

THOR-05F Repeatability and Reproducibility of Qualification Tests

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Table of Contents

1	BACKGROUND	4
2	OBJECTIVES	5
3	METHODOLOGY	9
4	HEAD	11
4.1	Methodology	11
4.2	Head Impact Repeatability Results	11
4.3	THOR-05F Head Impact Dummy Reproducibility Results.....	21
4.4	Lab-to-Lab Variability Analysis	22
4.5	Corridor Development	23
5	FACE	25
5.1	Methodology	25
5.2	Face Impact Repeatability Results.....	25
5.3	THOR-05F Face Impact Dummy Reproducibility Results.....	32
5.4	Lab-to-Lab Variability Analysis	33
5.5	Corridor Development	34
6	NECK FLEXION.....	36
6.1	Methodology	36
6.2	Neck Flexion Repeatability Results.....	36
6.3	Neck Flexion Dummy Reproducibility Results	55
6.4	Lab-to-Lab Variability Analysis	57
6.5	Corridor Development	59
7	NECK EXTENSION	62
7.1	Methodology	62
7.2	Neck Extension Repeatability Results	62
7.3	Neck Extension Dummy Reproducibility Results	81
7.4	Lab-to-Lab Variability Analysis	83
7.5	Corridor Development	85
8	NECK LATERAL FLEXION	88
8.1	Methodology	88
8.2	Neck Lateral Flexion Repeatability Results.....	88
8.3	Neck Lateral Flexion Dummy Reproducibility Results.....	125

8.4	Lab-to-Lab Variability Analysis	126
8.5	Corridor Development	129
9	NECK TORSION	133
9.1	Methodology	133
9.2	Neck Torsion Repeatability Results.....	133
9.3	Neck Torsion Dummy Reproducibility Results.....	170
9.4	Lab-to-Lab Variability Analysis	172
9.5	Corridor Development	175
10	UPPER THORAX	180
10.1	Methodology	180
10.2	Upper Thorax Repeatability Results	180
10.3	Upper Thorax Dummy Reproducibility Results	199
10.4	Lab-to-Lab Variability Analysis	200
10.5	Corridor Development	201
11	LOWER THORAX.....	203
11.1	Methodology	203
11.2	Lower Thorax Repeatability Results.....	203
11.3	Lower Thorax Impact Dummy Reproducibility Results.....	222
11.4	Lab-to-Lab Variability Analysis	223
11.5	Corridor Development	224
12	ABDOMEN	227
12.1	Methodology	227
12.2	Abdomen Repeatability Results.....	227
12.3	Abdomen Impact Dummy Reproducibility Results.....	238
12.4	Lab-to-Lab Variability Analysis	239
12.5	Corridor Development	240
13	UPPER LEG	242
13.1	Methodology	242
13.2	Upper Leg Repeatability Results	242
13.3	Upper Leg Dummy Reproducibility Results.....	267
13.4	Lab-to-Lab Variability	268
13.5	Corridor Development	269
14	KNEE.....	272

14.1	Methodology	272
14.2	Knee Repeatability Results	272
14.3	Knee Impact Dummy Reproducibility Results	284
14.4	Lab-to-Lab Variability	285
14.5	Corridor Development	286
15	ANKLE INVERSION	288
15.1	Methodology	288
15.2	Ankle Inversion Repeatability Results.....	288
15.3	Ankle Inversion Dummy Reproducibility Results.....	301
15.4	Lab-to-Lab Variability	302
15.5	Corridor Development	303
16	ANKLE EVERSION	305
16.1	Methodology	305
16.2	Ankle Eversion Repeatability Results.....	305
16.3	Ankle Eversion Dummy Reproducibility Results.....	318
16.4	Lab-to-Lab Variability	319
16.5	Corridor Development	320
17	BALL OF FOOT.....	322
17.1	Methodology	322
17.2	Ball of Foot Impact Repeatability Results	322
17.3	Ball of Foot Impact Dummy Reproducibility Results	335
17.4	Lab-to-Lab Variability Analysis	336
17.5	Corridor Development	337
18	HEEL	339
18.1	Methodology	339
18.2	Heel Impact Repeatability Results.....	340
18.3	Heel Impact Dummy Reproducibility Results	349
18.4	Lab-to-Lab Variability Analysis	350
18.5	Corridor Development	351
19	SUMMARY	353
20	REFERENCES	360

1 BACKGROUND

For several years, the National Highway Traffic Safety Administration (NHTSA) has actively supported the development of an advanced small female frontal anthropomorphic test dummy (ATD) that incorporates improved biofidelic features and significantly expanded instrumentation. The THOR-05F (Test Device for Human Occupant Restraint) represents the latest advanced frontal crash 5th percentile female 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-05F 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, femur, and abdomen, as well as neck and leg component qualification tests, as specified in the *THOR 5th Percentile Female (THOR-05F) Qualification Procedures and Requirements* (National Highway Traffic Safety Administration, 2025).

2 OBJECTIVES

Background. NHTSA has previously established qualification test procedures and acceptable corridors for the THOR-50M. Since the design of the THOR-05F is similar to the THOR-50M, the test modes included in the initial R&R test series were also similar. However, the probe masses, velocities, and other test conditions were appropriately modified for the THOR-05F based on the smaller size of the ATD (Lee et al., 2017).

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 comparable to what would be experienced during a vehicle crash test.

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-05F, the limits have been set at $\pm 10\%$ of a nominal target for each measurement; this establishes corridors which are wide enough to account for normal variations in dummy and laboratory differences but narrow enough to assure consistent and repeatable measurements in standardized testing with the dummy.

We also considered limits calculated from the mean response $\pm$ two standard deviations. If this practice were applied to the data collected herein, it would have narrowed the window of acceptability for almost all responses. However, most of the THOR-05F components were brand new at the time of testing. The allowance of $\pm 10\%$ thus accounts for slight variations that may arise from different dummy manufacturers, or lot-to-lot differences in the fabrication of parts from the same manufacturer. It also accounts for slight changes to individual THOR-05F units over time, either due to aging of polymeric components or wear and tear under normal use. Not only are the limits of $\pm 10\%$ for the THOR-05F consistent with the THOR-50M, but they are also in line with other Part 572 ATDs.

Purpose of this data collection exercise. This exercise sets out to perform tests at multiple labs using multiple THOR-05F units for the following purposes:

- Set the qualification target for each response.
- Assess the ability of a particular dummy to attain the targets (within +/- 10%).
- Identify possible errors, discrepancies, and ambiguities in the qualification procedures.
- Reveal and resolve functionality 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 trials for each type of qualification test on three dummies at one lab, and one of those dummies at three 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. We cannot determine whether small variations in a single dummy's repeated responses when tested at a single lab are due to the dummy itself or to minor, unquantifiable differences in the test setup. 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-05F Qualification Tests and Requirements

Test	Measurement	Units	Nominal Target	Acceptance Interval
1. Head Impact	Maximum Probe Force	N	5,073	4,566 – 5,581
	Maximum Head CG Resultant Acceleration	G	156	140 – 171
2. Face Impact	Maximum Probe Force	N	6,076	5,469 – 6,684
3. Neck – Flexion	Maximum Upper Neck My	N-m	17.8	16.0 – 19.5
	Upper Neck Fz Most Positive Value Prior to 40 ms	N	770	693 – 847
	Minimum Head Angular Velocity ω_y (relative to earth)	deg/sec	-2,136	-2,350 – -1,923
	Minimum Head Rotation (relative to pendulum)	deg	-78.2	-86.1 – -70.4
4. Neck – Extension	Minimum Upper Neck My	N-m	-18.9	-20.8 – -17.0
	Minimum Upper Neck Fz	N	-1,335	-1,469 – -1,202
	Maximum Head Angular Velocity ω_y (relative to earth)	deg/sec	2,393	2,154 – 2,632
	Maximum Head Rotation (relative to pendulum)	deg	87.9	79.1 – 96.7
5. Neck – Lateral	Maximum Upper Neck Mx After 40.0 ms	N-m	30.7	27.6 – 33.7
	Minimum Head Angular Velocity ω_x (relative to earth)	deg/sec	1,359	-1,495 – -1,223
	Minimum Head Rotation (relative to pendulum)	deg	49.3	-54.2 – -44.4
6. Neck – Torsion	Maximum Upper Neck Mz	N-m	20.4	18.3 – 22.4
	Minimum Upper Neck Angular Velocity ω_z (relative to earth)	deg/sec	1,284	-1,413 – -1,156
	Minimum Neck Fixture Rotation	deg	51.5	-56.6 – -46.3
7. Upper thorax	Maximum Probe Force	N	1,995	1,796 – 2,195
	Maximum Upper Resultant Deflection	mm	35.3	31.7 – 38.8
	Difference Between Maximum Left & Right Resultant Deflections	mm	0	5.0
	Force at Maximum Resultant Deflection	N	1,796	1,616 – 1,976
8. Lower thorax	Maximum Probe Force	N	2,008	1,807 – 2,209
	Resultant Deflection at Maximum Force	mm	42.7	38.4 – 46.9
9. Abdomen	Maximum Probe Force	N	4,502	4,052 – 4,952
	Left and Right Abdomen Maximum Pressure	kPa	210	189 – 231
	Difference Between Left and Right Maximum Pressure	kPa	0	15
10. Upper leg	Maximum Probe Force	N	7,894	7,105 – 8,684
	Minimum Femur Force, Fz	N	-4,123	-4,535 – -3,711
	Maximum Resultant Acetabulum Force	N	2,033	1,829 – 2,236
11. Knee	Minimum Femur Z-axis Force	N	-3,813	-4,194 – -3,431
	Knee Deflection at Minimum Femur Force	mm	-13.8	-15.2 – -12.4
12. Ankle inversion	Minimum Lower Tibia Fz	N	-318	-349 – -286
	Minimum Ankle Resistive Moment	N-m	-28.6	-31.4 – -25.7
	Minimum Ankle X-axis Rotation	deg	-27.8	-30.6 – -25.0
13. Ankle eversion	Minimum Lower Tibia Fz	N	-321	-353 – -289
	Maximum Ankle Resistive Moment	N-m	29.1	26.2 – 32.0
	Maximum Ankle X-axis Rotation	deg	27.6	24.8 – 30.3
14. Ball of foot	Minimum Lower Tibia Fz	N	-928	-1,020 – -835
	Maximum Ankle Resistive Moment	N-m	47.7	42.9 – 52.4
	Maximum Ankle Y-axis Rotation (in dorsiflexion)	deg	33.9	30.6 – 37.3
15. Heel	Maximum Probe Force	N	3,830	3,447 – 4,212
	Minimum Lower Tibia Fz	N	-2,018	-2,220 – -1,816
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-5th Percentile Female (THOR-05F) Qualification Procedures and Requirements*. The initial THOR-05F design was released by NHTSA in 2019 (National Highway Traffic Safety Administration, 2019) and several improvements have been made to improve performance (e.g. ankle bumpers, ribs, lower thorax IR-TRACC mounts, etc.). As tested, these ATDs meet the requirements of the most recent *THOR-05F Drawing Package* (National Highway Traffic Safety Administration, 2025). All test data in this report was collected in compliance with SAE J211 polarity specifications.

Three dummies were subjected to repeat tests in each test condition at VRTC, and one of the three dummies was tested at three other labs. 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 if the coefficient of variation (CV), defined as the percentage of the standard deviation divided by the mean, was less than 10% for all 6 test series combined (3 collected at VRTC and 3 collected at outside labs).

For each of the 15 test modes, a series of five repeat tests were conducted on each ATD. Some test modes required testing of both left and right side components (neck lateral bending, neck torsion, lower thorax, and upper leg tests), while others were only tested on the left side (knee, ankle inversion/eversion, ball of foot, and heel). This test data was used to generate the qualification targets for each requirement. Two separate assessments were carried out using this data: repeatability (calculated for each dummy using data from tests at NHTSA's Vehicle Research and Test Center (VRTC), Humanetics¹, Calspan², and TRC Inc³) and ATD-to-ATD reproducibility (calculated using the three dummies tested at VRTC).

Unless mentioned otherwise in the subsequent sections, THOR-05F S/Ns EU9863, EU3430, and EV4675 were tested at VRTC, and then EV4675 was tested at Humanetics, Calspan, and TRC Inc; for face, neck, knee, and ankle tests the part serial numbers, rather than the ATD serial number, were used to describe the tests.

Results were assessed using the following criteria for the CV:

- Below 5%: No further investigation; all trials within $\pm 10\%$ of target
- Between 5% - 10%: Sources of variability investigated; outliers may exist
- Greater than 10%: Test procedure thoroughly reviewed, and dummies inspected.

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

A set of responses with a CV below 5% indicates a highly repeatable and reproducible condition. Under these circumstances, the responses in all test trials were within $\pm 10\%$ 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%, a response in at least one test was outside the $\pm 10\%$ limits, and when the CV exceeded 10%, 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.

Only data collected through this analysis was 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 data from this report to compute the target responses ensures the 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 variables include the configuration of the dummy (older versions, or otherwise modified versions of the 2025 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 trials 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 $\pm 10\%$ 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 $\pm 2*CV$ in lieu of $\pm 10\%$. Thus, when CV values are below 5% 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 herein. Likewise, when CV values are above 5%, widening the limits beyond $\pm 10\%$ may be considered. But doing so would ignore any reductions in CV values 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-05F Qualification Procedures and Requirements*. 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 19.2 ± 0.02 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.

