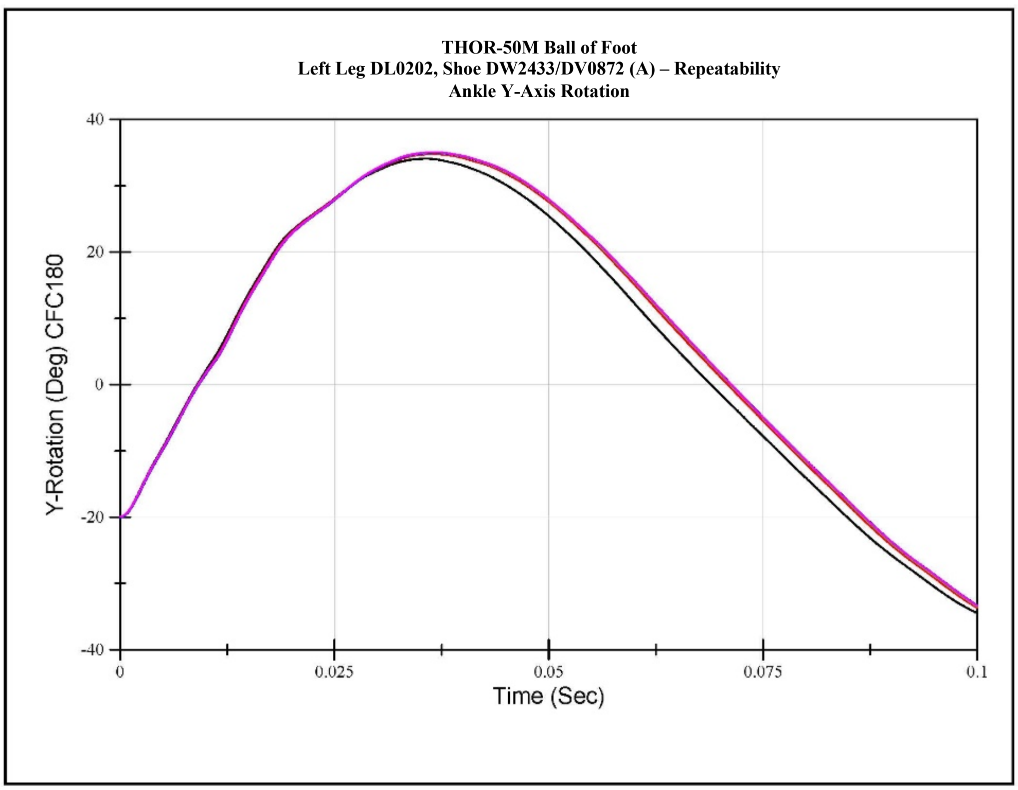

Figure 17-4. VRTC ball of foot ankle Y-axis rotation repeatability for DL0202

17.2.2 THOR-50M Right Lower Leg DL5404 Testing at VRTC

Repeatability results at VRTC for leg DL5404 yielded CV values all below 5 percent (Table 17-2, Figure 17-5 to Figure 17-7).

Table 17-2. VRTC THOR-50M Leg DL5404 Right Ball of Foot Repeatability Results

Leg Number Shoe Number	Test Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle Y-axis Rotation (in dorsiflexion) (deg)
DL5404 Right Leg DV0860/DV0874 (B) Shoe	**160512-1**	-3005	55.5	34.5
	160512-3	-2983	55.1	34.5
	160516-3	-3002	54.2	34.3
	160516-4	-2987	55.8	34.5
	160516-5	-2990	56.3	34.5
Mean		**-2994**	**55.4**	**34.5**
Std. Dev.		**10**	**0.8**	**0.1**
CV		**0.3%**	**1.4%**	**0.3%**

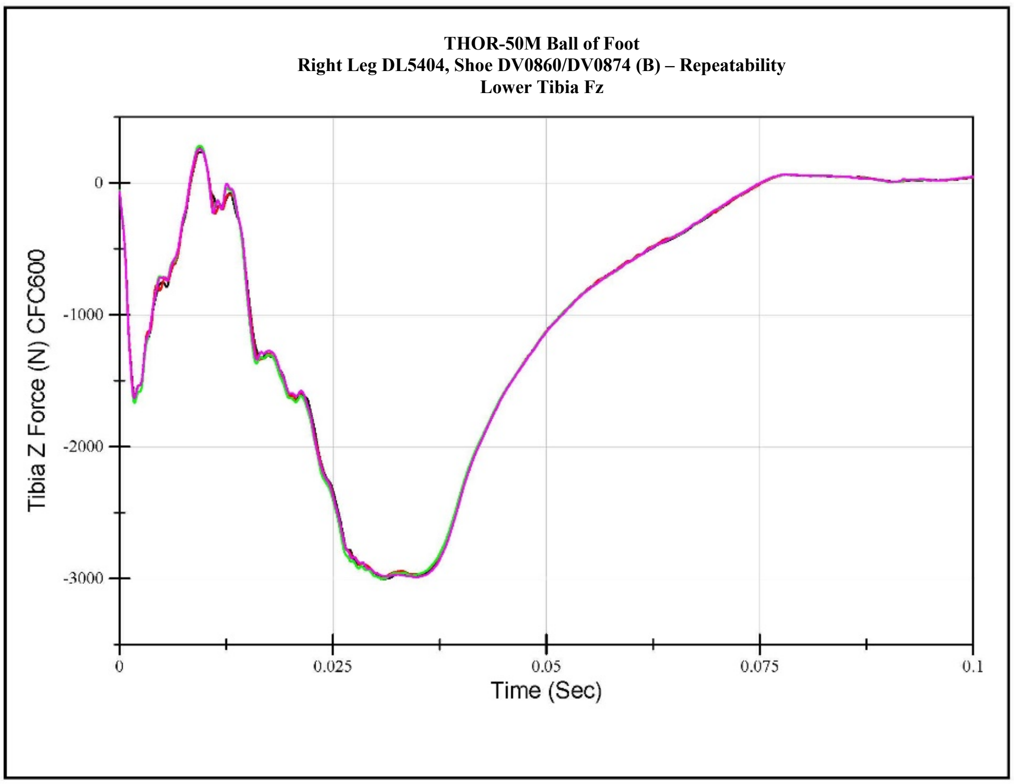

Figure 17-5. VRTC ball of foot lower tibia Z-force repeatability for DL5404

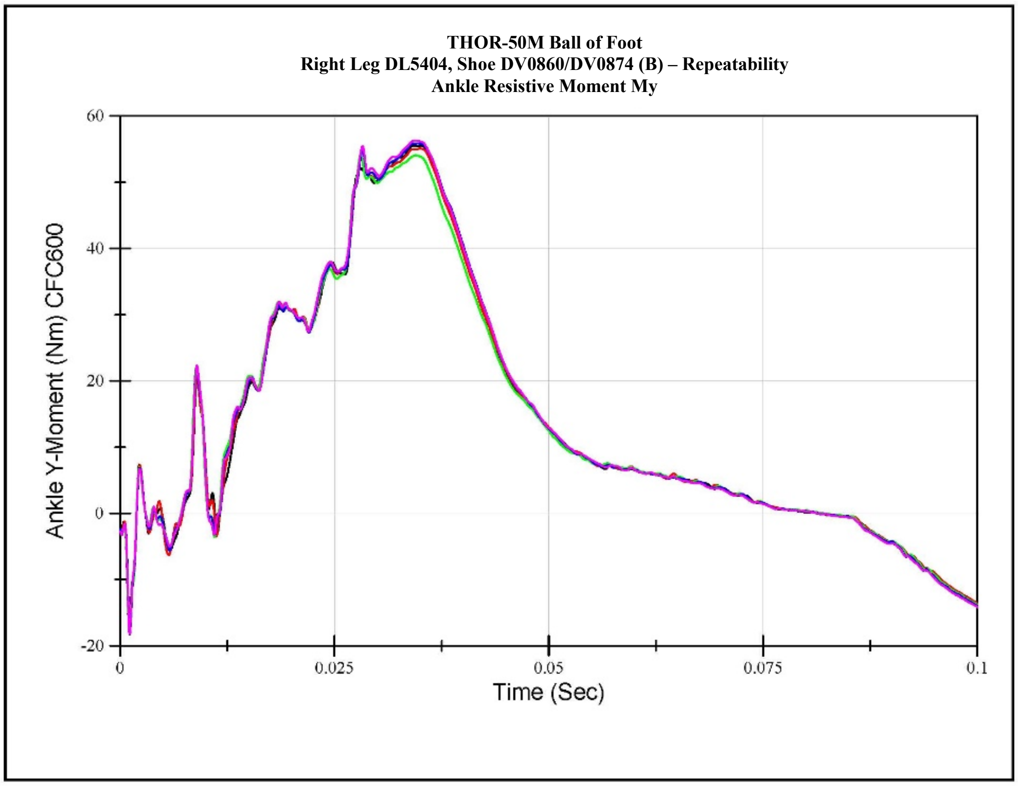

Figure 17-6. VRTC ball of foot ankle resistive Y-moment repeatability for DL5404

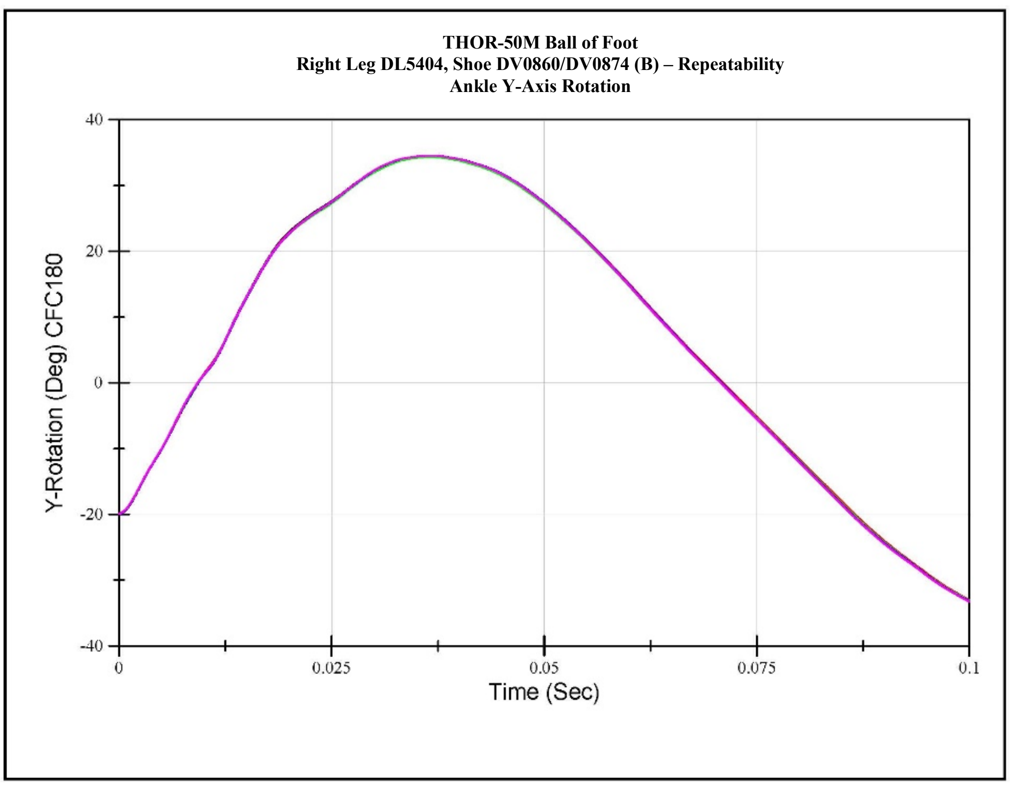

Figure 17-7. VRTC ball of foot ankle Y-axis rotation repeatability for DL5404

17.2.3 THOR-50M Left Lower Leg 069 Testing at VRTC

Repeatability results at VRTC for leg 069 yielded CV values all below 5 percent (Table 17-3, Figure 17-8 to Figure 17-10).