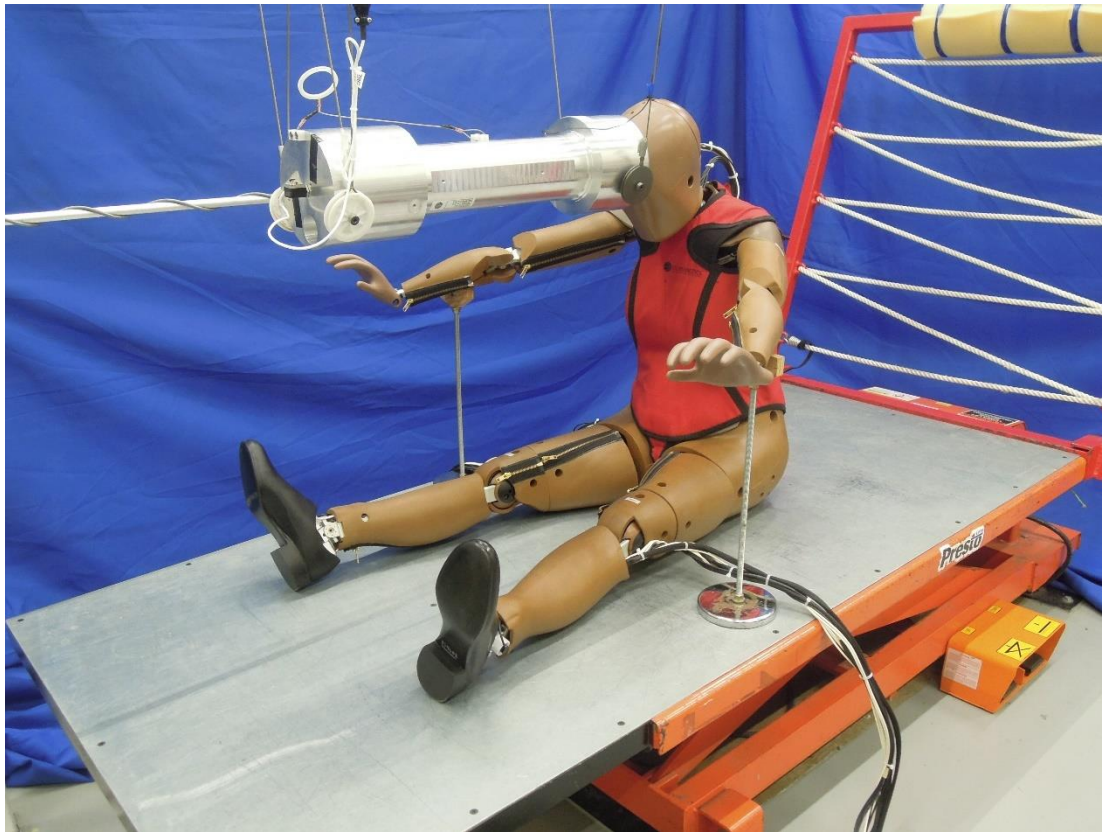


Figure 4-1. Head impact test setup

4.2 Head Impact Repeatability Results

Sections 4.2.1 through 4.2.6 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 four 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-05F EU9863 Testing at VRTC

Repeatability results at VRTC for EU9863 displayed CV values below 5 percent (Table 4-1, Figure 4-2, and Figure 4-3).

Table 4-1. VRTC THOR-05F EU9863 Head Impact Repeatability Results

Test Number	Maximum Probe Force (N)	Maximum Head CG Resultant (G)
240122-3	5,083	156
240122-8	5,141	159
240122-13	4,919	146
240122-16	5,130	158
240123-1	5,069	152
Mean	5,068	154
Standard Deviation	89	5.2
CV	1.8%	3.4%

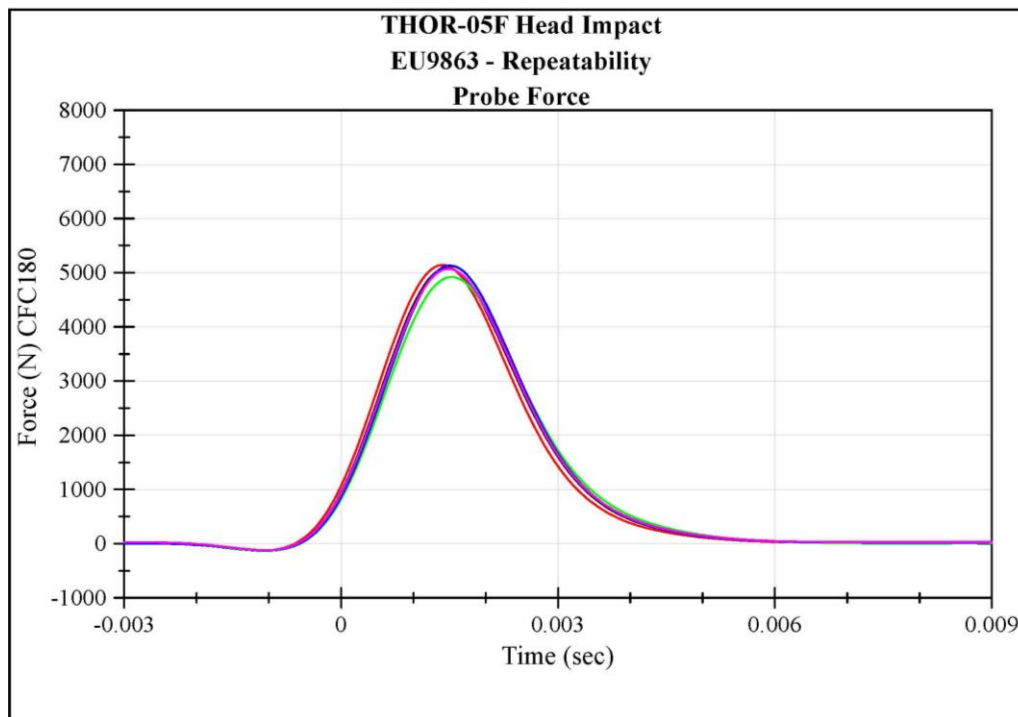


Figure 4-2. VRTC head impact probe force repeatability for EU9863

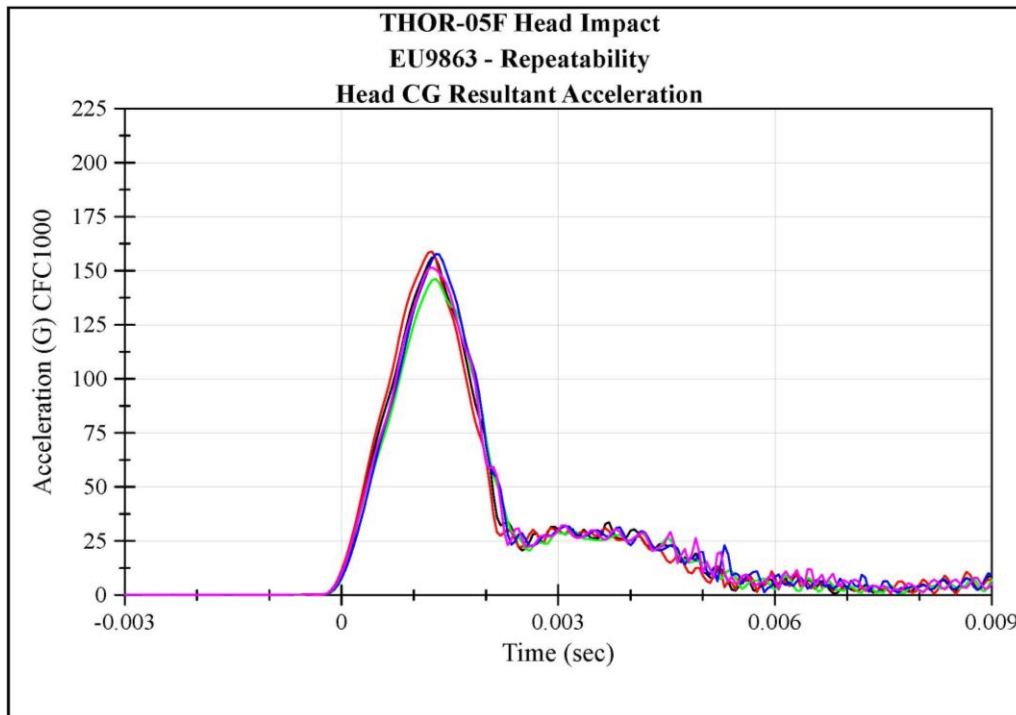


Figure 4-3. VRTC head impact head resultant CG acceleration repeatability for EU9863

4.2.2 THOR-05F EU3430 Testing at VRTC

Repeatability results at VRTC for EU3430 displayed CV values below 5 percent (Table 4-2, Figure 4-4, and Figure 4-5).

Table 4-2. VRTC EU3430 Head Impact Repeatability Results

Test Number	Maximum Probe Force (N)	Maximum Head CG Resultant (G)
240806-13	5,141	152
240806-16	5,242	159
240806-17	5,215	156
240807-1	5,237	157
240807-2	5,267	157
Mean	5,220	156
Standard Deviation	48	2.6
CV	0.9%	1.7%

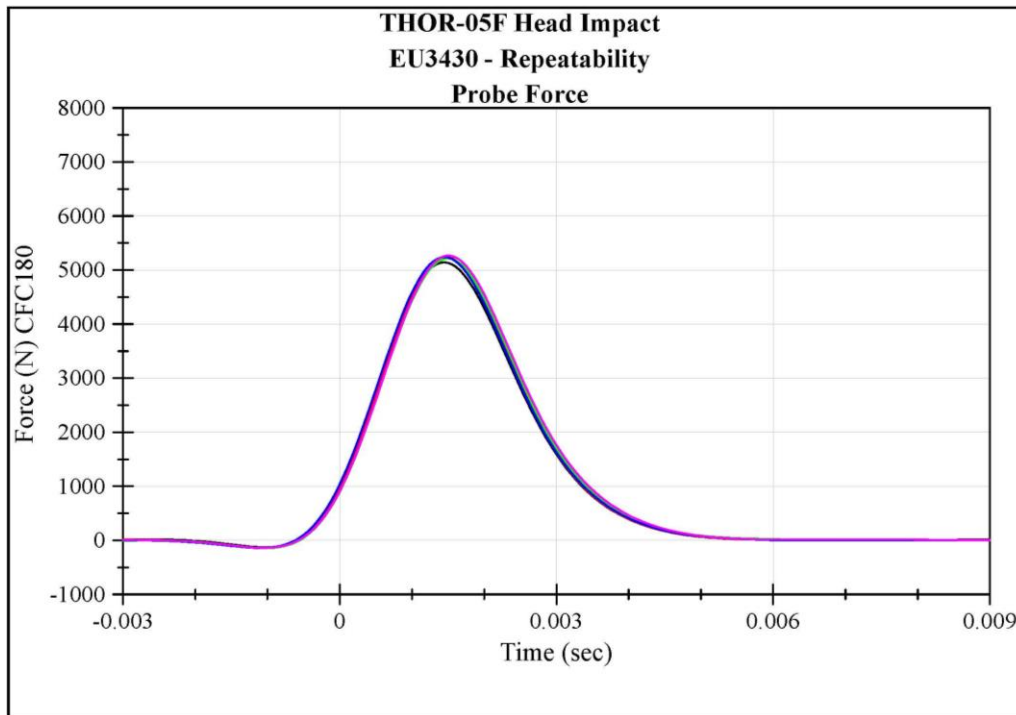


Figure 4-4. VRTC head impact probe force repeatability for EU3430

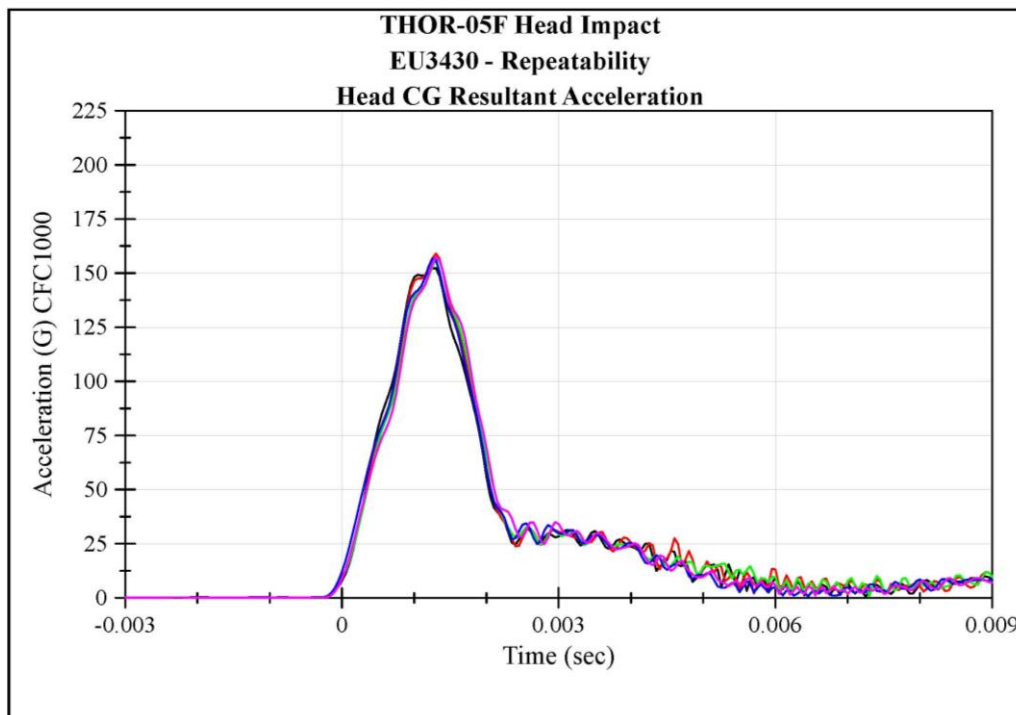


Figure 4-5. VRTC head impact head resultant CG acceleration repeatability for EU3430

4.2.3 THOR-05F EV4675 Testing at VRTC

Repeatability results at VRTC for EV4675 displayed CV values below 5 percent (Table 4-3, Figure 4-6, and Figure 4-7).

Table 4-3. VRTC EV4675 Head Impact Repeatability Results

Test Number	Maximum Probe Force (N)	Maximum Head CG Resultant (G)
240611-5	4,812	153
240611-6	4,856	156
240611-7	4,857	157
240612-1	4,859	156
240612-2	4,843	154
Mean	4,845	155
Standard Deviation	20	1.6
CV	0.4%	1.0%

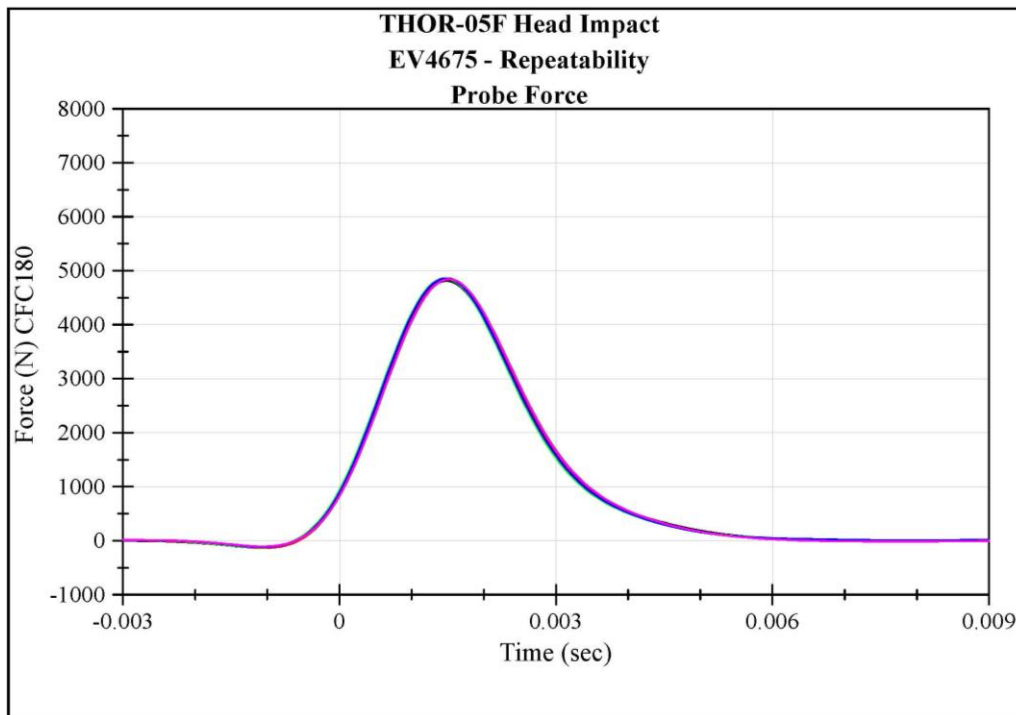


Figure 4-6. VRTC head impact probe force repeatability for EV4675

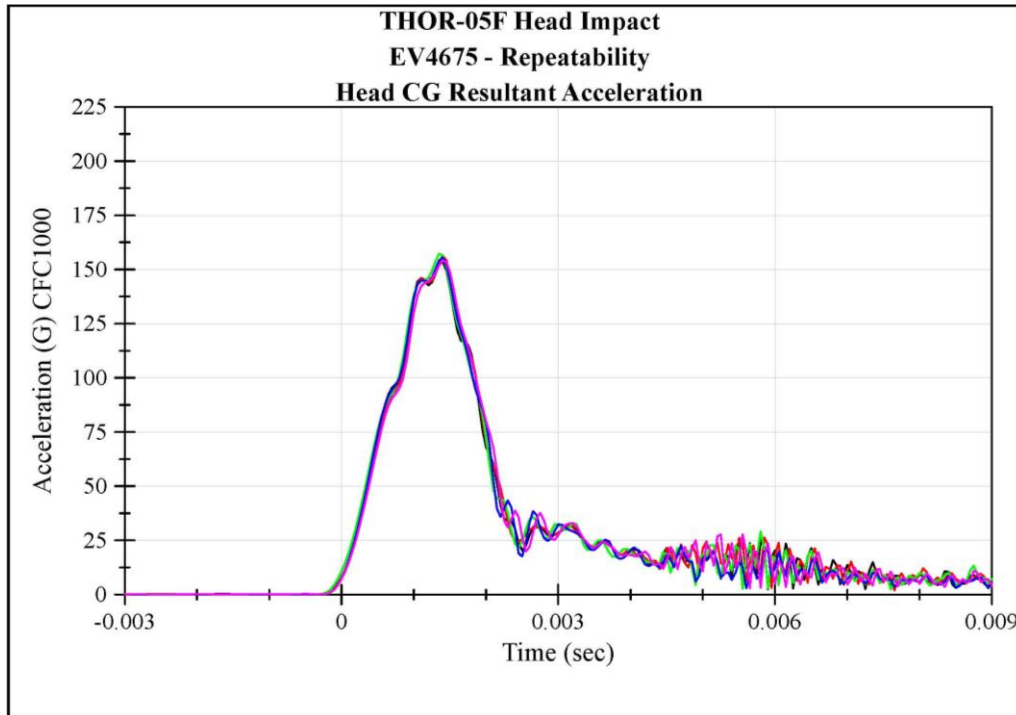


Figure 4-7. VRTC head impact head resultant CG acceleration repeatability for EV4675

4.2.4 THOR-05F EV4675 Testing at Humanetics

Repeatability results at Humanetics for EV4675 displayed CV values below 5 percent (Table 4-4, Figure 4-8, and Figure 4-9).

Table 4-4. Humanetics EV4675 Head Impact Repeatability Results

Test Number	Maximum Probe Force (N)	Maximum Head CG Resultant (G)
689367	5,120	152
689524	5,120	149
689537	5,094	145
689399	5,129	148
689384	5,168	150
Mean	5,126	149
Standard Deviation	27	2.8
CV	0.5%	1.9%

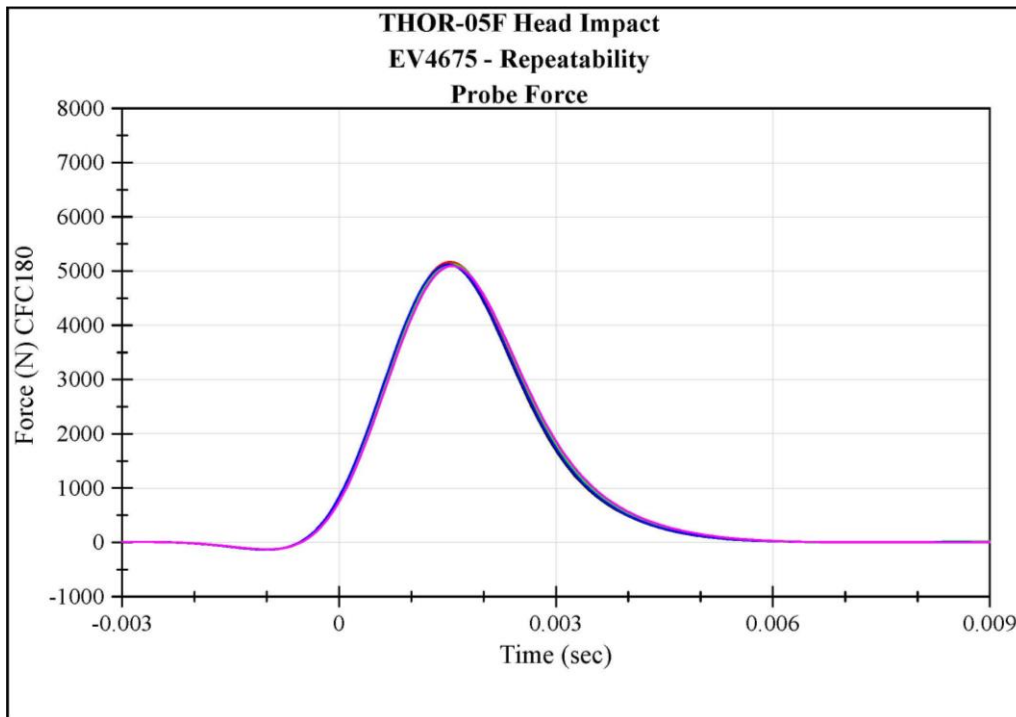


Figure 4-8. Humanetics head impact probe force repeatability for EV4675

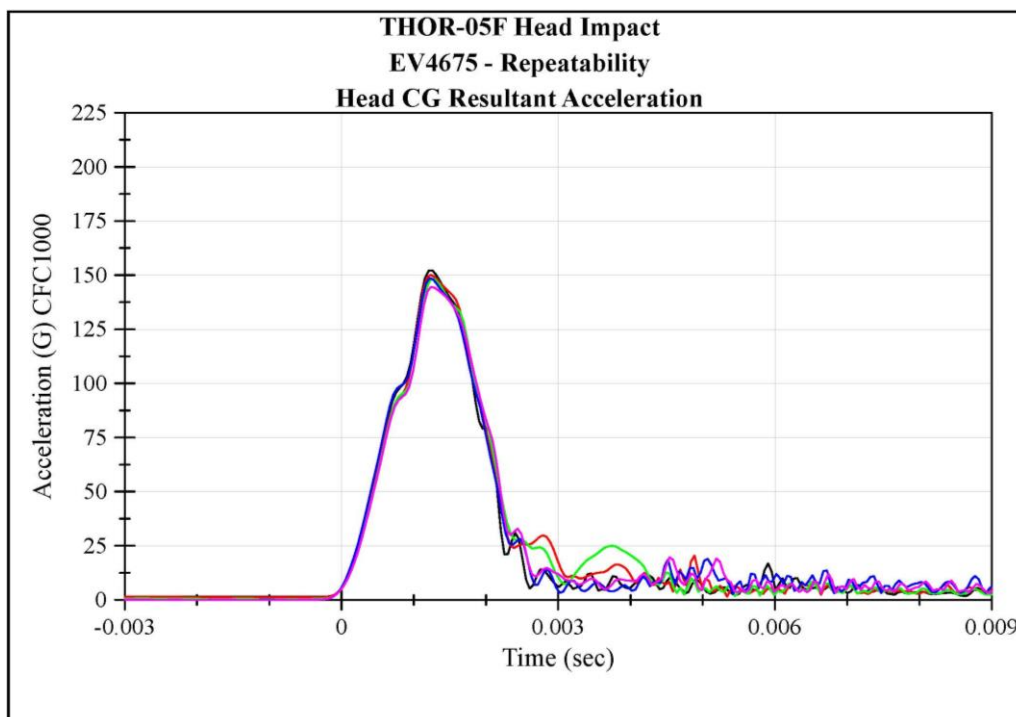


Figure 4-9. Humanetics head impact head resultant CG acceleration repeatability for EV4675

4.2.5 THOR-05F EV4675 Testing at Calspan

Repeatability results at Calspan for EV4675 displayed CV values below 5 percent (Table 4-5, Figure 4-10, and Figure 4-11).

Table 4-5. Calspan EV4675 Head Impact Repeatability Results

Test Number	Maximum Probe Force (N)	Maximum Head CG Resultant (G)
2025_03_19_18_17	5,175	162
2025_03_20_08_34	5,240	161
2025_03_20_09_15	5,137	158
2025_03_20_10_11	5,169	160
2025_03_20_11_15	5,206	161
Mean	5,185	160
Standard Deviation	39	1.5
CV	0.8%	0.9%

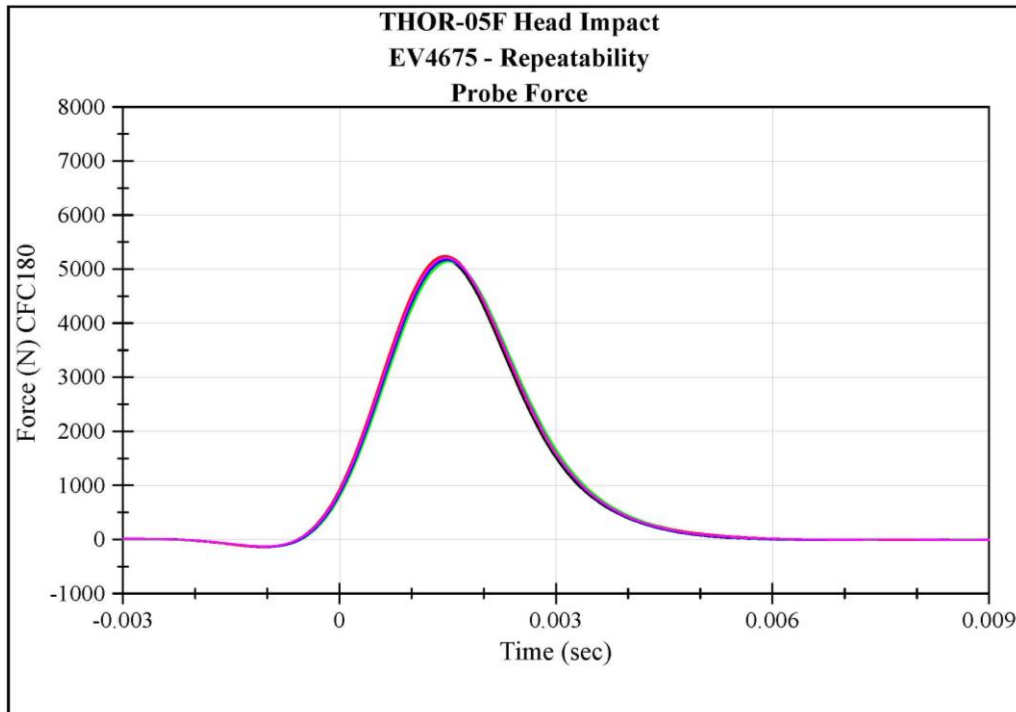


Figure 4-10. Calspan head impact probe force repeatability for EV4675

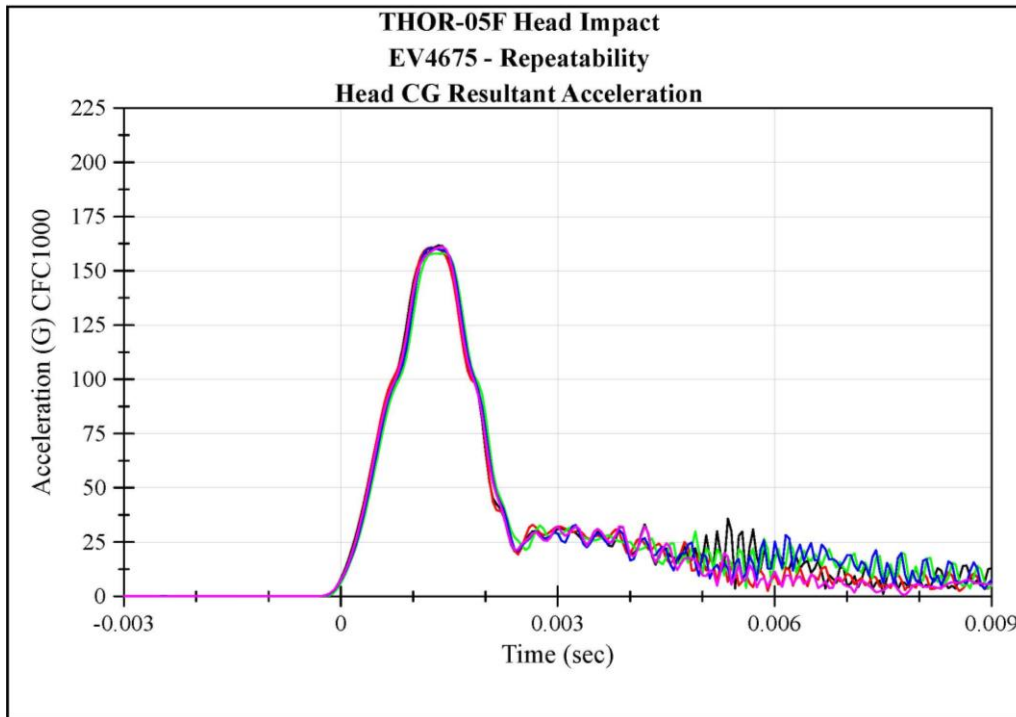


Figure 4-11. Calspan head impact head resultant CG acceleration repeatability for EV4675

4.2.6 THOR-05F EV4675 Testing at TRC

Repeatability results at TRC for EV4675 displayed CV values below 5 percent (Table 4-6, Figure 4-12, and Figure 4-13).