Table 17-3. VRTC THOR-50M Leg 069 Left Ball of Foot Repeatability Results

Leg Number Shoe Number	Test Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle Y-axis Rotation (in dorsiflexion) (deg)
Leg 069 Left Leg DV085/DW2435 (D) Shoe	**160420-6**	-3143	57.1	32.8
	160420-11	-3155	56.1	33.3
	160421-1	-3153	56.3	33.3
	160421-2	-3119	56.3	33.3
	160421-3	-3121	56.4	33.3
Mean		**-3138**	**56.4**	**33.2**
Std. Dev.		**17**	**0.4**	**0.2**
CV		**0.6%**	**0.7%**	**0.7%**

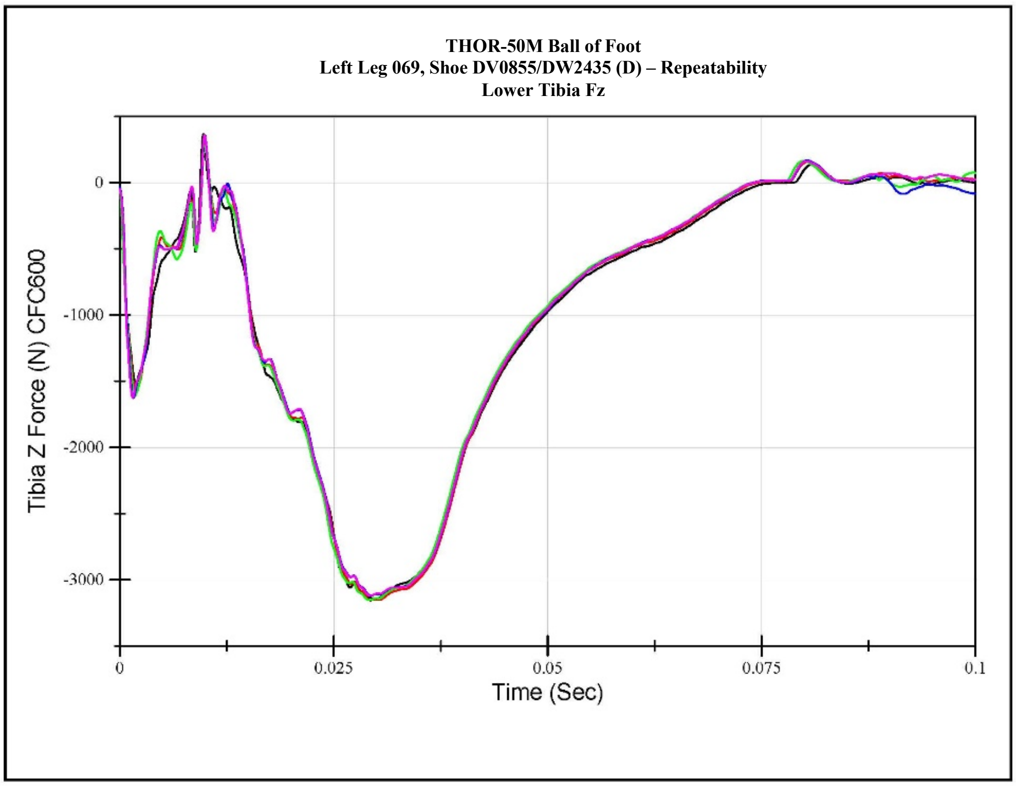

Figure 17-8. VRTC ball of foot lower tibia Z-force repeatability for 069

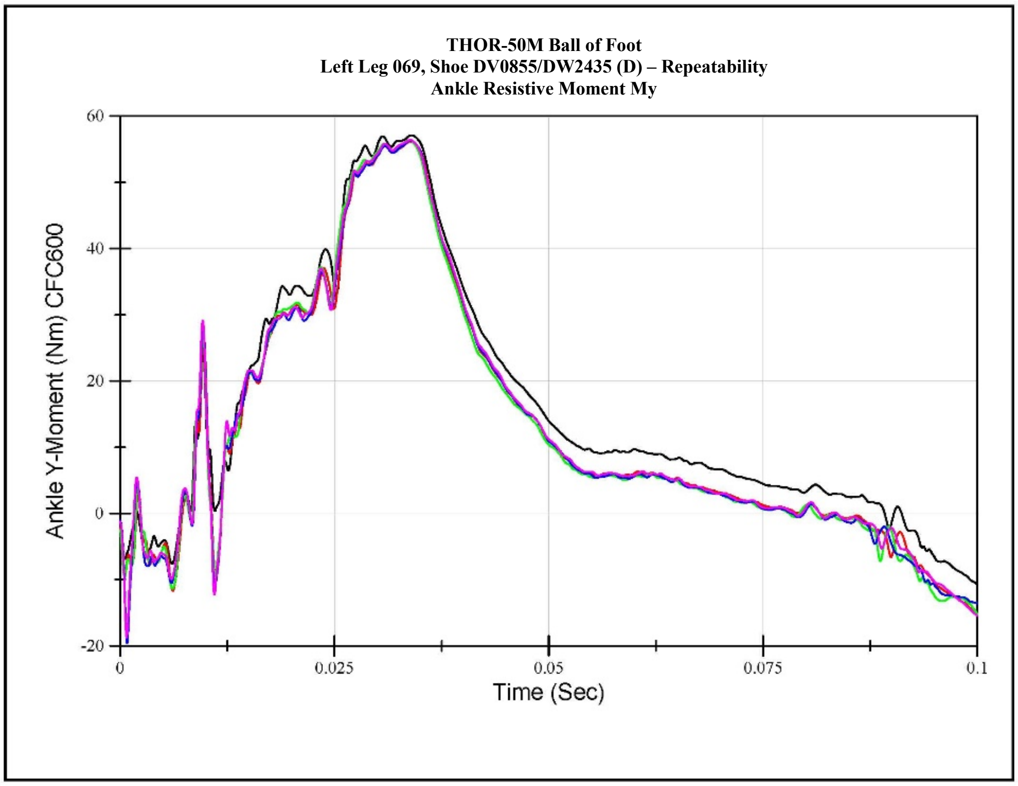

Figure 17-9. VRTC ball of foot ankle resistive Y-moment repeatability for 069

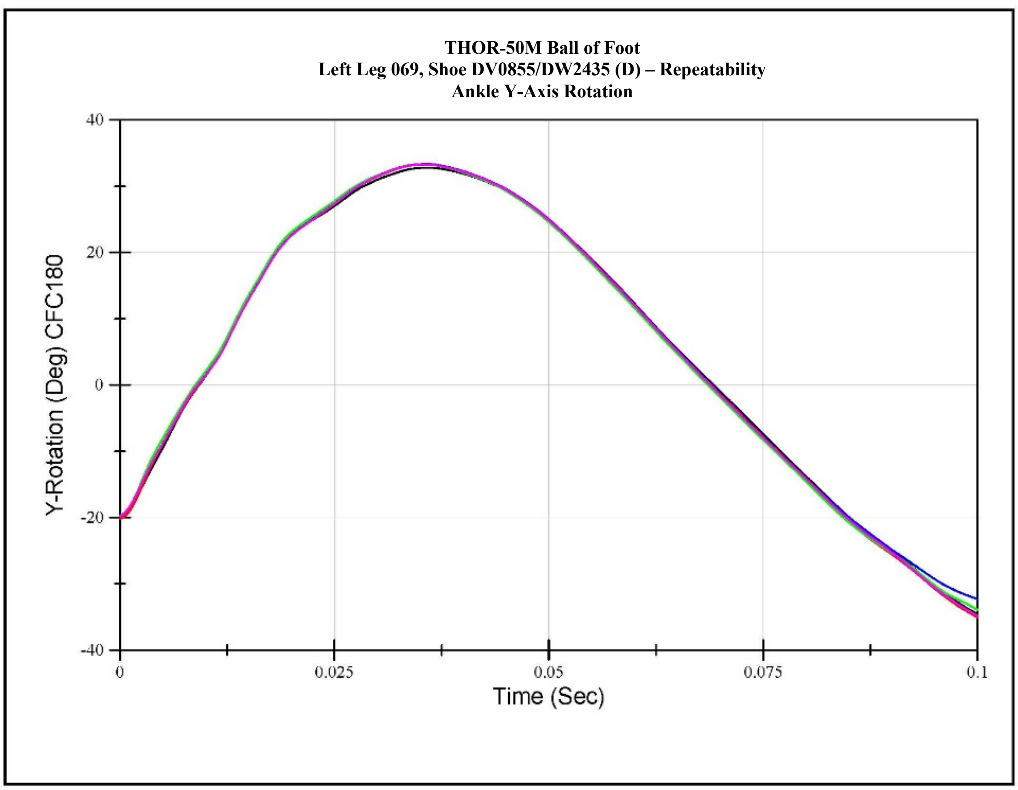

Figure 17-10. VRTC ball of foot ankle Y-axis rotation repeatability for 069

17.2.4 THOR-50M Left Lower Leg DL0202 Testing at Humanetics

Repeatability results at Humanetics for leg DL0202 yielded CV values all below 5 percent (Table 17-4, Figure 17-11 to Figure 17-13).

Table 17-4. Humanetics THOR-50M Leg DL0202 Left Ball of Foot Repeatability Results

Leg Number Shoe Number	Test Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle Y-axis Rotation (in dorsiflexion) (deg)
DL0202 Left Leg DW2433/DV0872 (A) Shoe	**730**	-3212	51.3	33.3
	733	-3219	51.9	33.9
	738	-3229	52.2	34.1
	740	-3207	53.3	34.2
	744	-3170	52.3	33.8
Mean		**-3207**	**52.2**	**33.9**
Std. Dev.		**23**	**0.7**	**0.3**
CV		**0.7%**	**1.4%**	**1.0%**

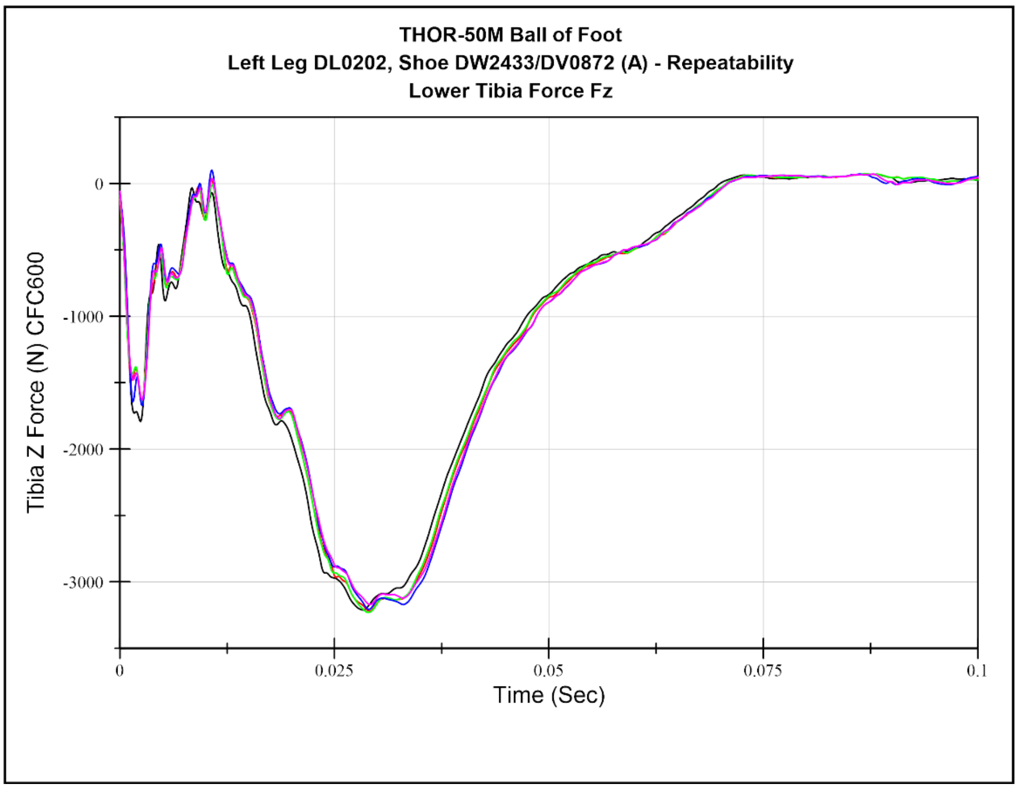

Figure 17-11. Humanetics ball of foot lower tibia Z-force repeatability for DL0202

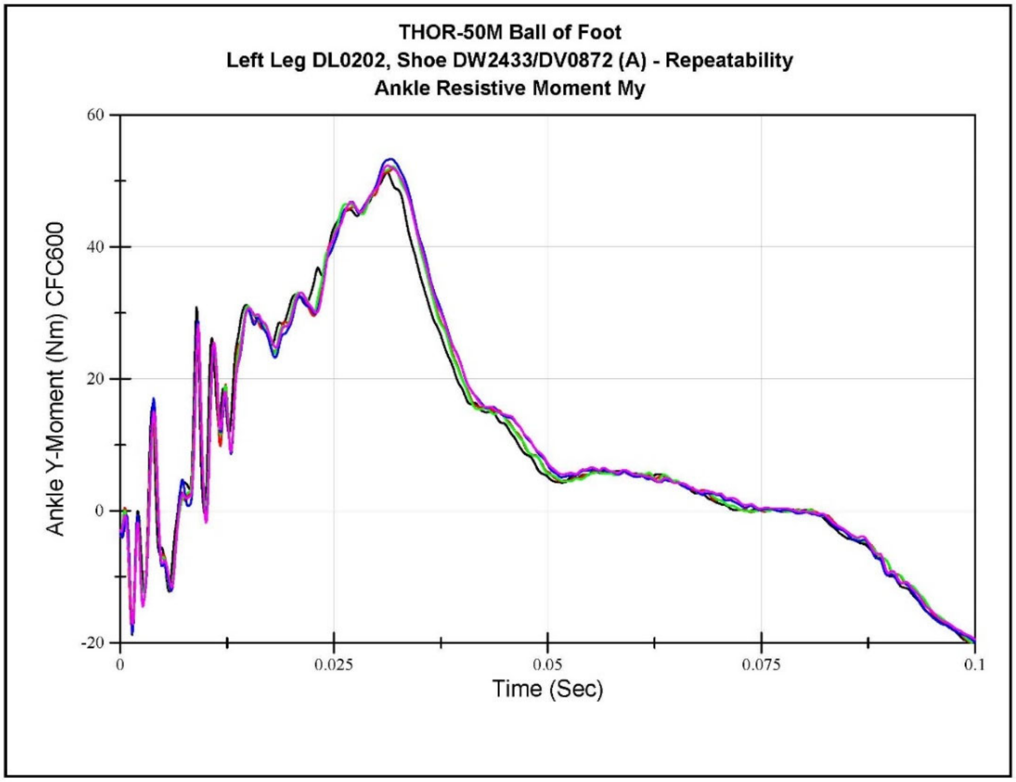

Figure 17-12. Humanetics ball of foot ankle resistive Y-moment repeatability for DL0202