Table 4-6. TRC EV4675 Head Impact Repeatability Results

Test Number	Maximum Probe Force (N)	Maximum Head CG Resultant (G)
2025_05_22_08_15	4,989	159
2025_05_22_08_41	4,998	160
2025_05_22_09_46	4,995	159
2025_05_22_11_23	4,993	160
2025_05_22_13_06	4,994	159
Mean	4,994	159
Standard Deviation	3	0.5
CV	0.1%	0.3%

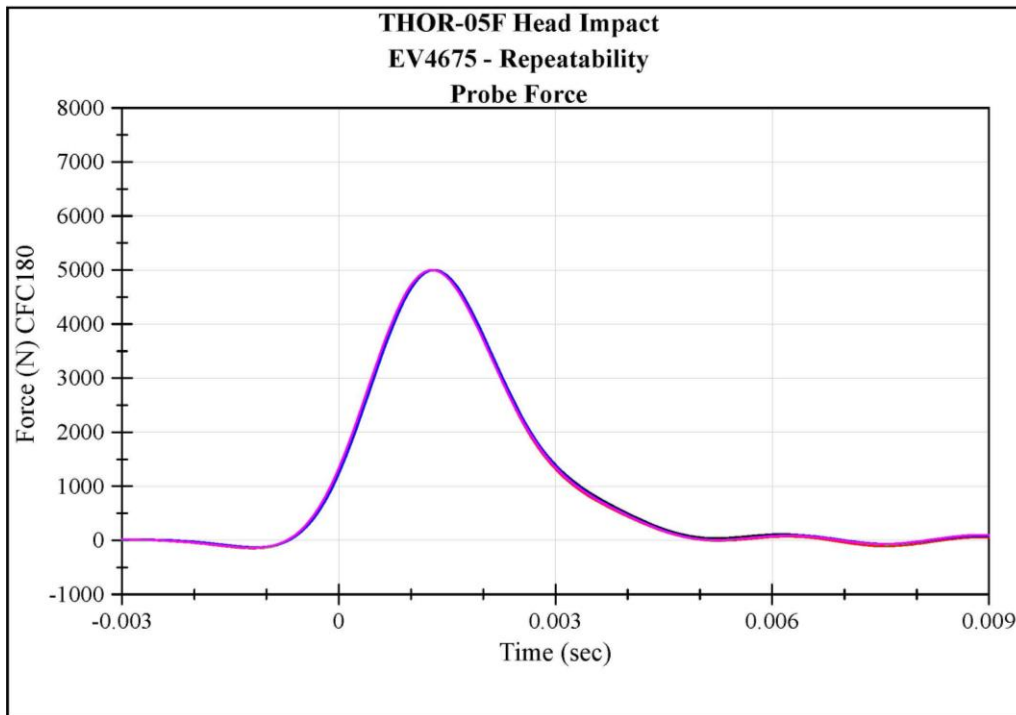


Figure 4-12. TRC head impact probe force repeatability for EV4675

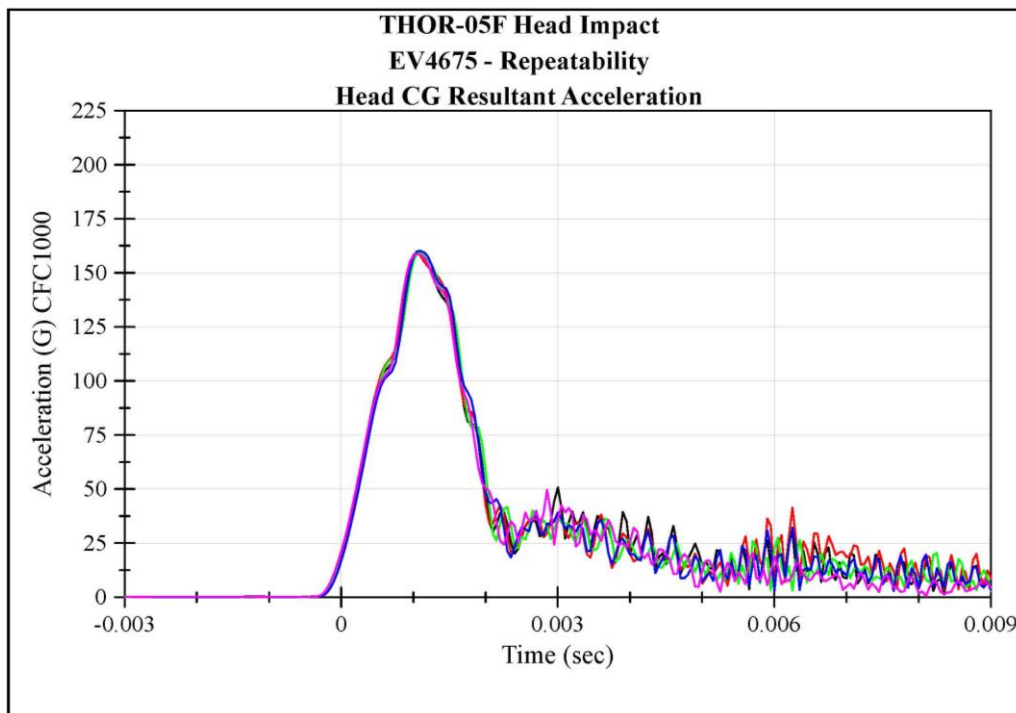


Figure 4-13. TRC head impact head resultant CG acceleration repeatability for EV4675

4.3 THOR-05F Head Impact Dummy Reproducibility Results

Dummy Reproducibility results at VRTC for the head impact qualification tests yielded CV values all below 5 percent (Table 4-7).

Table 4-7. THOR-05F Head Impact Reproducibility Results – VRTC Only

Dummy	Test Number	Maximum Probe Force (N)	Maximum Head CG Resultant (G)
VRTC EU9863	240122-3	5,083	156
	240122-8	5,141	159
	240122-13	4,919	146
	240122-16	5,130	158
	240123-1	5,069	152
VRTC EU3430	240806-13	5,141	152
	240806-16	5,242	159
	240806-17	5,215	156
	240807-1	5,237	157
	240807-2	5,267	157
VRTC EV4675	240611-5	4,812	153
	240611-6	4,856	156
	240611-7	4,857	157
	240612-1	4,859	156
	240612-2	4,843	154
Mean		5,045	155
Standard Deviation		169	3.3
CV		3.3%	2.2%

4.4 Lab-to-Lab Variability Analysis

The results of the head impact qualification tests from each lab are presented in Table 4-8. The last three rows of the table show the *Test Reproducibility* results when data from all four labs are combined. *Test Reproducibility* results at VRTC, Humanetics, Calspan, and TRC for the head impact tests displayed CV values below 5 percent for all specifications measured.

Table 4-8. THOR-05F Head Impact Dummy Reproducibility Results

Dummy	Test Number	Maximum Probe Force (N)	Maximum Head CG Resultant (G)
VRTC EV4675	240122-3	4,812	153
	240122-8	4,856	156
	240122-13	4,857	157
	240122-16	4,859	156
	240123-1	4,843	154
Humanetics EV4675	689367	5,120	152
	689524	5,120	149
	689537	5,094	145
	689399	5,129	148
	689384	5,168	150
Calspan EV4675	2025_03_19 18_17	5,175	162
	2025_03_20 08_34	5,240	161
	2025_03_20 09_15	5,137	158
	2025_03_20 10_11	5,169	160
	2025_03_20 11_15	5,206	161
TRC EV4675	2025_05_22 08_15	4,989	159
	2025_05_22 08_41	4,998	160
	2025_05_22 09_46	4,995	159
	2025_05_22 11_23	4,993	160
	2025_05_22 13_06	4,994	159
Test Reproducibility EV4675			
Mean		5,038	156
Standard Deviation		136	4.9
CV		2.7%	3.2%

4.5 Corridor Development

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

Table 4-9. THOR-05F Head Impact Qualification Corridor Results

Dummy	Test Number	Maximum Probe Force (N)	Maximum Head CG Resultant (G)
VRTC EU9863	240122-3	5,083	156
	240122-8	5,141	159
	240122-13	4,919	146
	240122-16	5,130	158
	240123-1	5,069	152
VRTC EU3430	240806-13	5,141	152
	240806-16	5,242	159
	240806-17	5,215	156
	240807-1	5,237	157
	240807-2	5,267	157
VRTC EV4675	240611-5	4,812	153
	240611-6	4,856	156
	240611-7	4,857	157
	240612-1	4,859	156
	240612-2	4,843	154
Humanetics EV4675	689367	5,120	152
	689524	5,120	149
	689537	5,094	145
	689399	5,129	148
	689384	5,168	150
Calspan EV4675	2025_03_19 18_17	5,175	162
	2025_03_20 08_34	5,240	161
	2025_03_20 09_15	5,137	158
	2025_03_20 10_11	5,169	160
	2025_03_20 11_15	5,206	161
TRC EV4675	2025_05_22 08_15	4,989	159
	2025_05_22 08_41	4,998	160
	2025_05_22 09_46	4,995	159
	2025_05_22 11_23	4,993	160
	2025_05_22 13_06	4,994	159
Mean		5,073	156
Standard Deviation		135	4.6
CV		2.7%	3.0%

Table 4-10. Head Impact Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Impact Velocity	m/s	1.95	2.05	2.0	
Maximum Probe Force	N	4566	5581	5073	10%
Maximum Head CG Resultant Acceleration	G	140	171	156	10%

Discussion. There were no instances in which a test did not achieve the target response $\pm 10\%$. All CV values 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-05F Qualification Procedures and Requirements*. The face rigid disk qualification test examines facial impact response to loading by a rigid 152.4 ± 0.3 mm diameter circular disk face of the 10.70 ± 0.02 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 3500N to 6600N. For this test series, face impact tests were conducted using honeycomb face inserts (474-1401) installed into the head. This testing was performed using three THOR-05F dummies; each dummy had a different honeycomb face insert installed. During these tests, the probe force was measured.

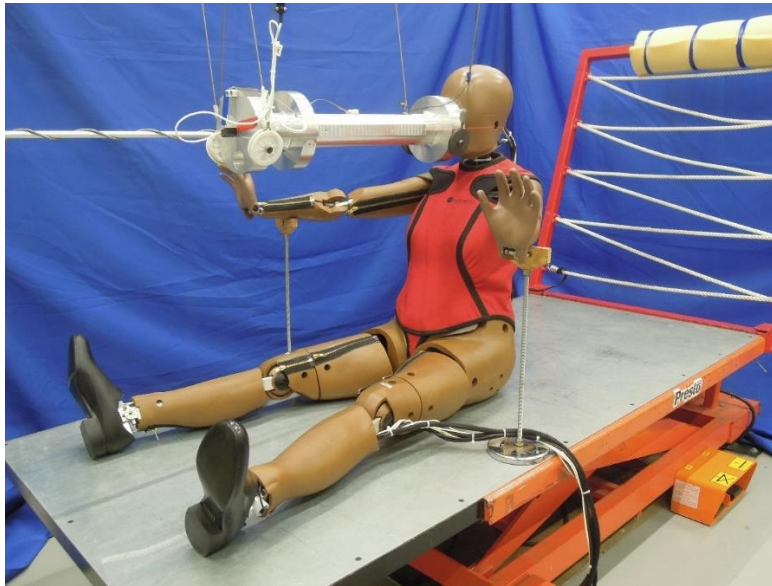


Figure 5-1. Face impact test setup

5.2 Face Impact Repeatability Results

Sections 5.2.1 through 5.2.5 illustrate the results of the face impact repeatability tests. Each section contains a table providing the test data, followed by plot overlays of the five repeat tests performed at all four 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.

5.2.1 THOR-05F Face Insert EU7671 Testing at VRTC

Repeatability results at VRTC for face testing on Honeycomb Face Insert EU7671 (installed on ATD EU9863) revealed a CV value below 5 percent for probe force (Table 5-1 and Figure 5-2).

Table 5-1. VRTC EU7671 Face Impact Repeatability Results

Test Number	Maximum Probe Force (N)
240124-7	6,078
240124-10	6,541
240124-11	6,314
240124-13	6,326
240125-2	6,475
Mean	6,347
Standard Deviation	179
CV	2.8%

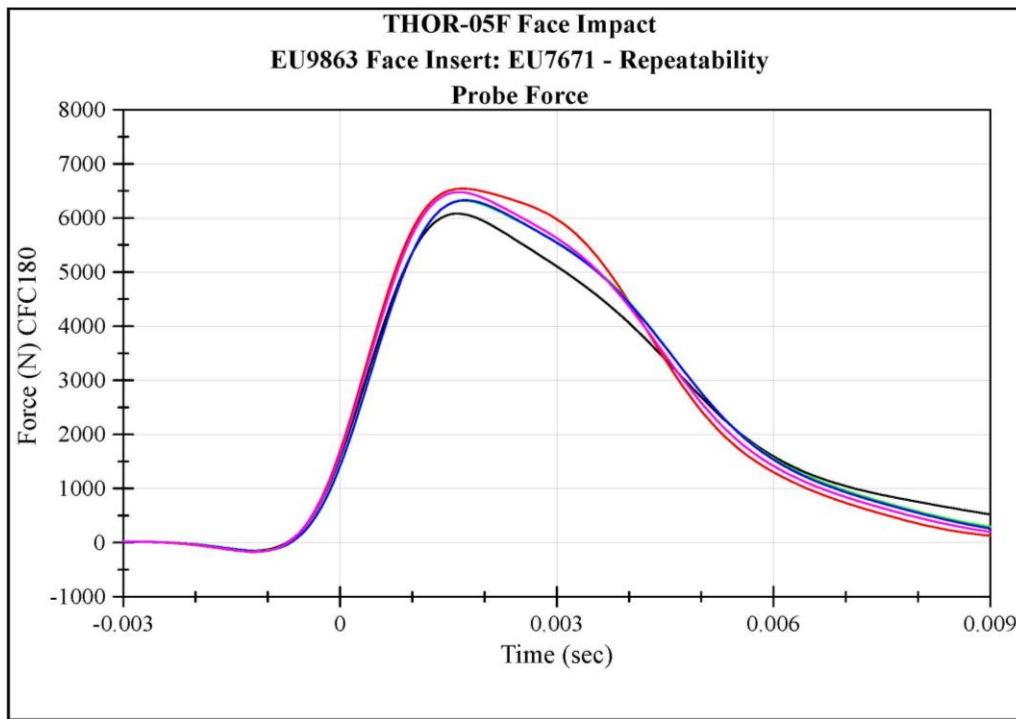


Figure 5-2. VRTC probe force for face impact repeatability tests for EU7671

5.2.1 THOR-05F Face Insert FB4256 Testing at VRTC

Repeatability results for face testing at VRTC on Honeycomb Face Insert FB4256 (installed on ATD EU3430) displayed a CV value below 5 percent for probe force (Table 5-2, Figure 5-3).

Table 5-2. VRTC FB4256 Face Impact Repeatability Results

Test Number	Maximum Probe Force (N)
240805-6	5,501
240805-10	5,348
240805-11	5,138
240806-3	5,111
240806-4	5,020
Mean	5,224
Standard Deviation	196
CV	3.8%

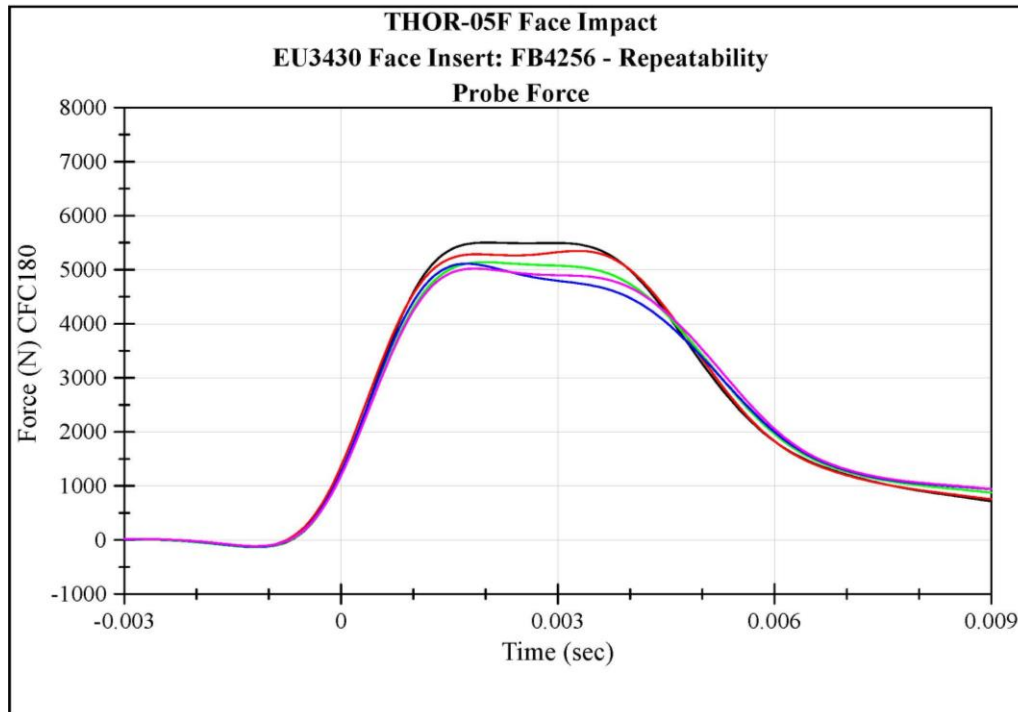


Figure 5-3. VRTC probe force for face impact repeatability tests for FB4256

5.2.2 THOR-05F Face Insert EV0769 Testing at VRTC

Repeatability results for face testing at VRTC on Honeycomb Face Insert EV0769 (installed on ATD EV4675) displayed a CV value below 5 percent for probe force (Table 5-3 and Figure 5-4).

Table 5-3. VRTC EV0769 Face Impact Repeatability Results

Test Number	Maximum Probe Force (N)
240612-3	6,513
240612-4	6,117
240612-5	6,539
240617-1	6,031
240617-2	6,055
Mean	6,251
Standard Deviation	253
CV	4.1%

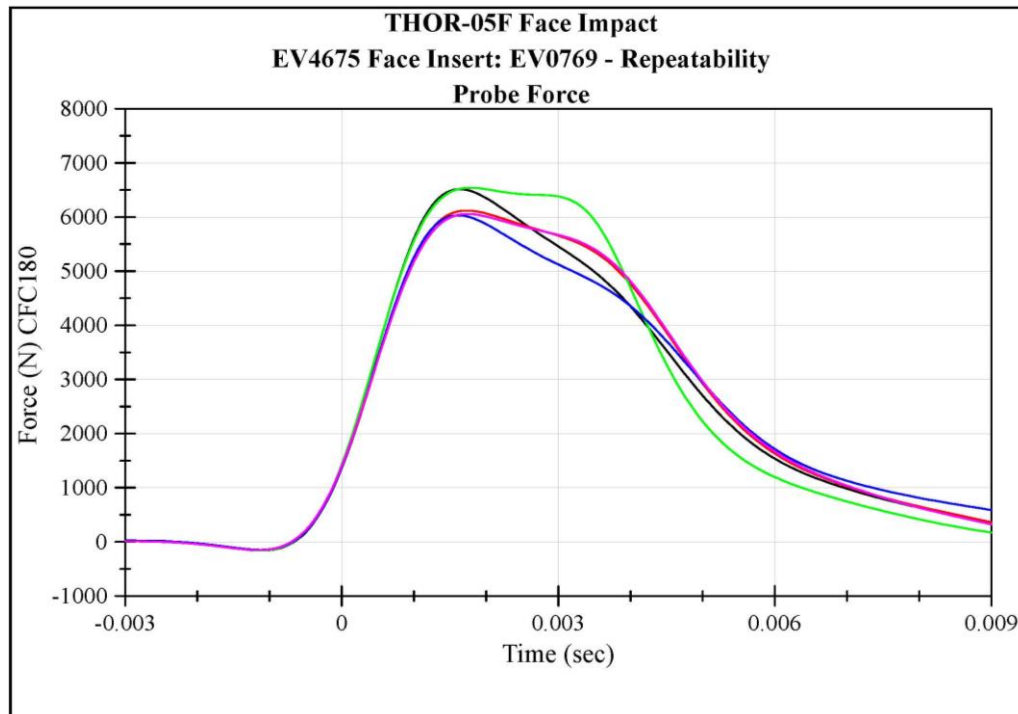


Figure 5-4. VRTC probe force for face impact repeatability tests for EV0769

5.2.3 THOR-05F Face Insert EV0769 Testing at Humanetics

Repeatability results for face testing at Humanetics on Honeycomb Face Insert EV0769 (installed on ATD EV4675) displayed a CV value below 5 percent for probe force (Table 5-4 and Figure 5-5).

Table 5-4. Humanetics EV0769 Face Impact Repeatability Results

Test Number	Maximum Probe Force (N)
689765	5,858
689753	5,935
689743	5,936
689625	6,013
689724	6,150
Mean	5,979
Standard Deviation	111
CV	1.8%

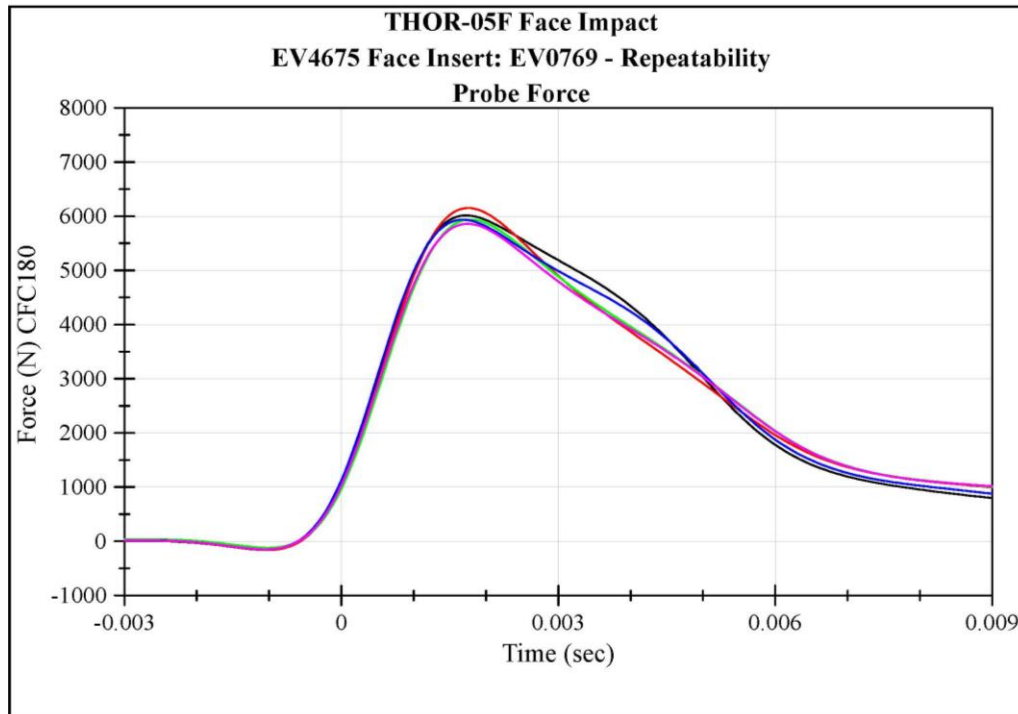


Figure 5-5. Humanetics probe force for face impact repeatability tests for EV0769

5.2.4 THOR-05F Face Insert EV0769 Testing at Calspan

Repeatability results for face testing at Calspan on Honeycomb Face Insert EV0769 (installed on ATD EV4765) displayed a CV value below 5 percent for probe force (Table 5-5 and Figure 5-6).

Table 5-5. Calspan EV0769 Face Impact Repeatability Results

Test Number	Maximum Probe Force (N)
2025_03_24 20_04	6,844
2025_03_25 09_51	6,695
2025_03_25 18_08	6,443
2025_03_25 19_08	6,150
2025_03_25 20_19	6,776
Mean	6,582
Standard Deviation	285
CV	4.3%

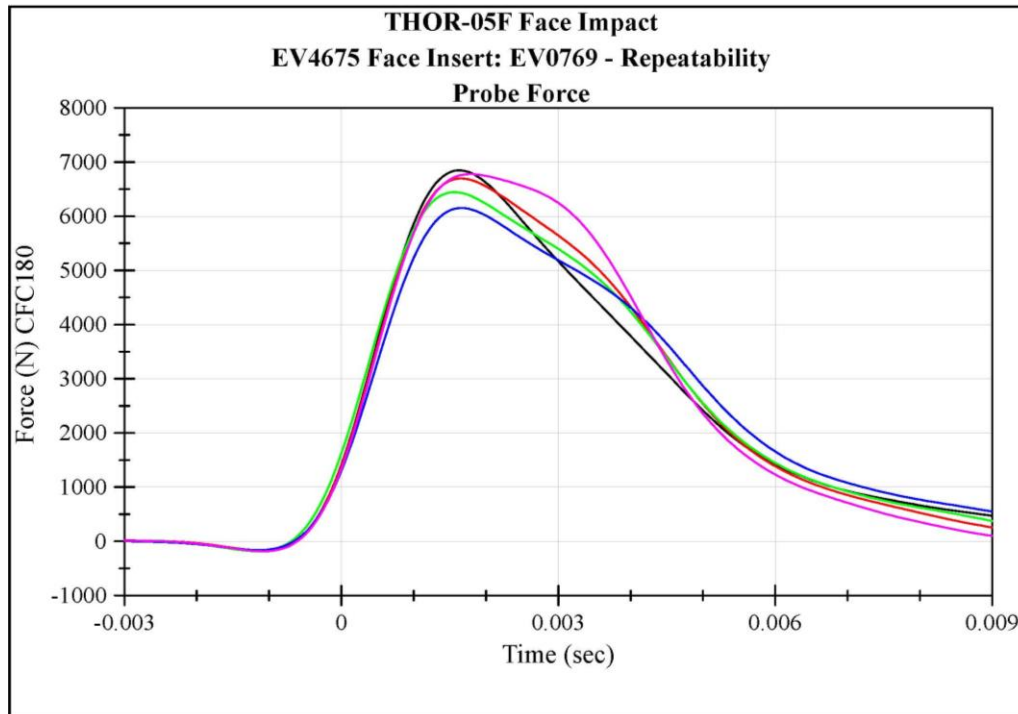


Figure 5-6. Calspan probe force for face impact repeatability tests for EV0769

5.2.5 THOR-05F Face Insert EV0769 Testing at TRC

Repeatability results for face testing at TRC on Honeycomb Face Insert EV0769 (installed on ATD EV4675) displayed a CV value below 5 percent for probe force (Table 5-6 and Figure 5-7).

Table 5-6. TRC Face Insert EV0769 Face Impact Repeatability Results

Test Number	Maximum Probe Force (N)
2025_05_13 13_11	5,739
2025_05_13 15_02	6,001
2025_05_14 08_23	6,306
2025_05_14 11_21	5,600
2025_05_14 14_47	5,700
Mean	5,869
Standard Deviation	285
CV	4.9%

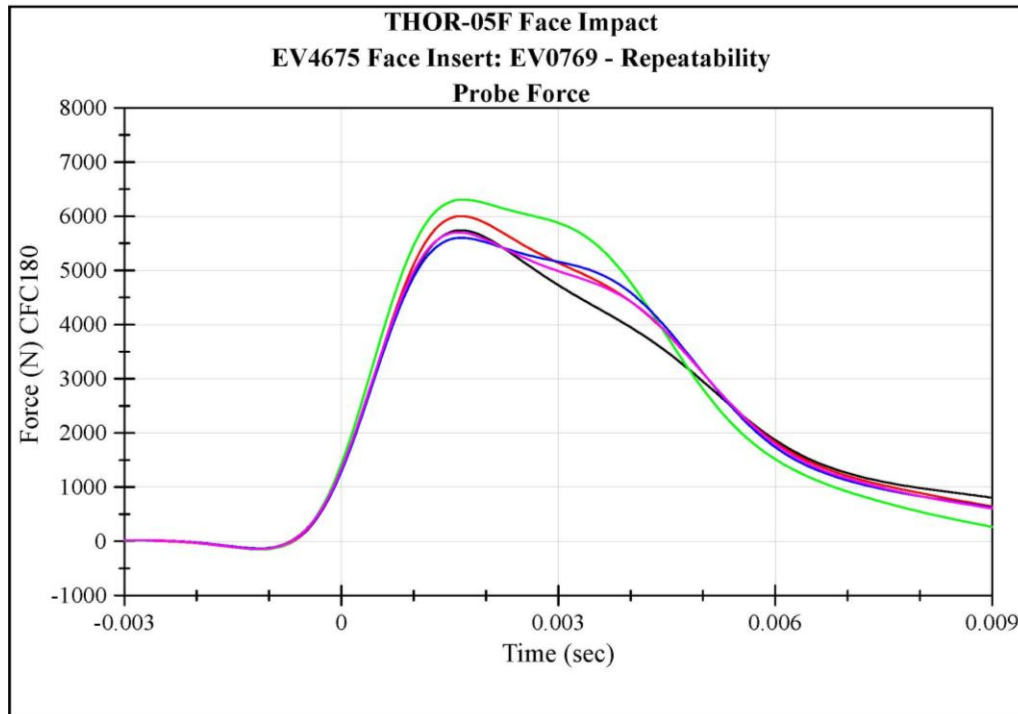


Figure 5-7. TRC probe force for face impact repeatability tests for EV0769

5.3 THOR-05F Face Impact Dummy Reproducibility Results

Dummy Reproducibility results at VRTC for the face impact tests, displayed a CV value between 5 and 10 percent for probe force (Table 5-7).