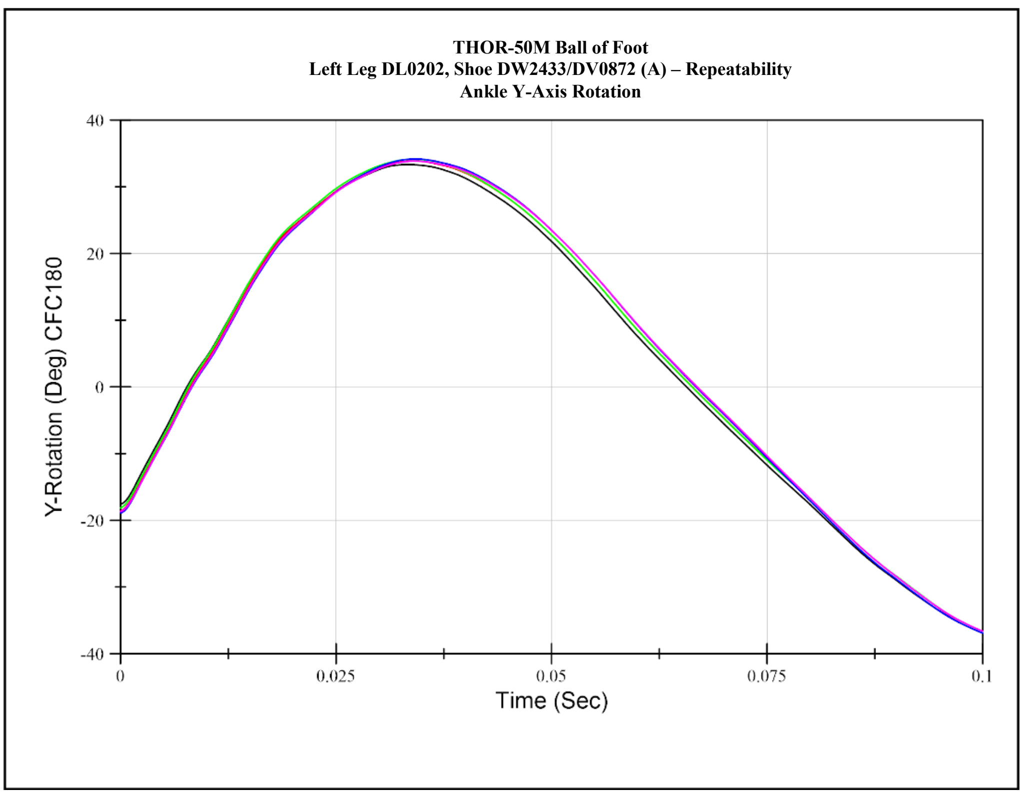

Figure 17-13. Humanetics ball of foot ankle Y-axis rotation repeatability for DL0202

17.2.5 THOR-50M Right Lower Leg DL5404 Testing at Humanetics

Repeatability results at Humanetics for leg DL5404 yielded CV values all below 5 percent (Table 17-5, Figure 17-14 to Figure 17-16).

Table 17-5. Humanetics THOR-50M Leg DL5404 Right Ball of Foot Repeatability Results

Leg Number Shoe Number	Test Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle Y-axis Rotation (in dorsiflexion) (deg)
DL5404 Right Leg DV0860/DV0874 (B) Shoe	**675**	-3342	48.3	32.7
	677	-3412	51.8	33.5
	678	-3405	52.1	33.6
	681	-3385	50.6	33.8
	685	-3371	50.6	34.0
Mean		**-3383**	**50.7**	**33.5**
Std. Dev.		**28**	**1.5**	**0.5**
CV		**0.8%**	**2.9%**	**1.6%**

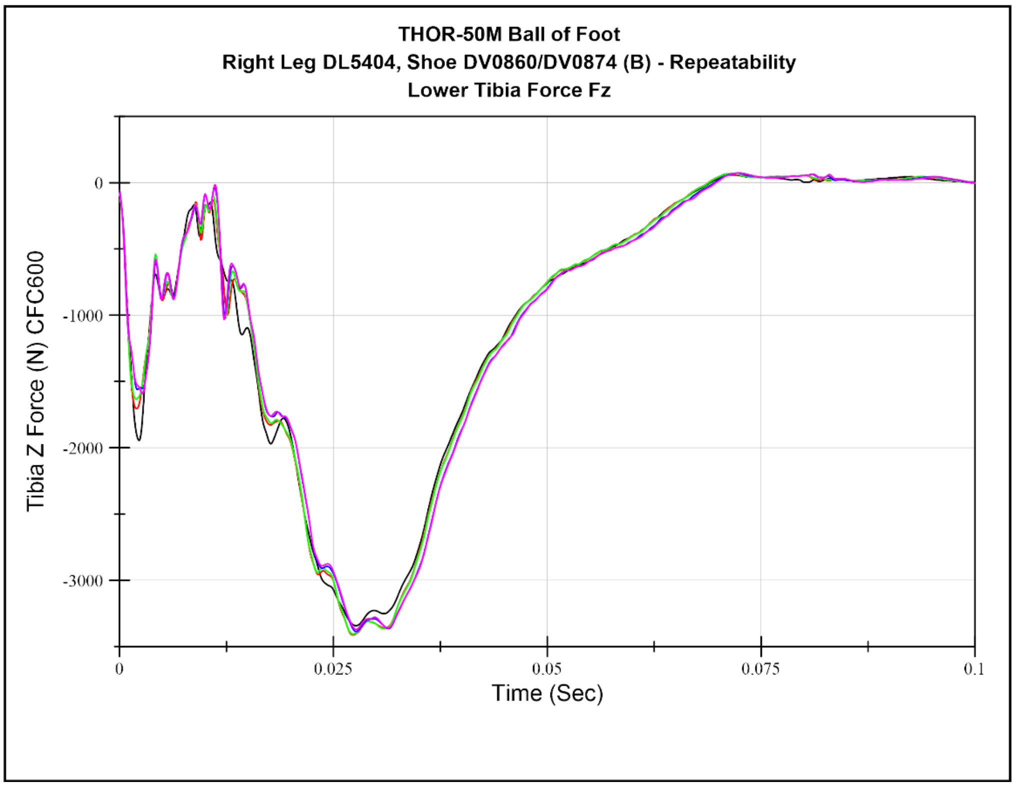

Figure 17-14. Humanetics ball of foot lower tibia Z-force repeatability for DL5404

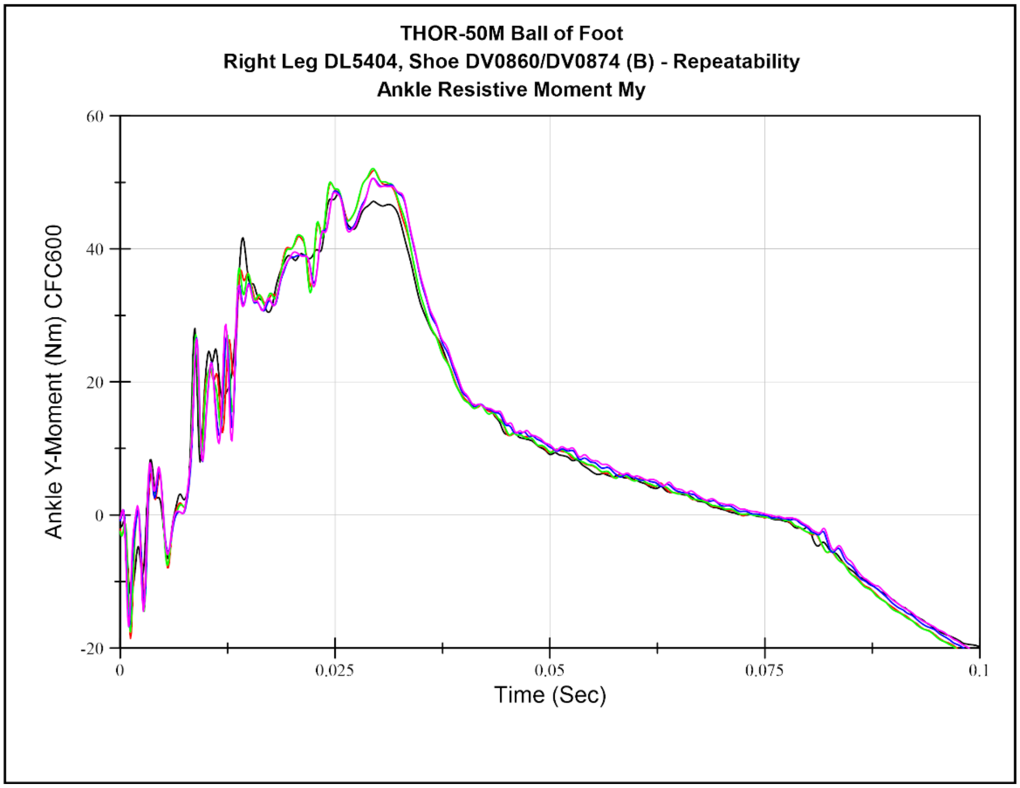

Figure 17-15. Humanetics ball of foot ankle resistive Y-moment repeatability for DL5404

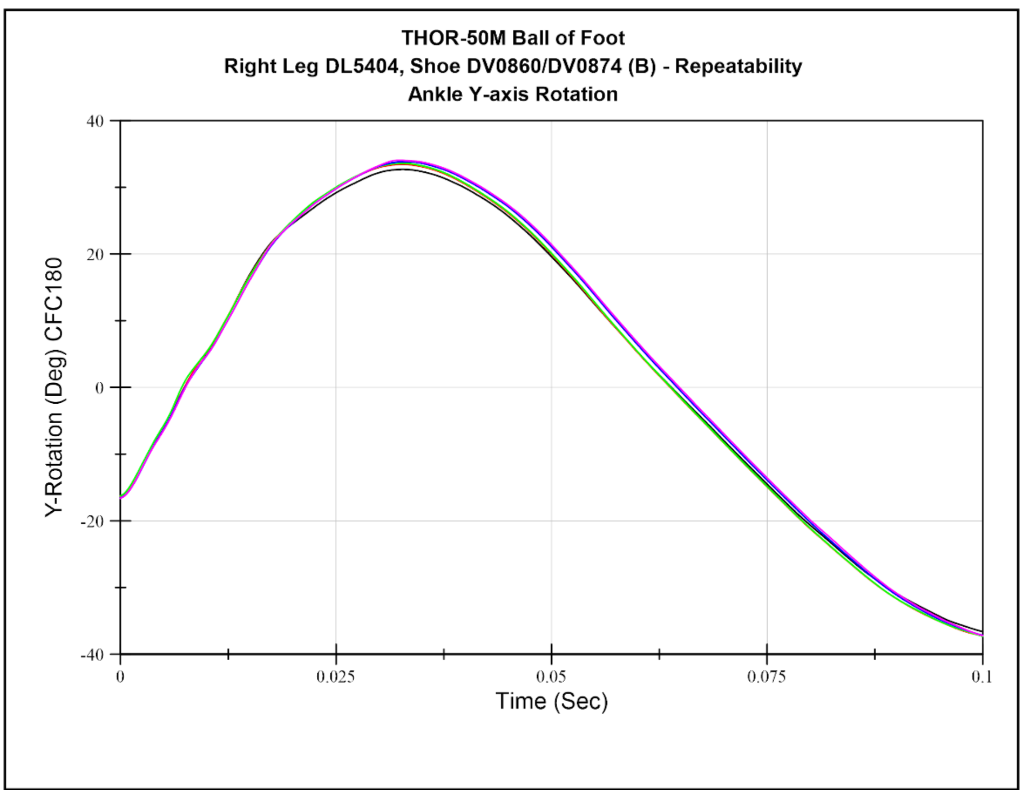

Figure 17-16. Humanetics ball of foot ankle Y-axis rotation repeatability for DL5404

17.2.6 THOR-50M Left Lower Leg DL0202 Testing at Calspan

Although only two tests met the input requirements, repeatability results from these tests at Calspan for leg DL0202 yielded CV values all below 5 percent (Table 17-6, Figure 17-17 to Figure 17-19).