Table 5-7. THOR-05F Face Impact Reproducibility Results

Dummy	Test Number	Maximum Probe Force (N)
VRTC EU9863 Face Insert EU7671	240124-7	6,078
	240124-10	6,541
	240124-11	6,314
	240124-13	6,326
	240125-2	6,475
VRTC EU3430 Face Insert FB4256	240805-6	5,501
	240805-10	5,348
	240805-11	5,138
	240806-3	5,111
	240806-4	5,020
VRTC EV4675 Face Insert EV0769	240612-3	6,513
	240612-4	6,117
	240612-5	6,539
	240617-1	6,031
	240617-2	6,055
Mean		6,017
Standard Deviation		570
CV		9.5%

5.4 Lab-to-Lab Variability Analysis

The results of the face impact qualification tests from each lab are presented in Table 5-8. The last three rows of the table show the *Test Reproducibility* results when data from all four labs are combined. *Test Reproducibility* results at VRTC, Humanetics, Calspan, and TRC for the face impact tests displayed a CV value between 5 and 10 percent for probe force (Table 5-8).

Table 5-8. THOR-05F Face Impact Reproducibility Results

Dummy	Test Number	Maximum Probe Force (N)
VRTC EV4675 Face Insert EV0769	240612-3	6513
	240612-4	6117
	240612-5	6539
	240617-1	6031
	240617-2	6055
Humanetics EV4675 Face Insert EV0769	689765	5858
	689753	5935
	689743	5936
	689625	6013
	689724	6150
Calspan EV4675 Face Insert EV0769	2025_03_24 20_04	6844
	2025_03_25 09_51	6695
	2025_03_25 18_08	6443
	2025_03_25 19_08	6150
	2025_03_25 20_19	6776
TRC EV4675 Face Insert EV0769	2025_05_13 13_11	5739
	2025_05_13 15_02	6001
	2025_05_14 08_23	6306
	2025_05_14 11_21	5600
	2025_05_14 14_47	5700
Test Reproducibility Face Insert EV0769		
Mean		6170
Standard Deviation		361
CV		5.8%

5.5 Corridor Development

All the data used to determine the face qualification corridors is shown in Table 5-9. The qualification corridors were calculated using the mean plus or minus 10 percent of the maximum for the specified measured or calculated channels (Table 5-10).

Table 5-9. THOR-05F Face Impact Qualification Corridor Results
(Highlighted values fell outside average $\pm 10\%$.)

Dummy	Test Number	Maximum Probe Force (N)
VRTC EU9863 Face Insert EU7671	240124-7	6,078
	240124-10	6,541
	240124-11	6,314
	240124-13	6,326
	240125-2	6,475
VRTC EU3430 Face Insert FB4256	240805-6	5,501
	240805-10	5,348
	240805-11	5,138
	240806-3	5,111
	240806-4	5,020
VRTC EV4675 Face Insert EV0769	240612-3	6,513
	240612-4	6,117
	240612-5	6,539
	240617-1	6,031
	240617-2	6,055
Humanetics EV4675 Face Insert EV0769	689765	5,858
	689753	5,935
	689743	5,936
	689625	6,013
	689724	6,150
Calspan EV4675 Face Insert EV0769	2025_03_24 20_04	6,844
	2025_03_25 09_51	6,695
	2025_03_25 18_08	6,443
	2025_03_25 19_08	6,150
	2025_03_25 20_19	6,776
TRC EV4675 Face Insert EV0769	2025_05_13 13_11	5,739
	2025_05_13 15_02	6,001
	2025_05_14 08_23	6,306
	2025_05_14 11_21	5,600
	2025_05_14 14_47	5,700
Mean		6,076
Standard Deviation		492
CV		8.1%

Table 5-10. Face Rigid Disk Impact Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Impact Velocity	m/s	6.68	6.78	6.73	
Maximum Probe Force	N	5,469	6,684	6,076	10%

Discussion.

Highlighted cells in Table 5-9 indicate test values that failed to achieve their respective target response $\pm$ 10%. There were 7 tests which produced results outside of the $\pm$ 10% range. The non-conforming tests were present at VRTC and Calspan labs and on face inserts FB4256 and EV0769.

Repeatability (Table 5-1 through Table 5-6) for probe force was consistent, with CV values below 5 percent across all face insert samples and all labs.

Dummy Reproducibility (Table 5-7) CV values for probe force were between 5 and 10 percent.

Results for lab-to-lab *Test Reproducibility* (Table 5-8) shows that the probe force had a CV value over 5 percent, but under 10 percent.

6 NECK FLEXION

6.1 Methodology

Repeatability and reproducibility tests were performed using the neck flexion qualification procedures described in the *THOR-05F Qualification Procedures and Requirements*. The flexion tests resemble the Hybrid III head-neck pendulum test defined in CFR Title 49, Part 572, Subpart E with 152.4 mm 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 via the neck mounting plate (TF-200-2357); the pendulum was decelerated from the specified speed during contact with a Hexcel aluminum honeycomb. During these tests, the upper neck moment (M_Y), upper neck force (F_Z), head angular velocity (ω_Y), and head rotation (θ_Y) were measured.



Figure 6-1. Neck flexion test setup

6.2 Neck Flexion Repeatability Results

Sections 6.2.1 through 6.2.6 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 four 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-05F Neck EU9734 Testing at VRTC

Repeatability results at VRTC for neck flexion testing on neck EU9734 (removed from ATD EU9863) displayed CV values below 5 percent (Table 6-1 through Table 6-2, Figure 6-2 through Figure 6-5).

Table 6-1. VRTC EU9734 Neck 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)
240326-8	1.69	3.38	4.84
240326-9	1.75	3.57	4.97
240326-10	1.81	3.61	5.08
240326-11	1.76	3.56	5.01
240327-1	1.77	3.56	5.02
Mean	1.76	3.53	4.98
Standard Deviation	0.04	0.09	0.09
CV	2.4%	2.4%	1.8%

Table 6-2. VRTC EU9734 Neck Flexion Repeatability Results

Test Number	Maximum Upper Neck M_y (N-m)	Maximum Upper Neck F_z Prior to 40 ms (N)	Minimum Head ω_y (deg/s)	Minimum Head θ_y (deg)
240326-8	17.5	741	-2,157	-79.8
240326-9	17.6	760	-2,196	-80.2
240326-10	17.8	812	-2,250	-80.5
240326-11	17.4	767	-2,208	-81.3
240327-1	18.2	771	-2,175	-78.8
Mean	17.7	770	-2,197	-80.1
Standard Deviation	0.28	26.1	35.7	0.90
CV	1.6%	3.4%	1.6%	1.1%

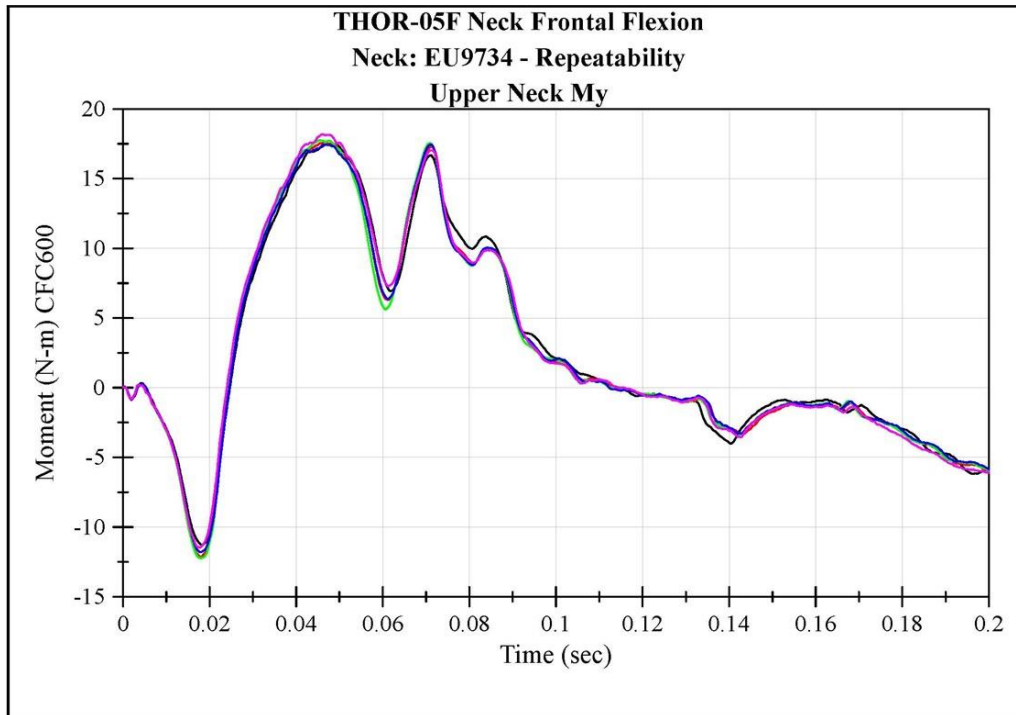


Figure 6-2. VRTC neck frontal flexion upper neck moment M_y repeatability for Neck EU9734

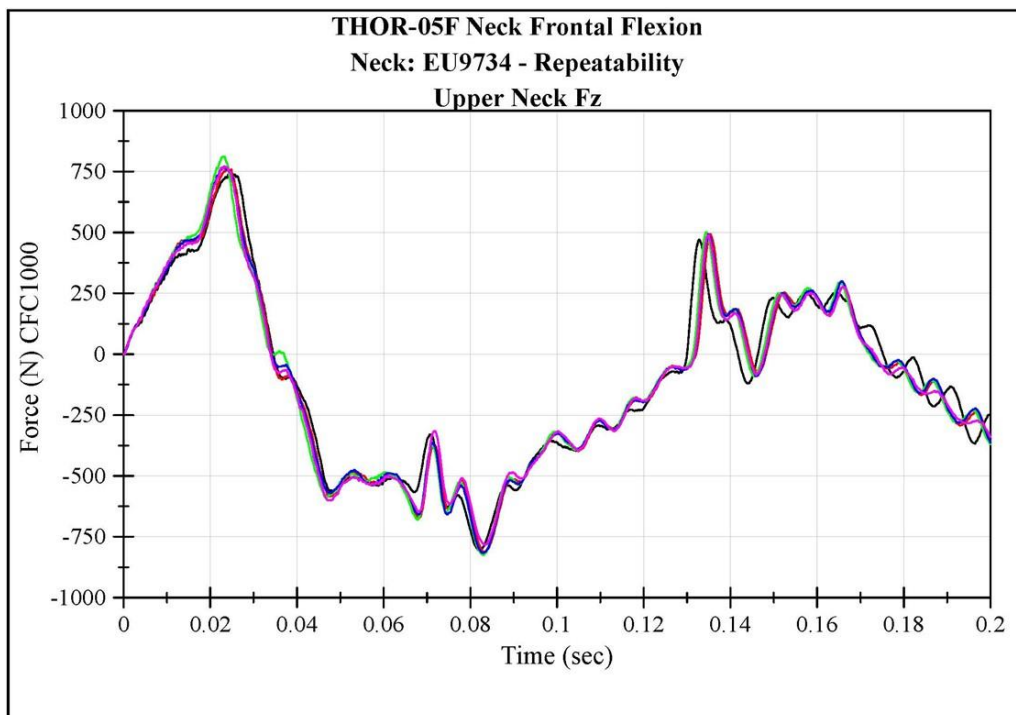


Figure 6-3. VRTC neck frontal flexion upper neck force F_z repeatability for Neck EU9734

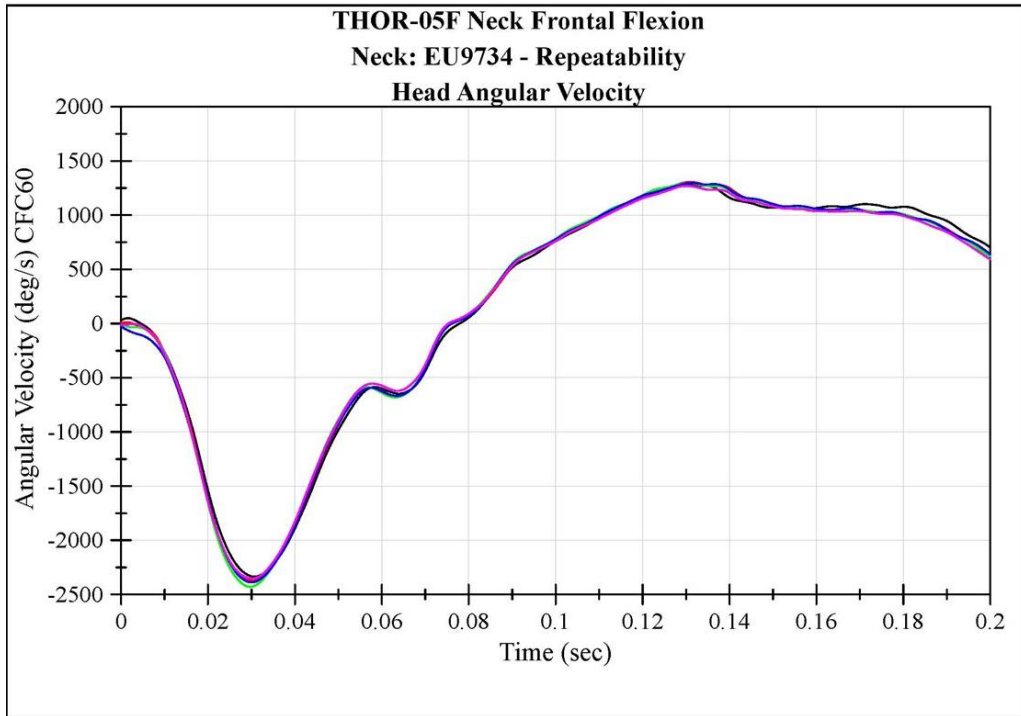


Figure 6-4. VRTC neck frontal flexion angular velocity ω_y repeatability for Neck EU9734