Table 17-6. Calspan THOR-50M Leg DL0202 Left Ball of Foot Repeatability Results

Leg Number Shoe Number	Test Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle Y-axis Rotation (in dorsiflexion) (deg)
DL0202 Left Leg DW2433/DV0872 (A) Shoe	**20160623093709**	-3113	58.1	33.5
	20160623101023	-3084	59.1	33.3
Mean		**-3099**	**58.6**	**33.4**
Std. Dev.		**21**	**0.7**	**0.1**
CV		**0.7%**	**1.2%**	**0.4%**

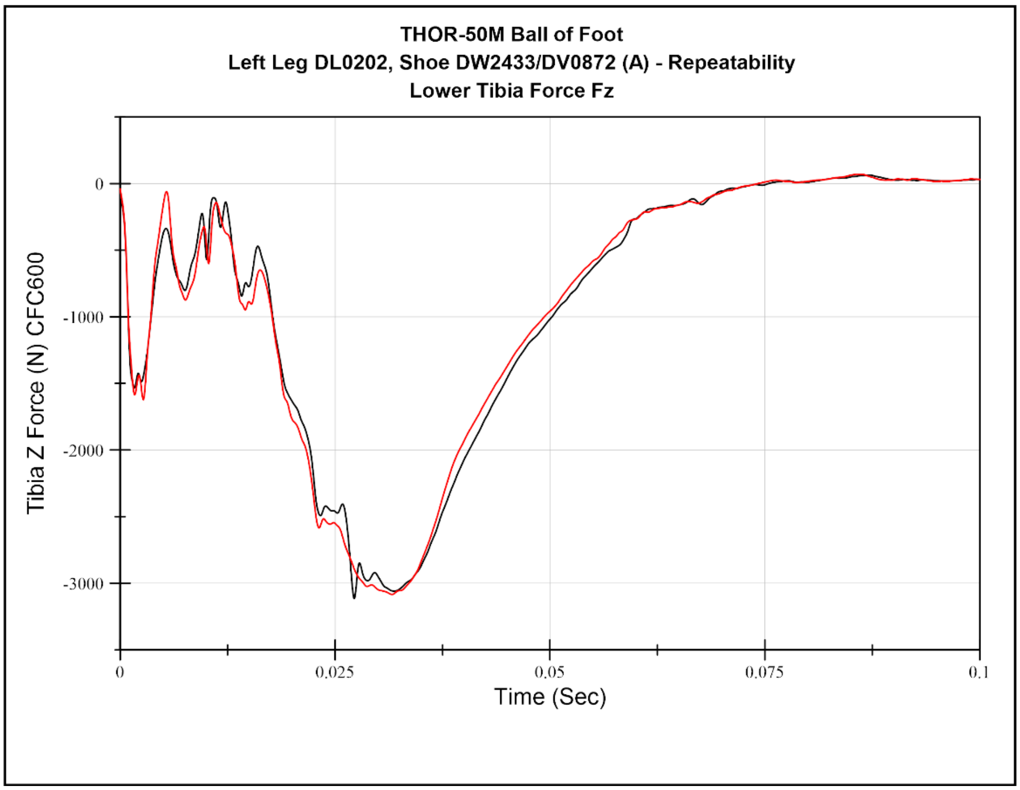

Figure 17-17. Calspan ball of foot lower tibia Z-force repeatability for DL0202

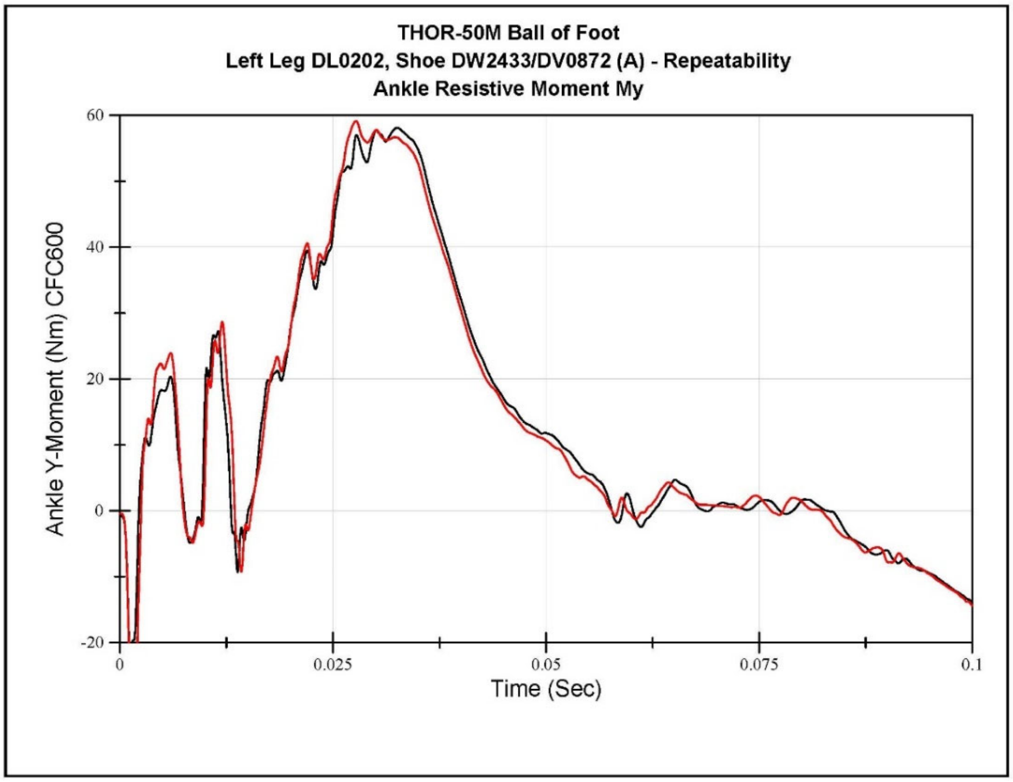

Figure 17-18. Calspan ball of foot ankle resistive Y-moment repeatability for DL0202

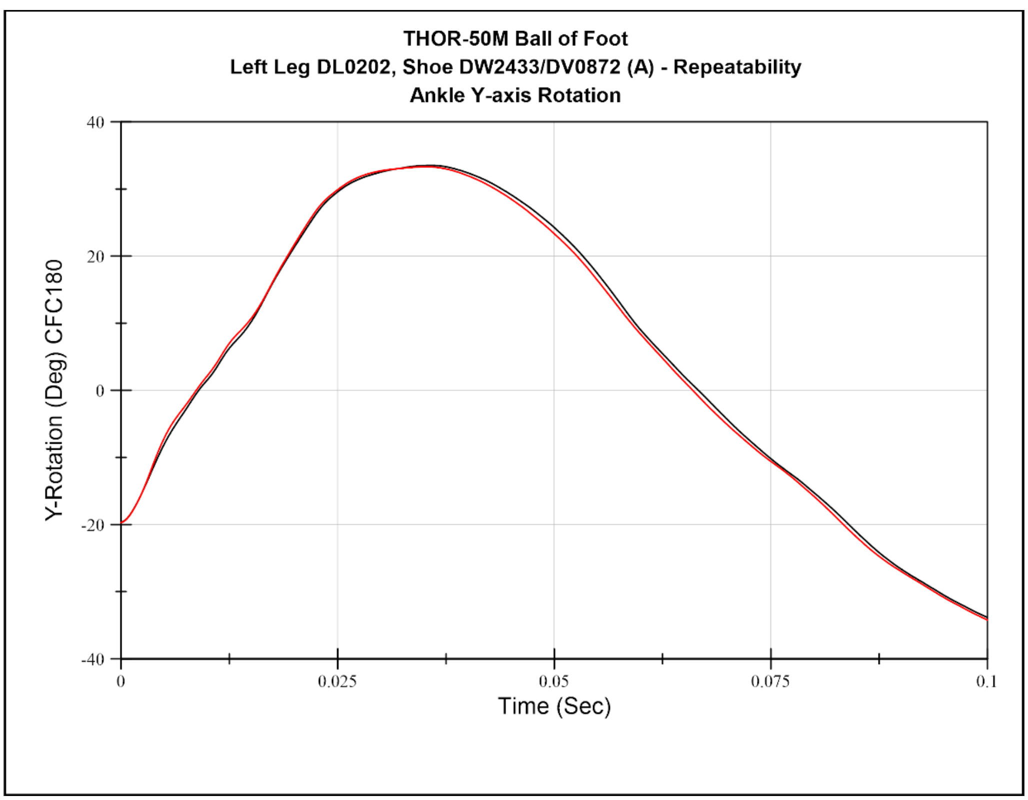

Figure 17-19. Calspan ball of foot ankle Y-axis rotation repeatability for DL0202

17.2.7 THOR-50M Right Lower Leg DL5404 Testing at Calspan

Repeatability results at Calspan for leg DL5404 yielded CV values all below 5 percent (Table 17-7, Figure 17-20 to Figure 17-22).

Table 17-7. Calspan THOR-50M Leg DL5404 Right Ball of Foot Repeatability Results

Leg Number Shoe Number	Test Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle Y-axis Rotation (in dorsiflexion) (deg)
DL5404 Right Leg DV0860/DV0874 (B) Shoe	**20160629095614**	-3253	60.6	33.1
	20160629103002	-3271	61.5	33.2
	20160629113819	-3326	61.3	33.3
	20160629124035	-3328	61.8	33.3
	20160629131338	-3327	61.7	33.4
Mean		**-3301**	**61.4**	**33.3**
Std. Dev.		**36**	**0.5**	**0.1**
CV		**1.1%**	**0.8%**	**0.3%**

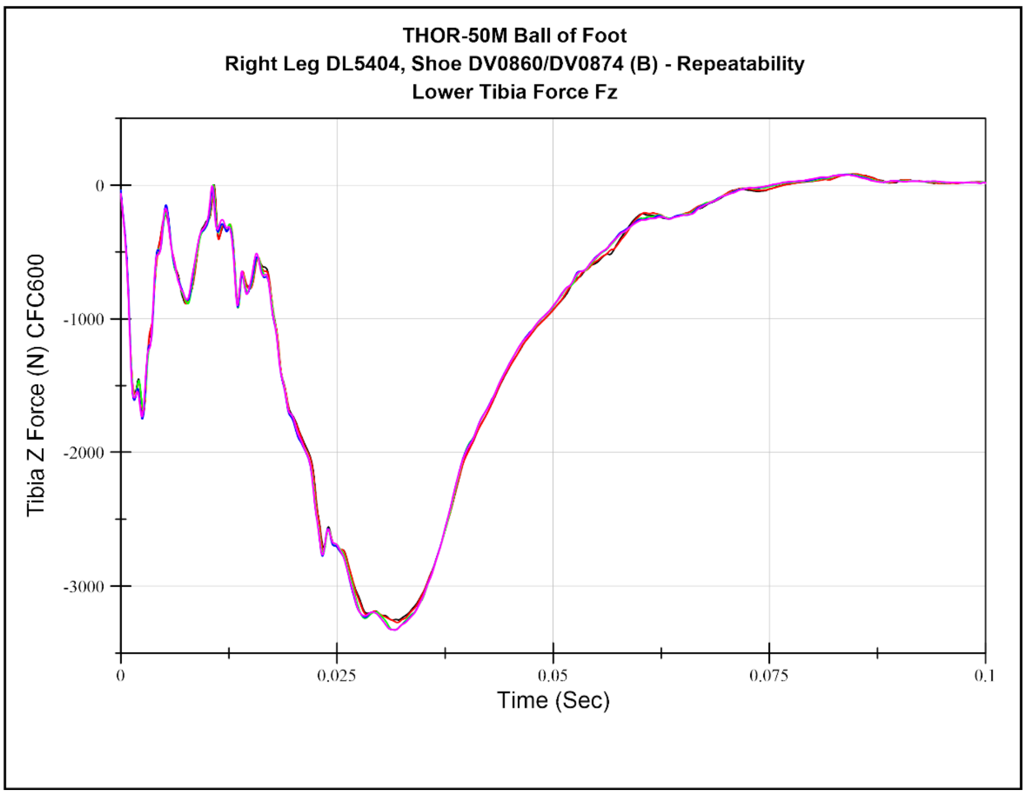

Figure 17-20. Calspan ball of foot lower tibia Z-force repeatability for DL5404

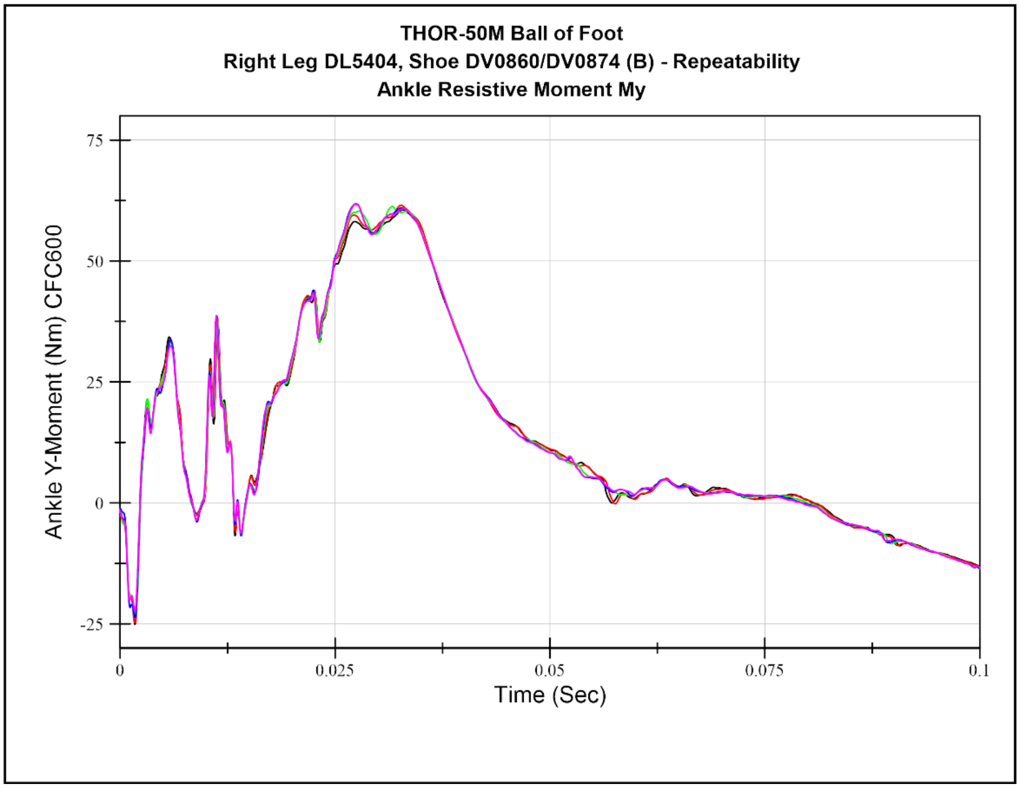

Figure 17-21. Calspan ball of foot ankle resistive Y-moment repeatability for DL5404

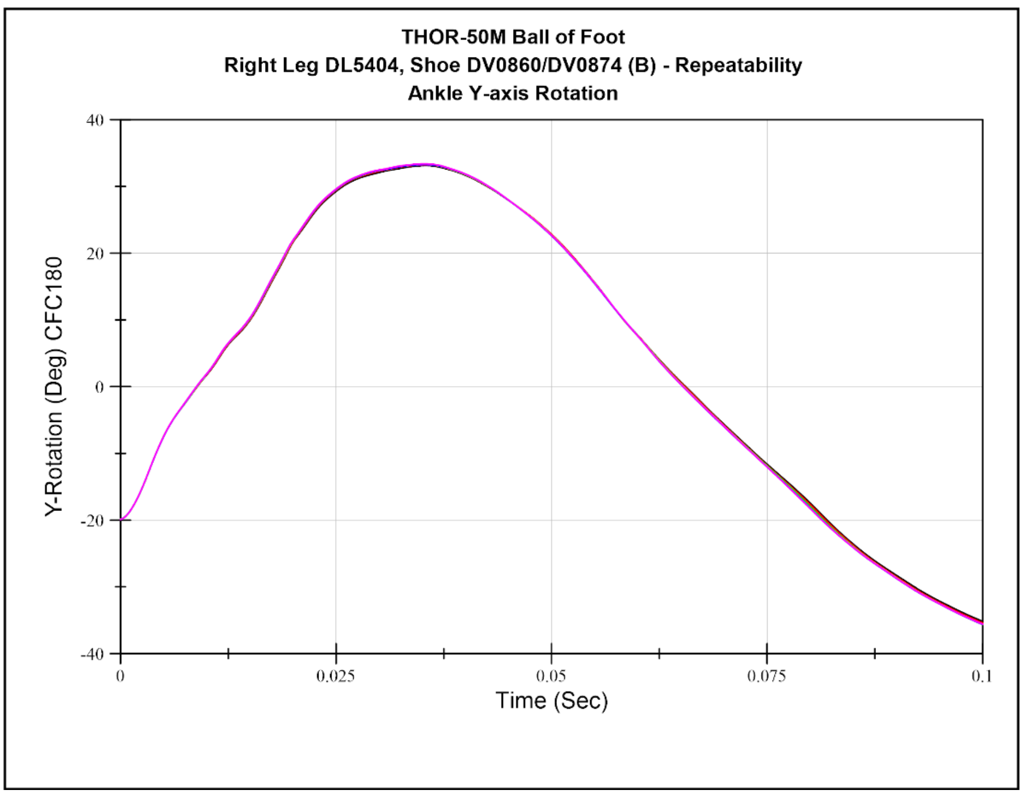

Figure 17-22. Calspan ball of foot ankle Y-axis rotation repeatability for DL5404

17.3 Ball of Foot Impact Dummy Reproducibility Results

Dummy Reproducibility results at VRTC for the ball of foot qualification yielded CV values all below 5 percent (Table 17-8).

Table 17-8. THOR-50M Ball of Foot Reproducibility Results

Leg Number Shoe Number	Test Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle Y-axis Rotation (in dorsiflexion) (deg)
VRTC DL0202 Left Leg DW2433/DV0872 (A) Shoe	**160518-5**	-3106	53.5	34.1
	160518-6	-3024	54.6	34.8
	160518-7	-3008	54.5	34.9
	160518-8	-3002	54.5	35.0
	160518-9	-3000	54.5	35.1
VRTC DL5404 Right Leg DV0860/DV0874 (B) Shoe	**160512-1**	-3005	55.5	34.5
	160512-3	-2983	55.1	34.5
	160516-3	-3002	54.2	34.3
	160516-4	-2987	55.8	34.5
	160516-5	-2990	56.3	34.5
VRTC Leg 069 Left DV085/DW2435 (D) Shoe	**160420-6**	-3143	57.1	32.8
	160420-11	-3155	56.1	33.3
	160421-1	-3153	56.3	33.3
	160421-2	-3119	56.3	33.3
	160421-3	-3121	56.4	33.3
Mean		**-3053**	**55.4**	**34.2**
Std. Dev.		**69**	**1.0**	**0.7**
CV		**2.3%**	**1.9%**	**2.2%**

17.4 Lab-to-Lab Variability Analysis

The results for the ball of foot tests from each lab are presented in Table 17-9 and Table 17-10. Data where the velocity exceeded the ± 0.05 m/s tolerance were excluded from the lab-to-lab comparison. For the left ankle ball of foot tests, the last four rows of Table 17-9 show the *Test Reproducibility* results when data from all three labs are combined. The results for the left leg yielded CV values all below 5 percent.

For the right ankle ball of foot tests, the last four rows of Table 17-10 show *Test Reproducibility* results when data from all three labs are combined. The results for the right ankle yielded a CV below 5 percent for the peak Y-axis rotation, and the peak lower tibia Fz and peak ankle resistive moment produced CV values above 5 percent but below 10 percent.

Table 17-9. THOR-50M Left Ball of Foot Lab-to-Lab Variability Results

Leg Number Shoe Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle Y-axis Rotation (in dorsiflexion) (deg)
VRTC DL0202 Left Leg DW2433/DV0872 (A) Shoe	-3106	53.5	34.1
	-3024	54.6	34.8
	-3008	54.5	34.9
	-3002	54.5	35.0
	-3000	54.5	35.1
Humanetics DL0202 Left Leg DW2433/DV0872 (A) Shoe	-3212	51.3	33.3
	-3219	51.9	33.9
	-3229	52.2	34.1
	-3207	53.3	34.2
	-3170	52.3	33.8
Calspan DL0202 Left Leg DW2433/DV0872 (A) Shoe	-3113	58.1	33.5
	-3084	59.1	33.3
Test Reproducibility DL0202 Left			
Mean	**-3115**	**54.2**	**34.2**
Std. Dev.	**91**	**2.4**	**0.6**
CV	**2.9%**	**4.4%**	**1.9%**

Table 17-10. THOR-50M Right Ball of Foot Lab-to-Lab Variability Results

Leg Number Shoe Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle Y-axis Rotation (in dorsiflexion) (deg)
VRTC DL5404 Right Leg DV0860/DV0874 (B) Shoe	-3005	55.5	34.5
	-2983	55.1	34.5
	-3002	54.2	34.3
	-2987	55.8	34.5
	-2990	56.3	34.5
Humanetics DL5404 Right Leg DV0860/DV0874 (B) Shoe	-3342	48.3	32.7
	-3412	51.8	33.5
	-3405	52.1	33.6
	-3385	50.6	33.8
	-3371	50.6	34.0
Calspan DL5404 Right Leg DV0860/DV0874 (B) Shoe	-3253	60.6	33.1
	-3271	61.5	33.2
	-3326	61.3	33.3
	-3328	61.8	33.3
	-3327	61.7	33.4
Test Reproducibility DL5404 Right			
Mean	**-3226**	**55.8**	**33.8**
Std. Dev.	**175**	**4.6**	**0.6**
CV	**5.4%**	**8.3%**	**1.8%**

17.5 Corridor Development

All the data used to determine the ball of foot qualification corridors is shown in Table 17-11. Data where the velocity exceeded the ± 0.05 m/s tolerance were excluded from the corridor development. The qualification corridors were calculated using the mean plus or minus 10 percent of the peak for the specified measured or calculated channels (Table 17-12).

Table 17-11. THOR-50M Ball of Foot Qualification Corridor Results

Leg Number Shoe Number	Test Number	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment (N-m)	Peak Ankle Y-axis Rotation (in dorsiflexion) (deg)
VRTC DL0202 Left Leg DW2433/DV0872 (A) Shoe	160518-5	-3106	53.5	34.1
	160518-6	-3024	54.6	34.8
	160518-7	-3008	54.5	34.9
	160518-8	-3002	54.5	35.0
	160518-9	-3000	54.5	35.1
VRTC DL5404 Right Leg DV0860/DV0874 (B) Shoe	160512-1	-3005	55.5	34.5
	160512-3	-2983	55.1	34.5
	160516-3	-3002	54.2	34.3
	160516-4	-2987	55.8	34.5
	160516-5	-2990	56.3	34.5
VRTC Leg 069 Left Leg DV085/DW2435 (D) Shoe	160420-6	-3143	57.1	32.8
	160420-11	-3155	56.1	33.3
	160421-1	-3153	56.3	33.3
	160421-2	-3119	56.3	33.3
	160421-3	-3121	56.4	33.3
Humanetics DL0202 Left Leg DW2433/DV0872 (A) Shoe	730	-3212	51.3	33.3
	733	-3219	51.9	33.9
	738	-3229	52.2	34.1
	740	-3207	53.3	34.2
	744	-3170	52.3	33.8
Humanetics DL5404 Right Leg DV0860/DV0874 (B) Shoe	675	-3342	48.3	32.7
	677	-3412	51.8	33.5
	678	-3405	52.1	33.6
	681	-3385	50.6	33.8
	685	-3371	50.6	34.0
Calspan DL0202 Left Leg DW2433/DV0872 (A) Shoe	20160623093709	-3113	58.1	33.5
	20160623101023	-3084	59.1	33.3
Calspan DL5404 Right Leg DV0860/DV0874 (B) Shoe	20160629095614	-3253	60.6	33.1
	20160629103002	-3271	61.5	33.2
	20160629113819	-3326	61.3	33.3
	20160629124035	-3328	61.8	33.3
	0160629131338	-3327	61.7	33.4
Mean		**-3170**	**55.3**	**33.8**
Std. Dev.		**140**	**3.5**	**0.7**
CV		**4.4%**	**6.4%**	**1.9%**

Table 17-12. Ball of Foot Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Impact Velocity	**m/s**	4.95	5.05	5.00	
Peak Lower Tibia Fz	**N**	-3487	-2853	-3170	10%
Peak Ankle Resistive Moment	**Nm**	49.8	60.8	55.3	10%
Peak Ankle Y-axis Rotation (in dorsiflexion)	**deg**	30.4	37.2	33.8	10%

Discussion. At each lab, all responses were highly repeatable. In addition, when testing different legs at the same lab (VRTC), the same responses were highly reproducible across all legs, including right and left combined. Thus, *Dummy/Test Repeatability*, and *Dummy Reproducibility* do not appear to be factors affecting variability.

However, lab-to-lab variability may be an issue in future ball of foot tests. The resistive moments were clustered by lab such that Calspan always produced the highest moments and Humanetics always produced the lowest moments. At Calspan, four of five tests on serial no. DL5404-R produced moments that were over the 10 percent target responses. Test labs such as Calspan may need to adjust their set-ups and fixtures (within allowable tolerances) to attain a response within 10 percent of the target for ankle moment.

18 Heel Impact

18.1 Methodology

Repeatability and reproducibility 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. In these tests, the molded shoe was utilized as described in the *THOR-50M Drawing Package*, while the leg is held rigidly with the tibia horizontal (Figure 18-1). The test utilizes the NHTSA Dynamic Impactor (TLX-9000-013) with an *effective* mass of 5.00 ± 0.02 kg. 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 pendulum impacts the heel at a velocity of 4.00 ± 0.05 m/s. During these tests, the peak lower tibia force (Fz) was measured.

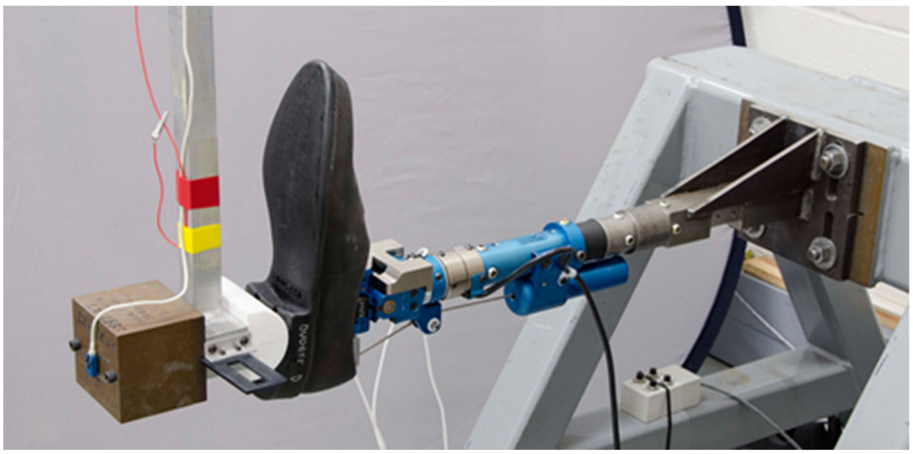

Figure 18-1. Heel impact test setup

18.2 Heel Impact Repeatability Results

Sections 18.2.1 to 18.2.7 illustrate the results of the heel impact repeatability tests. Each section contains a table providing the test data, followed by plot overlays of the five repeat tests conducted at all three labs. Note that the data in the tables containing the results of each test series are listed sequentially, with the test at the top of the table beginning the test series.