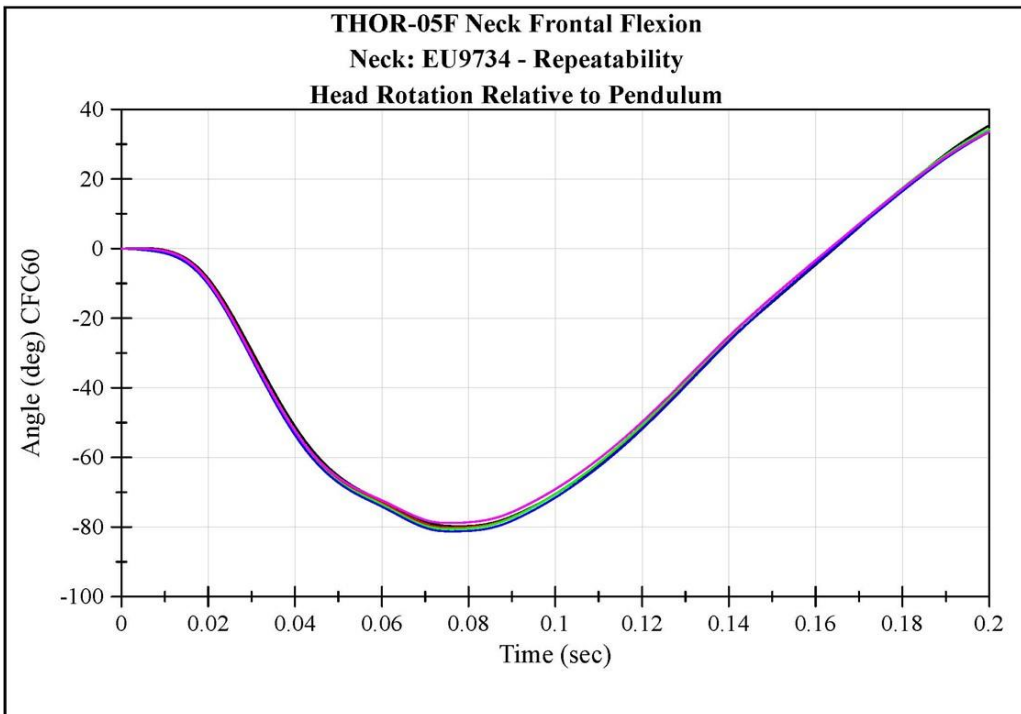


Figure 6-5. VRTC neck frontal flexion head rotation θ_y repeatability for Neck EU9734

6.2.2 THOR-05F Neck EV1357 Testing at VRTC

Repeatability results at VRTC for neck flexion testing on Neck EV1357 (removed from ATD EV0674) displayed CV values below 5 percent (Table 6-3 through Table 6-4, Figure 6-6 through Figure 6-9).

Table 6-3. VRTC EV1357 Neck 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)
240529-17	1.71	3.41	4.84
240529-18	1.72	3.39	4.86
240529-19	1.68	3.35	4.84
240529-20	1.73	3.36	4.80
240529-22	1.72	3.44	4.92
Mean	1.71	3.39	4.85
Standard Deviation	0.02	0.03	0.04
CV	1.0%	1.0%	0.9%

Table 6-4. VRTC EV1357 Neck Flexion Repeatability Results

Test Number	Maximum Upper Neck M_y (N-m)	Maximum Upper Neck F_z Prior to 40 ms (N)	Minimum Head ω_y (deg/s)	Minimum Head θ_y (deg)
240529-17	18.1	738	-2,079	-78.0
240529-18	18.2	756	-2,094	-78.6
240529-19	18.2	756	-2,089	-78.3
240529-20	18.1	727	-2,075	-78.0
240529-22	18.2	761	-2,125	-78.5
Mean	18.2	748	-2,092	-78.3
Standard Deviation	0.05	14.5	19.7	0.27
CV	0.3%	1.9%	0.9%	0.3%

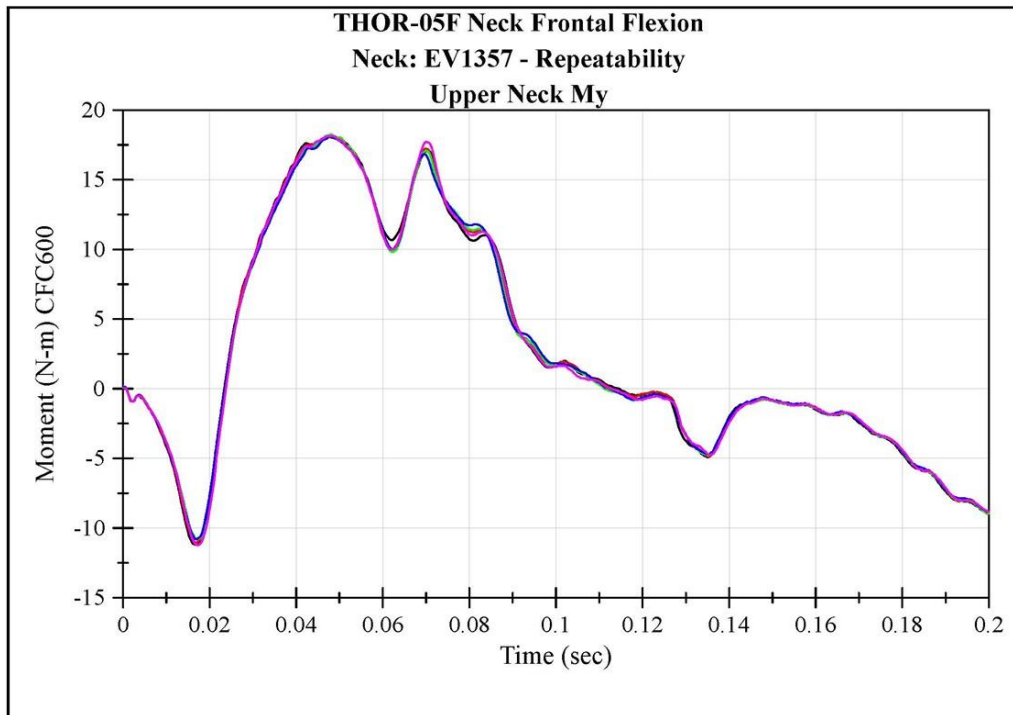


Figure 6-6. VRTC neck frontal flexion upper neck moment M_y repeatability for Neck EV1357

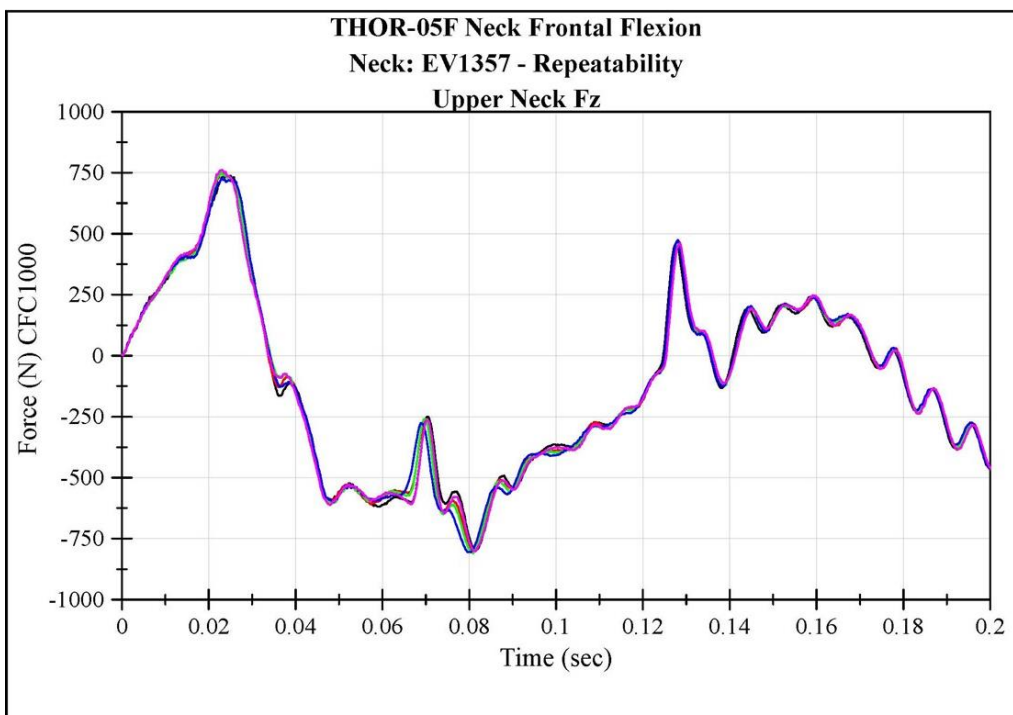


Figure 6-7. VRTC neck frontal flexion upper neck force F_z repeatability for Neck EV1357

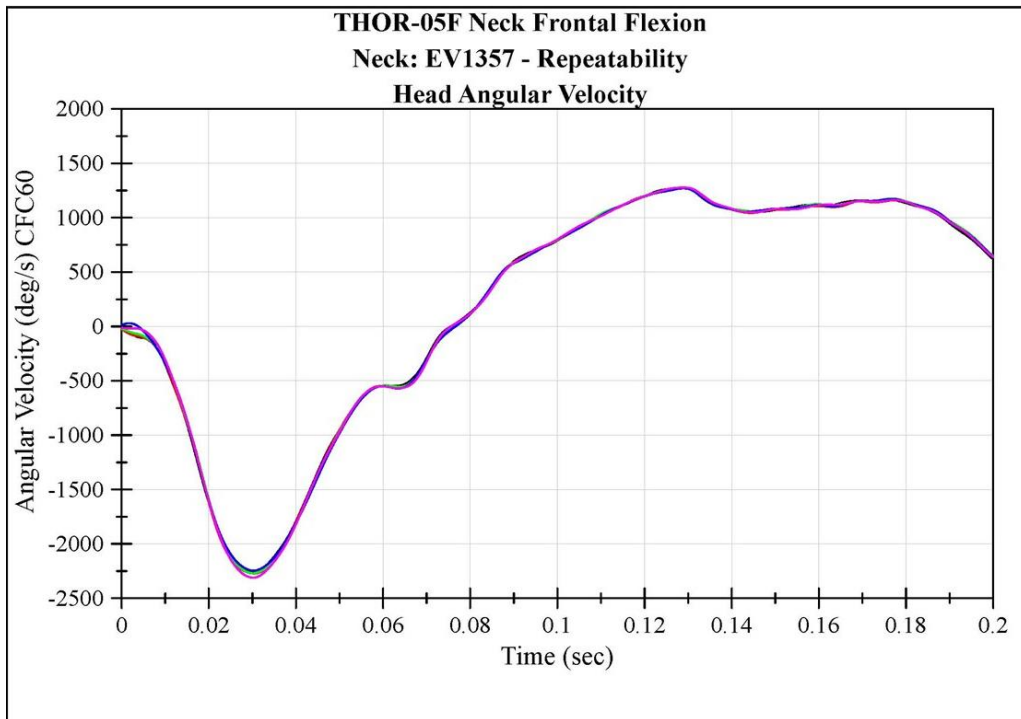


Figure 6-8. VRTC neck frontal flexion angular velocity ω_y repeatability for Neck EV1357

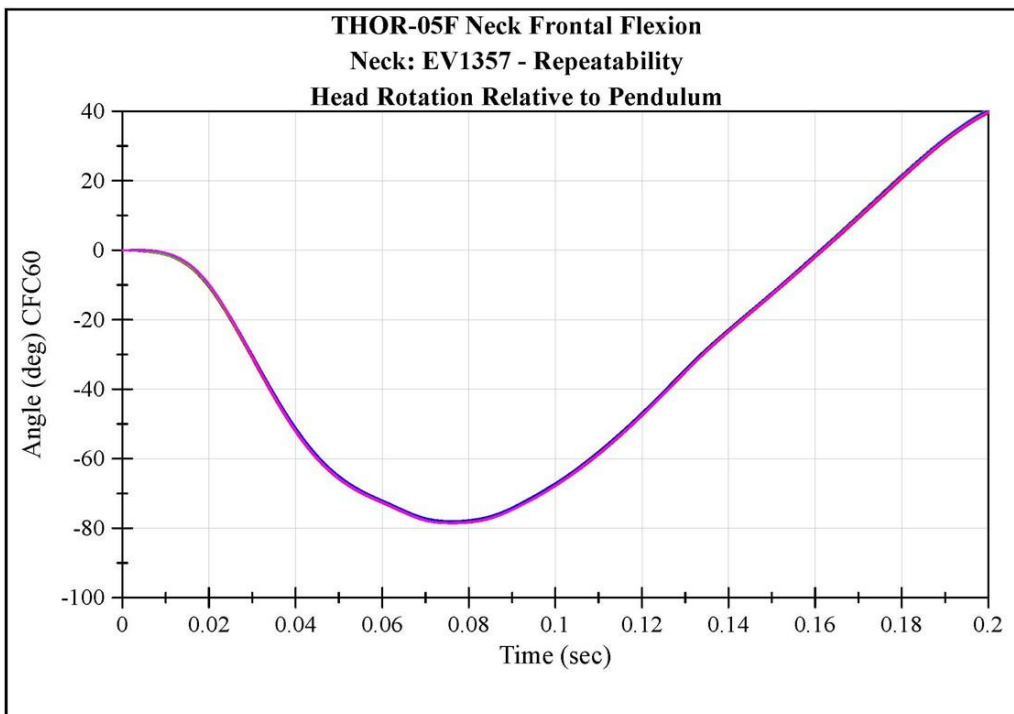


Figure 6-9. VRTC neck frontal flexion head rotation θ_y repeatability for Neck EV1357

6.2.3 THOR-05F Neck EV0095 Testing at VRTC

Repeatability results for neck flexion testing on Neck EV0095 (removed from ATD EV4675) at VRTC displayed CV values below 5 percent (Table 6-5 through Table 6-6, Figure 6-10 through Figure 6-13).