18.2.1 THOR-50M Left Lower Leg DL0202 Testing at VRTC

Repeatability results at VRTC for leg DL0202 yielded a CV value below 5 percent (Table 18-1 and Figure 18-2).

Table 18-1. VRTC THOR-50M Leg DL0202 Left Heel Repeatability Results

Leg Number Shoe Number	Test Number	Peak Lower Tibia Fz (N)
DL0202 Left Leg DW2433/DV0872 (A) Shoe	**160518-11**	-3078
	160518-13	-3080
	160518-14	-3093
	160518-16	-3090
	160518-20	-3086
Mean		**-3086**
Std. Dev.		**6**
CV		**0.2%**

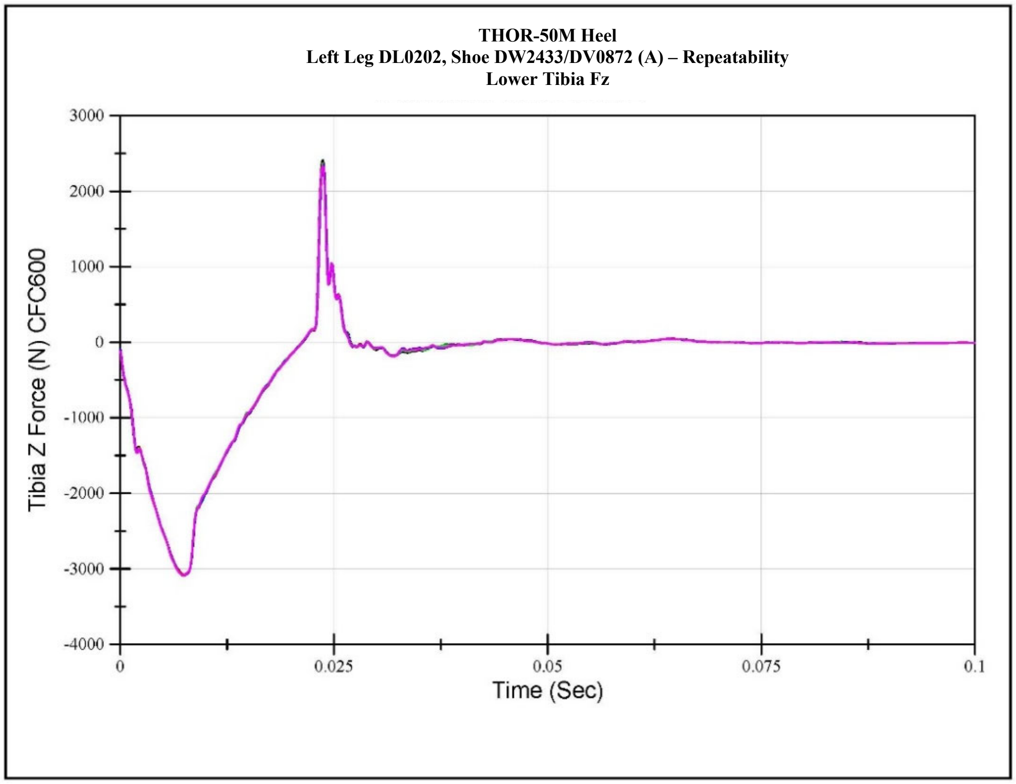

Figure 18-2. VRTC heel lower tibia Z-force repeatability for DL0202

18.2.2 THOR-50M Right Lower Leg DL5404 Testing at VRTC

Repeatability results at VRTC for leg DL5404 yielded a CV value below 5 percent (Table 18-2 and Figure 18-3).

Table 18-2. VRTC THOR-50M Leg DL5404 Right Heel Repeatability Results

Leg Number **Shoe Number**	**Test Number**	**Peak Lower Tibia Fz (N)**
DL5404 Right Leg **DV0860/DV0874 (B) Shoe**	**160516-6**	-3300
	160516-9	-3337
	160516-11	-3319
	160516-14	-3313
	160516-16	-3308
Mean		**-3315**
Std. Dev.		**14**
CV		**0.4%**

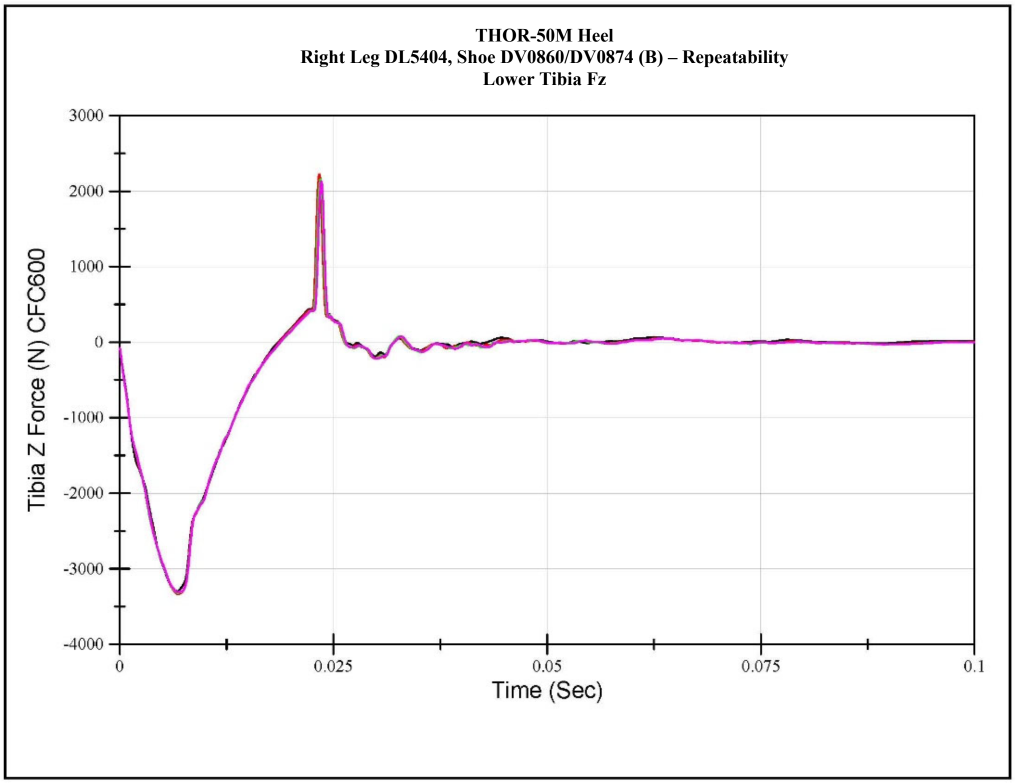

Figure 18-3. VRTC heel lower tibia Z-force repeatability for DL5404

18.2.3 THOR-50M Left Lower Leg 069 Testing at VRTC

Repeatability results at VRTC for leg 069 yielded a CV value below 5 percent (Table 18-3 and Figure 18-4).

Table 18-3. VRTC THOR-50M Leg 069 Left Heel Repeatability Results

Leg Number Shoe Number	Test Number	Peak Lower Tibia Fz (N)
069 Left Leg DV085/DW2435 (D) Shoe	**160421-5**	-2818
	160421-14	-2927
	160421-19	-2871
	160421-20	-2836
	160421-25	-2815
Mean		**-2853**
Std. Dev.		**47**
CV		**1.6%**

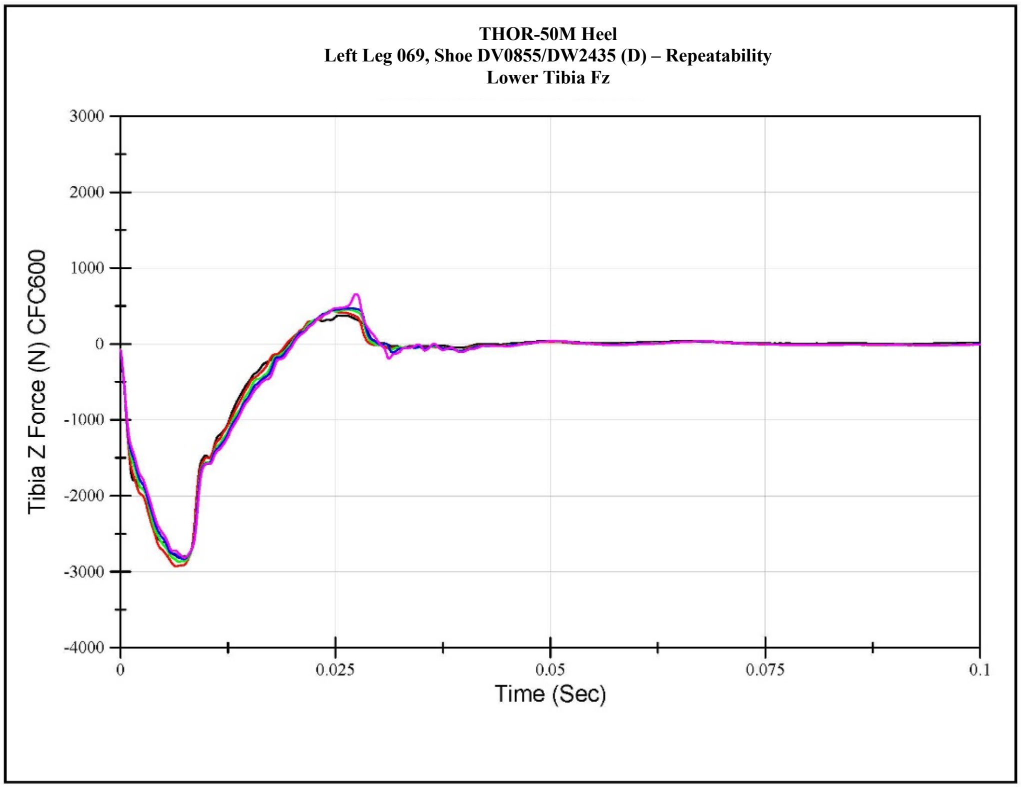

Figure 18-4. VRTC heel lower tibia Z-force repeatability for 069

18.2.4 THOR-50M Left Lower Leg DL0202 Testing at Humanetics

Repeatability results at Humanetics for leg DL0202 yielded a CV value below 5 percent (Table 18-4, Figure 18-5).

Table 18-4. Humanetics THOR-50M Leg DL0202 Left Heel Repeatability Results

Leg Number Shoe Number	Test Number	Peak Lower Tibia Fz (N)
DL0202 Left Leg DW2433/DV0872 (A) Shoe	**745**	-2886
	746	-3028
	747	-3075
	748	-3096
	749	-3105
Mean		**-3038**
Std. Dev.		**90**
CV		**3.0%**

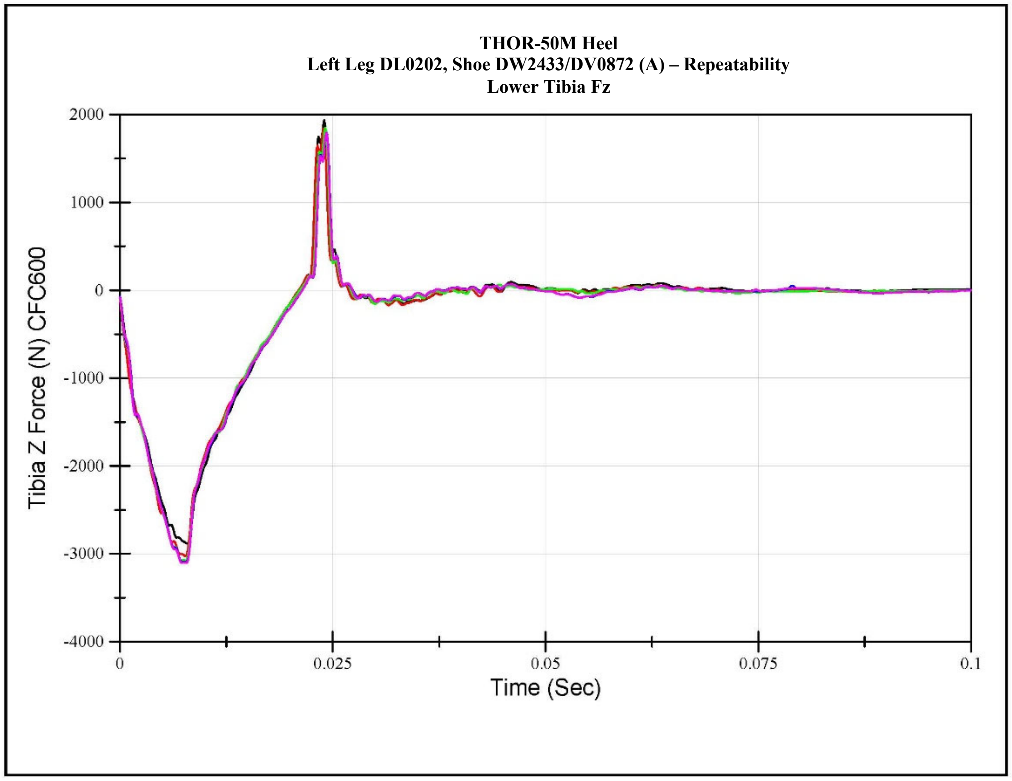

Figure 18-5. Humanetics heel lower tibia Z-force repeatability for DL0202

18.2.5 THOR-50M Right Lower Leg DL5404 Testing at Humanetics

Repeatability results at Humanetics for leg DL5404 yielded a CV value below 5 percent (Table 18-5, Figure 18-6).

Table 18-5. Humanetics THOR-50M Leg DL5404 Right Heel Repeatability Results

Leg Number Shoe Number	Test Number	Peak Lower Tibia Fz (N)
DL5404 Right Leg DV0860/DV0874 (B) Shoe	**688**	-3303
	691	-3307
	694	-3330
	697	-3328
	700	-3341
Mean		**-3322**
Std. Dev.		**16**
CV		**0.5%**

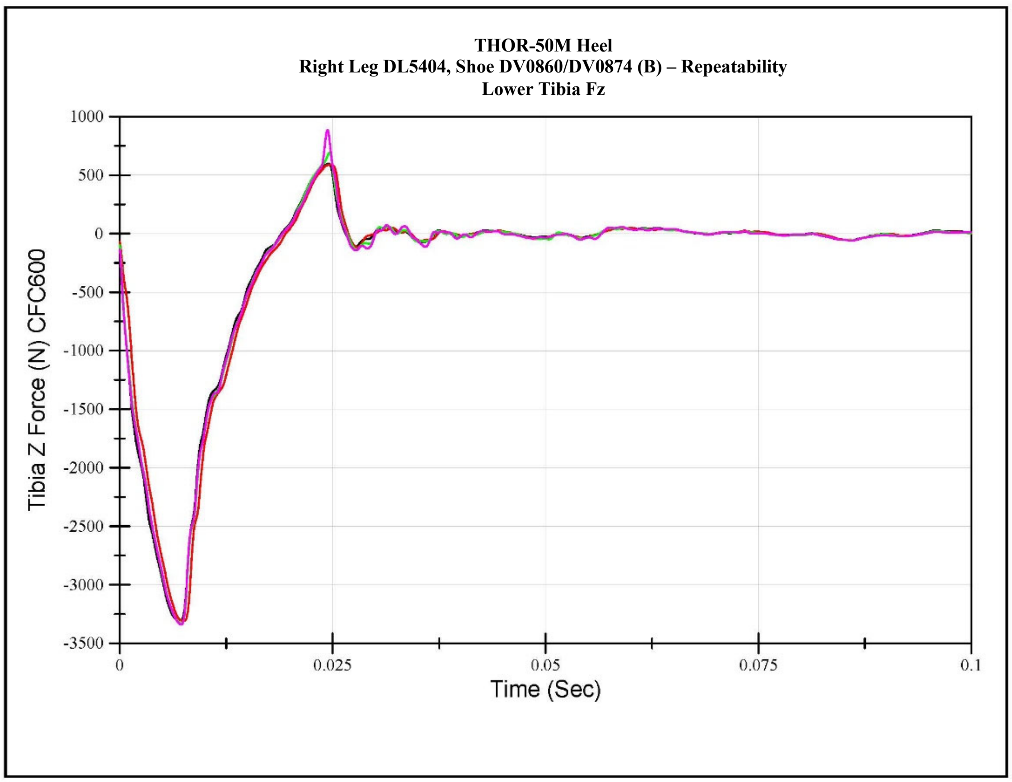

Figure 18-6. Humanetics heel lower tibia Z-force repeatability for DL5404

18.2.6 THOR-50M Left Lower Leg DL0202 Testing at Calspan

Only three tests conducted at Calspan met the input criteria for the repeatability tests on leg DL0202; the results yielded a CV value below 5 percent (Table 18-6, Figure 18-7).

Table 18-6. Calspan THOR-50M Leg DL0202 Left Heel Repeatability Results

Leg Number Shoe Number	Test Number	Peak Lower Tibia Fz (N)
DL0202 Left Leg DW2433/DV0872 (A) Shoe	**20160622160040**	-2987
	20160622163106	-2991
	20160623081008	-3004
Mean		**-2994**
Std. Dev.		**9**
CV		**0.3%**

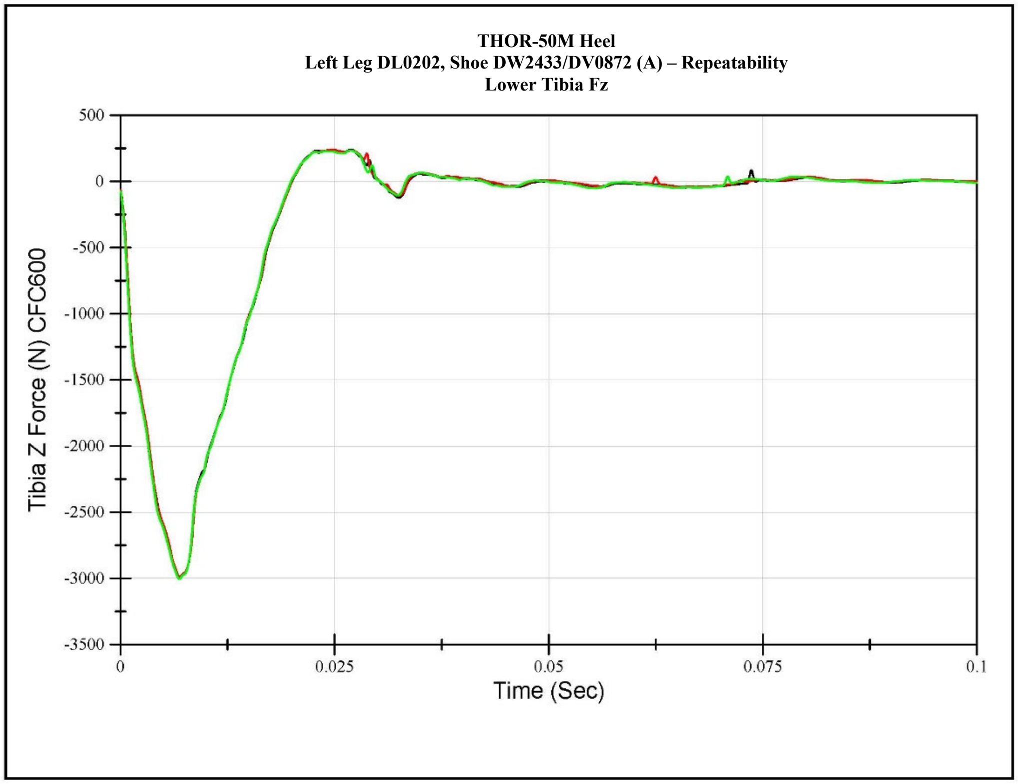

Figure 18-7. Calspan heel lower tibia Z-force repeatability for DL0202

18.2.7 THOR-50M Right Lower Leg DL5404 Testing at Calspan

Repeatability results at Calspan for leg DL5404 yielded a CV value below 5 percent (Table 18-7, Figure 18-8).

Table 18-7. Calspan THOR-50M Leg DL5404 Right Heel Repeatability Results

Leg Number Shoe Number	Test Number	Peak Lower Tibia Fz (N)
DL5404 Right Leg DV0860/DV0874 (B) Shoe	**20160624133614**	-3514
	20160624140949	-3538
	20160624144316	-3528
	20160624155309	-3550
Mean		**-3532**
Std. Dev.		**15**
CV		**0.4%**

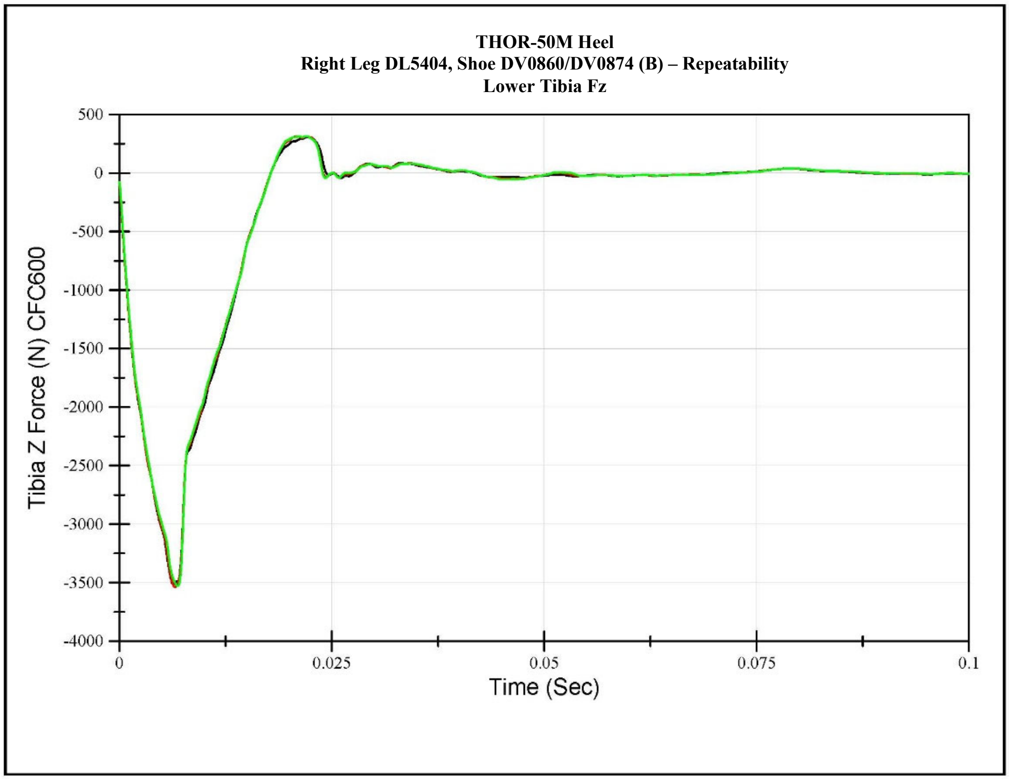

Figure 18-8. Calspan heel lower tibia Z-force repeatability for DL5404

18.3 Heel Impact Dummy Reproducibility Results

Dummy Reproducibility results at VRTC for the heel impact qualification yielded a peak lower tibia Fz that was above 5 percent but less than 10 percent (Table 18-8).

Table 18-8. THOR-50M Heel Dummy Reproducibility Results

Leg Number Shoe Number	Test Number	Peak Lower Tibia Fz (N)
DL0202 Left Leg DW2433/DV0872 (A) Shoe	160518-11	-3078
	160518-13	-3080
	160518-14	-3093
	160518-16	-3090
	160518-20	-3086
DL5404 Right Leg DV0860/DV0874 (B) Shoe	160516-6	-3300
	160516-9	-3337
	160516-11	-3319
	160516-14	-3313
	160516-16	-3308
069 Left Leg DV085/DW2435 (D) Shoe	160421-5	-2818
	160421-14	-2927
	160421-19	-2871
	160421-20	-2836
	160421-25	-2815
Mean		**-3085**
Std. Dev.		**197**
CV		**6.4%**

18.4 Lab-to-Lab Variability Analysis

The results for the heel impact tests from each lab are presented in Table 18-9 and Table 18-10. Data where the input criteria were not met were excluded from the lab-to-lab comparison. For the left heel impact tests, the last four rows of Table 18-9 show the *Test Reproducibility* results when data from all three labs are combined. The results for the left leg yielded a CV value below 5 percent.

For the right heel impact tests, the last four rows of Table 18-10 show the *Test Reproducibility* results when data from all three labs are combined. The results for the right leg yielded a CV value below 5 percent.

Table 18-9. THOR-50M Left Heel Test – Dummy Repeatability and Test Reproducibility

Leg Number Shoe Number	**Peak Lower Tibia Fz (N)**
VRTC DL0202 Left Leg DW2433/DV0872 (A) Shoe	-3078
	-3080
	-3093
	-3090
	-3086
Humanetics DL0202 Left Leg DW2433/DV0872 (A) Shoe	-2886
	-3028
	-3075
	-3096
	-3105
Calspan DL0202 Left Leg DW2433/DV0872 (A) Shoe	-2987
	-2991
	-3004
Test Reproducibility DL0202 Left ALL Labs	
Mean	**-3046**
Std. Dev.	**64**
CV	**2.1%**

Table 18-10. THOR-50M Right Heel Lab-to-Lab Variability Results

Leg Number Shoe Number	Peak Lower Tibia Fz (N)
VRTC DL5404 Right Leg DV0860/DV0874 (B) Shoe	-3300
	-3337
	-3319
	-3313
	-3308
Humanetics DL5404 Right Leg DV0860/DV0874 (B) Shoe	-3303
	-3307
	-3330
	-3328
	-3341
Calspan DL5404 Right Leg DV0860/DV0874 (B) Shoe	-3514
	-3538
	-3528
	-3550
Test Reproducibility DL5404 Right	
Mean	**-3380**
Std. Dev.	**101**
CV	**3.0%**

18.5 Corridor Development

All the data used to determine the heel impact qualification corridors is shown in Table 18-11. Data where the input criteria were not met were excluded from the corridor development. The qualification corridors were calculated using the mean plus or minus 10 percent of the peak for the specified measured or calculated channels (Table 18-12).

Table 18-11. THOR-50M Heel Qualification Corridor Results

Leg Number Shoe Number	Test Number	Peak Lower Tibia Fz (N)
VRTC DL0202 Left Leg DW2433/DV0872 (A) Shoe	**160518-11**	-3078
	160518-13	-3080
	160518-14	-3093
	160518-16	-3090
	160518-20	-3086
VRTC DL5404 Right Leg DV0860/DV0874 (B) Shoe	**160516-6**	-3300
	160516-9	-3337
	160516-11	-3319
	160516-14	-3313
	160516-16	-3308
VRTC 069 Left Leg DV085/DW2435 (D) Shoe	**160421-5**	-2818
	160421-14	-2927
	160421-19	-2871
	160421-20	-2836
	160421-25	-2815
Humanetics DL0202 Left Leg DW2433/DV0872 (A) Shoe	**745**	-2886
	746	-3028
	747	-3075
	748	-3096
	749	-3105
Humanetics DL5404 Right Leg DV0860/DV0874 (B) Shoe	**688**	-3303
	691	-3307
	694	-3330
	697	-3328
	700	-3341
Calspan DL0202 Left Leg DW2433/DV0872 (A) Shoe	**20160622160040**	-2987
	20160622163106	-2991
	20160623081008	-3004
Calspan DL5404 Right Leg DV0860/DV0874 (B) Shoe	**20160624133614**	-3514
	20160624140949	-3538
	20160624144316	-3528
	20160624155309	-3550
Mean		**-3162**
Std. Dev.		**220**
CV		**7.0%**

Table 18-12. Heel Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width %
Impact Velocity	**m/s**	3.95	4.05	4.00	
Peak Lower Tibia Fz	**N**	-3478	-2846	-3162	10%

Discussion. The assessment reveals that *Dummy Reproducibility* may be an issue in the future. The Tibia Fz responses of all units were repeatable, but they were different from each other such that the CV for *Dummy Reproducibility* was elevated (CV of 6.4%) (Table 18-8). The responses were clustered such that serial no. 069 produced the lowest responses (2 of 5 trials at VRTC were below the -10% limit) and serial no. 5404 produced the highest (all four trials at Calspan were above the +10%). In cases where passing qualification results cannot be achieved, a test lab may need to replace the molded shoe assembly (472-7800 -1 (left) or -2 (right)) and/or the upper tibia compliant bushing assembly (472-7315) in order to attain a peak lower tibia Fz within 10 percent of the target.

Another factor contributing to the variability may be *Test Reproducibility*, where testing at Calspan produced the highest responses in leg 5404 and the lowest responses in leg 0202. The tibia Fz forces for 5404 were more than 10 percent above the target response of 3162 N in each of its tests as seen in Table 18-11 (average of 3532 N).

Dummy/Test Repeatability do not appear to be factors affecting variability.

19 Summary

Below is a synopsis of the tests and results. For comparison purposes, only positive values are shown for the Nominal Targets and Acceptance Intervals.

1. Head Impact

Requirements:

Measurement	Peak Probe Force (N)	Head Resultant Acceleration (G)
Nominal Target	5580	117.0
Acceptance Interval	5022 - 6138	105.3 – 128.7
Dummy/Test Repeatability: Average CV	*0.7%*	*2.2%*
Test Reproducibility: CV	*1.0%*	*3.7%*
Dummy Reproducibility: CV	*0.5%*	*1.4%*

Special needs: None. All tests were within the ± 10 percent range.

2. Face Impact

Requirements:

Measurement	Peak Probe Force (N)	Head Resultant Acceleration (G)
Nominal Target	7087	138
Acceptance Interval	6378-7796	124-152
Dummy/Test Repeatability: Average CV	*8.7%*	*9.6%*
Test Reproducibility: CV	*N/A*	*N/A*
Dummy Reproducibility: CV	*8.4%*	*9.3%*

Special needs: Test labs may need to track the responses of the foam from one qualification test to the next in order to make an informed decision on whether to replace the foam. If a response is too low, the foam may simply need an additional test to qualify; for the most part, progressive increases in both peak probe force and head CG resultant acceleration were evident with each successive test as the test matrix proceeded. If a response is too high, the foam may need to be replaced.

3. Neck – Flexion

Requirements:

Measurement	Peak Upper Neck (My) (N-m)	Peak Upper Neck (Fz @ < 40 ms) (N)	Peak Angular Velocity (ωy) (deg/s)	Peak Head Rotation (deg)
Nominal Target	31.0	860	1975	64.5
Acceptance Interval	27.9 – 34.1	774 - 946	1777 - 2172	58.1 – 71.0
Dummy/Test Repeatability: Average CV	*3.3%*	*3.8%*	*1.7%*	*1.0%*
Test Reproducibility: CV	*4.5%*	*7.5%*	*2.0%*	*2.5%*
Dummy Reproducibility: CV	*5.4%*	*4.2%*	*1.9%*	*2.3%*

Special needs: Labs may find that the first test performed on a new dummy neck may produce results which exhibit a high My (a *Dummy Repeatability* issue). Labs should be aware that, depending on the newness of the neck, the My value produced in a subsequent test may be lower than what would be indicated by an initial qualification test.

Also, labs may need to adjust the input pulse by experimenting with honeycomb cell configurations to achieve the target response.

4. Neck – Extension

Requirements:

Measurement	**Peak Upper Neck (My) (N-m)**	**Peak Upper Neck (Fz) (N)**	**Peak Angular Velocity (ωy) (deg/s)**	**Peak Head Rotation (deg)**
Nominal Target	23.0	2918	2061	65.0
Acceptance Interval	20.7 – 25.3	2626 – 3210	1855 – 2267	58.5 – 71.5
Dummy/Test Repeatability: Average CV	*2.3%*	*2.4%*	*1.6%*	*1.1%*
Test Reproducibility: CV	*5.6%*	*12.2%*	*4.4%*	*2.0%*
Dummy Reproducibility: CV	*3.9%*	*3.7%*	*2.7%*	*1.7%*

Special needs: This situation is similar to the one for Neck Flexion. Labs may need to adjust the input pulse by experimenting with honeycomb cell configurations to achieve the target response.

5. Neck – Lateral

Requirements:

Measurement	**Peak Moment (Mx @ > 40 ms) (N-m)**	**Peak Angular Velocity (ωx) (deg/s)**	**Peak Head Rotation (deg)**
Nominal Target	49.7	1362	41.7
Acceptance Interval	44.8 – 54.7	1226 – 1498	37.6 – 45.9
Dummy/Test Repeatability: Average CV	*1.7%*	*1.6%*	*1.3%*
Test Reproducibility: CV	*3.8%*	*1.5%*	*3.2%*
Dummy Reproducibility: CV	*1.9%*	*2.8%*	*2.6%*

Special needs: None. All tests were within the ± 10 percent range.

6. Neck – Torsion

Requirements:

Measurement	**Peak Moment (Mz @ > 40 ms) (N-m)**	**Peak Angular Velocity (ωz) (deg/s)**	**Peak Fixture Rotation (deg)**
Nominal Target	41.4	1390	47.9
Acceptance Interval	37.3 – 45.6	1251 - 1529	43.1 – 52.7
Dummy/Test Repeatability: Average CV	*0.9%*	*2.3%*	*1.6%*
Test Reproducibility: CV	*1.5%*	*4.5%*	*1.2%*
Dummy Reproducibility: CV	*2.5%*	*2.5%*	*3.5%*

Special needs: None. All tests were within the ± 10 percent range.

7. Upper Thorax

Requirements:

Measurement	**Peak Probe Force (N)**	**Peak Upper Resultant Deflection (mm)**	**Probe Force @ Peak Resultant Deflection (N)**	**Max. Diff Between L and R Deflection (mm)**
Nominal Target	N/A	53.6	2677	0
Acceptance Interval	0 – 3039	48.3 – 59.0	2409 – 2944	-5 to 5
Dummy/Test Repeatability: Average CV	*1.8%*	*1.8%*	*1.7%*	*N/A*
Test Reproducibility: Average CV	*2.8%*	*3.2%*	*2.3%*	*N/A*
Dummy Reproducibility: CV	*2.3%*	*3.7%*	*2.2%*	*N/A*

Special needs: None. All tests were within the ± 10 percent range.

8. Lower Thorax

Requirements:

Measurement	**Resultant Deflection at Peak Probe Force (mm)**	**Peak Probe Force (N)**
Nominal Target	50.9	3484
Acceptance Interval	45.8 – 56.0	3136 – 3832
Dummy/Test Repeatability: Average CV	*3.3%*	*1.9%*
Test Reproducibility: Average CV	*6.6%*	*4.7%*
Dummy Reproducibility: CV	*4.5%*	*3.4%*

Special needs: Given the asymmetric setup of this test, test labs may need to be diligent on aligning the dummy with the impact probe. Otherwise, they may experience difficulties attaining the targeted response.

9. Lower Abdomen

Requirements:

Measurement	**Peak Probe Force (N)**	**Deflection at Peak Probe Force (mm)**	**Max. Diff Between L and R Deflection (mm)**
Nominal Target	2918	83.0	0
Acceptance Interval	2626 – 3210	74.4 – 91.3	-8 to 8
Dummy/Test Repeatability: Average CV	*2.6%*	*4.9%*	*N/A*
Test Reproducibility: Average CV	*3.4%*	*5.5%*	*N/A*
Dummy Reproducibility: CV	*2.3%*	*5.3%*	*N/A*

Special needs: Labs may have difficulty attaining the left versus right response if the test set-up is not sufficiently symmetric. However, once the dummy is properly aligned, labs should be able to attain the desired response.

10. Knee

Requirements:

Measurement	**Peak Probe Fz (N)**	**Knee Deflection at Peak Femur Fz (mm)**
Nominal Target	6506	20.2
Acceptance Interval	5855 – 7156	18.2 – 22.2
Dummy/Test Repeatability: Average CV	*1.7%*	*0.5%*
Test Reproducibility: Average CV	*5.3%*	*2.0%*
Dummy Reproducibility: CV	*5.1%*	*1.8%*

Special needs: Some labs may need to fine-tune the test setup to achieve the specified femur force.

11. Upper Leg

Requirements:

Measurement	**Peak Probe Force (N)**	**Peak Femur Fz (N)**	**Peak Acetabulum Resultant Force (N)**
Nominal Target	8333	4920	2738
Acceptance Interval	7500-9166	4428-5412	2464-3012
Dummy/Test Repeatability: Average CV	*0.7%*	*1.2%*	*3.1%*
Test Reproducibility: Average CV	*3.7%*	*3.9%*	*4.4%*
Dummy Reproducibility: CV	*4.7%*	*4.7%*	*4.3%*

Special needs: Some labs may need to fine-tune the test setup to achieve the specified femur force.

12. Ankle Inversion

Requirements:

Measurement	**Peak Lower Tibia Fz (N)**	**Peak Ankle Resistive Moment, Mx (N-m)**	**Peak Ankle X-axis Rotation (deg)**
Nominal Target	505	3901	34.5
Acceptance Interval	454-555	35.2-43.0	31.0-37.9
Dummy/Test Repeatability: Average CV	*2.9%*	*3.1%*	*1.1%*
Test Reproducibility: Average CV	*5.1%*	*3.6%*	*1.7%*
Dummy Reproducibility: CV	*3.7%*	*4.9%*	*1.6%*

Special needs: The ankle moment, tibia Fz, and ankle rotation may be slightly low in an initial qualification test if there has been an extended period of non-use of the Ensolite pad on the test fixture. This is only a concern if the tibia force and moment are just below the upper qualification limits, since subsequent tests may be expected to produce slightly higher moments and forces (which might be out of the qualification range). Labs can simply perform an additional test to confirm that the response of the ankle is within the requirements.

13. Ankle Eversion

Requirements:

Measurement	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment, Mx (N-m)	Peak Ankle X-axis Rotation (deg)
Nominal Target	571	43.0	29.6
Acceptance Interval	514-629	38.7-47.3	26.6-32.5
Dummy/Test Repeatability: Average CV	*3.6%*	*3.8%*	*1.4%*
Test Reproducibility: Average CV	*5.4%*	*4.7%*	*2.5%*
Dummy Reproducibility: CV	*5.6%*	*4.2%*	*2.0%*

Special needs: Similar to inversion, the ankle moment, tibia Fz, and ankle rotation may be slightly low in an initial qualification test if there has been an extended period of non-use of the Ensolite pad on the test fixture. This is only a concern if the tibia force and moment are just below the upper qualification limits, since subsequent tests may be expected to produce slightly higher moments and forces (which might be out of the qualification range). Labs can simply perform an additional test to confirm that the response of the ankle is within the requirements.

14. Ball of Foot

Requirements:

Measurement	Peak Lower Tibia Fz (N)	Peak Ankle Resistive Moment, My (N-m)	Peak Ankle Y-axis Rotation (deg)
Nominal Target	3170	55.3	33.8
Acceptance Interval	2853-3487	49.8-60.8	30.4-37.2
Dummy/Test Repeatability: Average CV	*0.8%*	*1.3%*	*0.8%*
Test Reproducibility: Average CV	*4.2%*	*6.4%*	*1.9%*
Dummy Reproducibility: CV	*2.3%*	*1.9%*	*2.2%*

Special needs: Test labs may need to adjust their set-ups and fixtures (within allowable tolerances) to attain a response within 10 percent of the target for ankle moment.

15. Heel

Requirements:

Measurement	Peak Lower Tibia Fz (N)
Nominal Target	3162
Acceptance Interval	2846 - 3478
Dummy/Test Repeatability: Average CV	*0.9%*
Test Reproducibility: Average CV	*2.6%*
Dummy Reproducibility: CV	*6.4%*

Special needs: In cases where passing qualification results cannot be achieved, a test lab may need to replace the molded shoe assembly (472-7800 -1 (left) or -2 (right)) and/or the upper tibia compliant bushing assembly (472-7315) in order to attain a peak lower tibia Fz within 10 percent of the target.

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DOT HS 813 258
October 2022

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15500-100522-v4