Table 6-5. VRTC EV0095 Neck 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)
241202-4	1.82	3.57	5.04
241202-6	1.79	3.57	5.08
241202-7	1.82	3.63	5.08
241203-2	1.80	3.59	5.08
241203-4	1.89	3.70	5.08
Mean	1.82	3.61	5.07
Standard Deviation	0.04	0.06	0.02
CV	2.0%	1.5%	0.4%

Table 6-6. VRTC EV0095 Neck Flexion Repeatability Results

Test Number	Maximum Upper Neck M_y (N-m)	Maximum Upper Neck F_z Prior to 40 ms (N)	Minimum Head ω_y (deg/s)	Minimum Head θ_y (deg)
241202-4	18.6	752	-2,230	-78.9
241202-6	18.2	772	-2,234	-80.1
241202-7	17.8	797	-2,260	-80.9
241203-2	18.1	769	-2,227	-79.6
241203-4	17.9	786	-2,278	-80.7
Mean	18.1	775	-2,246	-80.0
Standard Deviation	0.31	17.1	22.3	0.82
CV	1.7%	2.2%	1.0%	1.0%

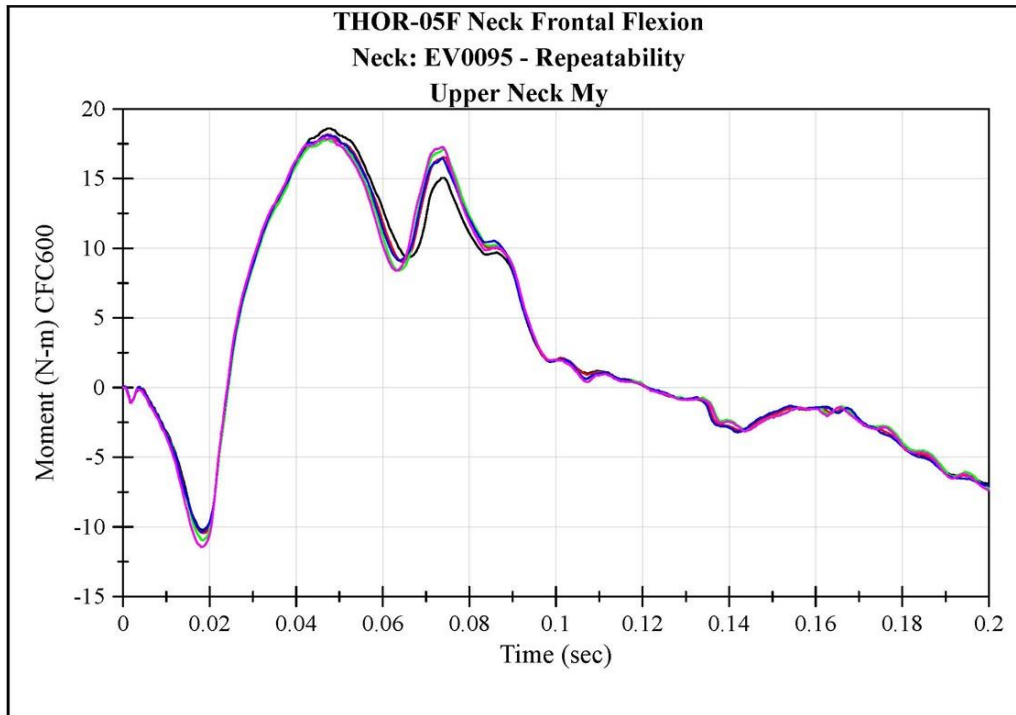


Figure 6-10. VRTC neck frontal flexion upper neck moment M_y repeatability for Neck EV0095

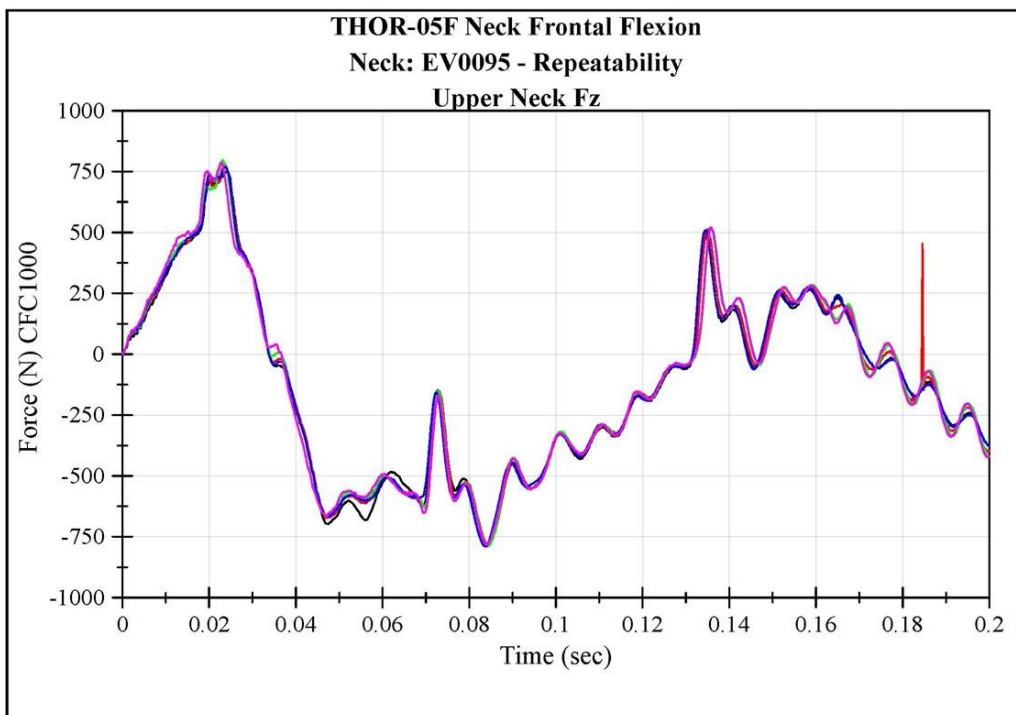


Figure 6-11. VRTC neck frontal flexion upper neck force F_z repeatability for Neck EV0095

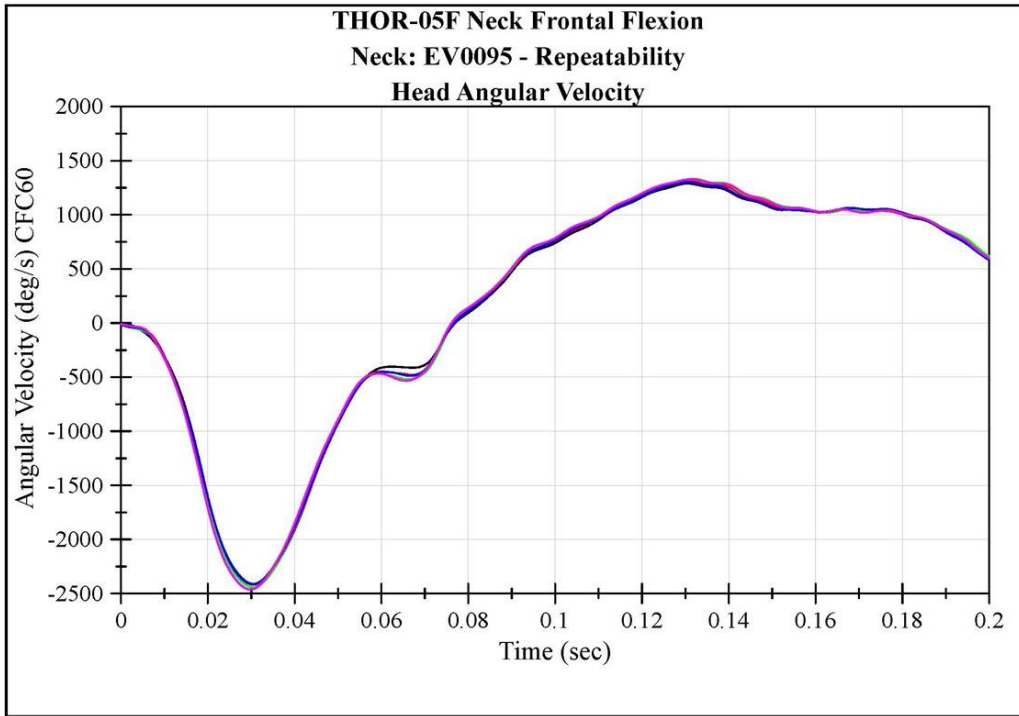


Figure 6-12. VRTC neck frontal flexion angular velocity ω_y repeatability for Neck EV0095

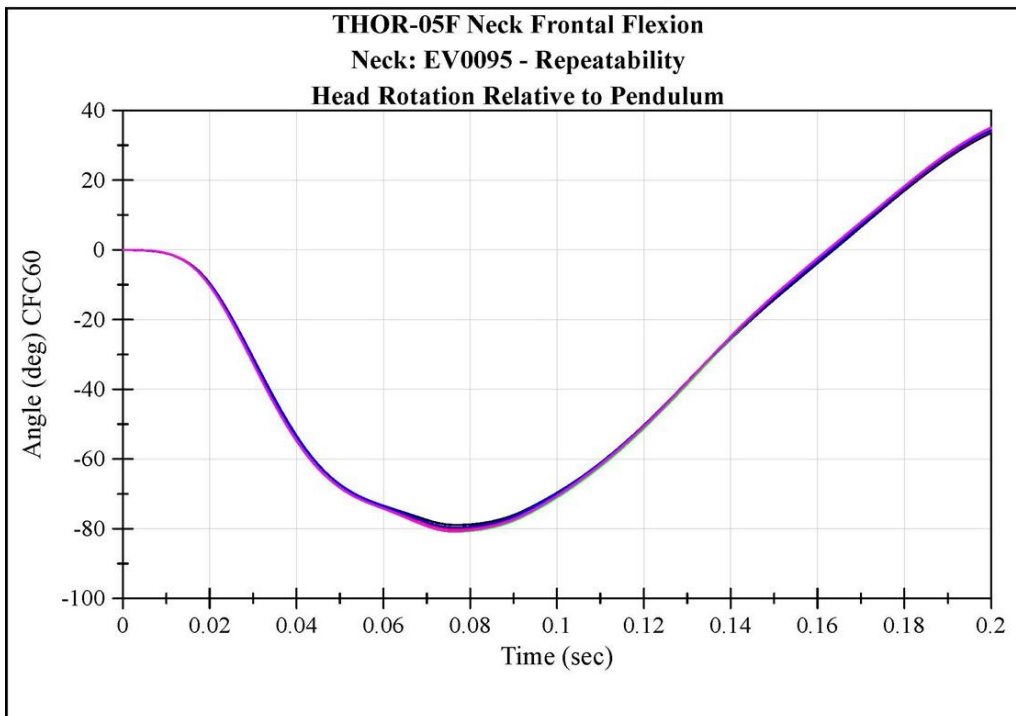


Figure 6-13. VRTC neck frontal flexion head rotation θ_y repeatability for Neck EV0095

6.2.4 THOR-05F Neck EV0095 Testing at Humanetics

Repeatability results at Humanetics for neck flexion testing on Neck EV0095 (removed from ATD EV4675) displayed CV values below 5 percent (Table 6-7 through Table 6-8, Figure 6-14 through Figure 6-17).

Table 6-7. Humanetics EV0095 Neck 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)
686837	1.59	3.14	4.54
686932	1.64	3.24	4.69
686938	1.60	3.18	4.59
686942	1.65	3.31	4.73
686950	1.66	3.28	4.74
Mean	1.63	3.23	4.66
Standard Deviation	0.03	0.07	0.09
CV	1.9%	2.2%	1.9%

Table 6-8. Humanetics EV0095 Neck Flexion Repeatability Results

Test Number	Maximum Upper Neck M_y (N-m)	Maximum Upper Neck F_z Prior to 40 ms (N)	Minimum Head ω_y (deg/s)	Minimum Head θ_y (deg)
686837	17.0	685	-1,965	-75.1
686932	17.3	710	-1,987	-74.6
686938	16.9	688	-1,983	-75.5
686942	17.1	713	-2,014	-75.6
686950	16.9	717	-2,011	-75.6
Mean	17.0	703	-1,992	-75.3
Standard Deviation	0.17	15.2	20.6	0.44
CV	1.0%	2.2%	1.0%	0.6%

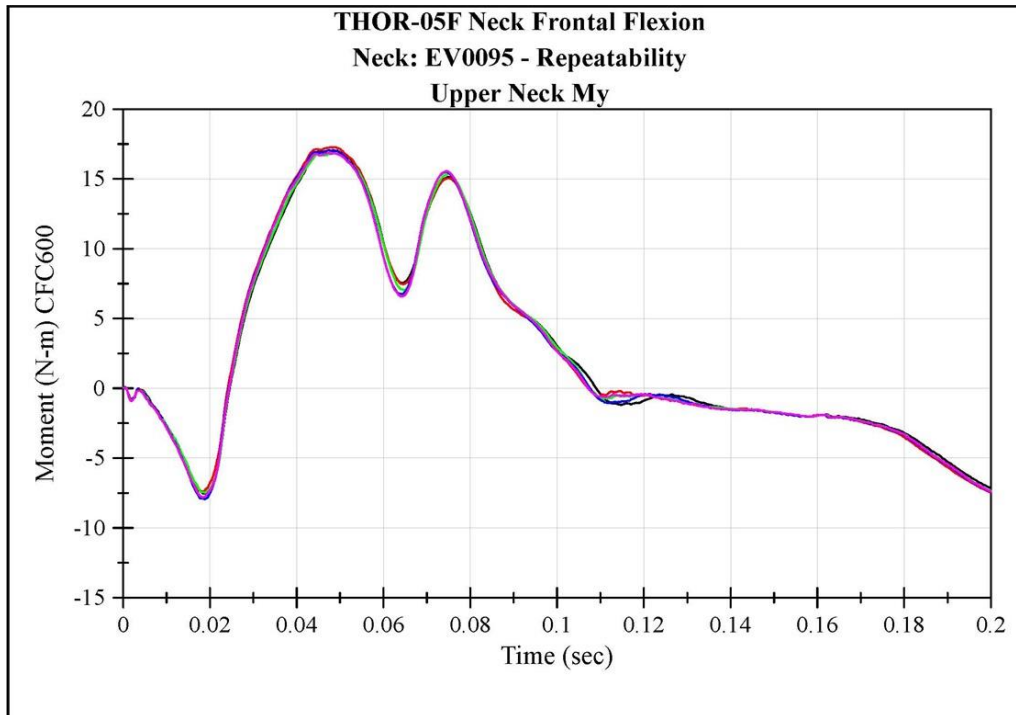


Figure 6-14. Humanetics neck frontal flexion upper neck moment M_y repeatability for Neck EV0095

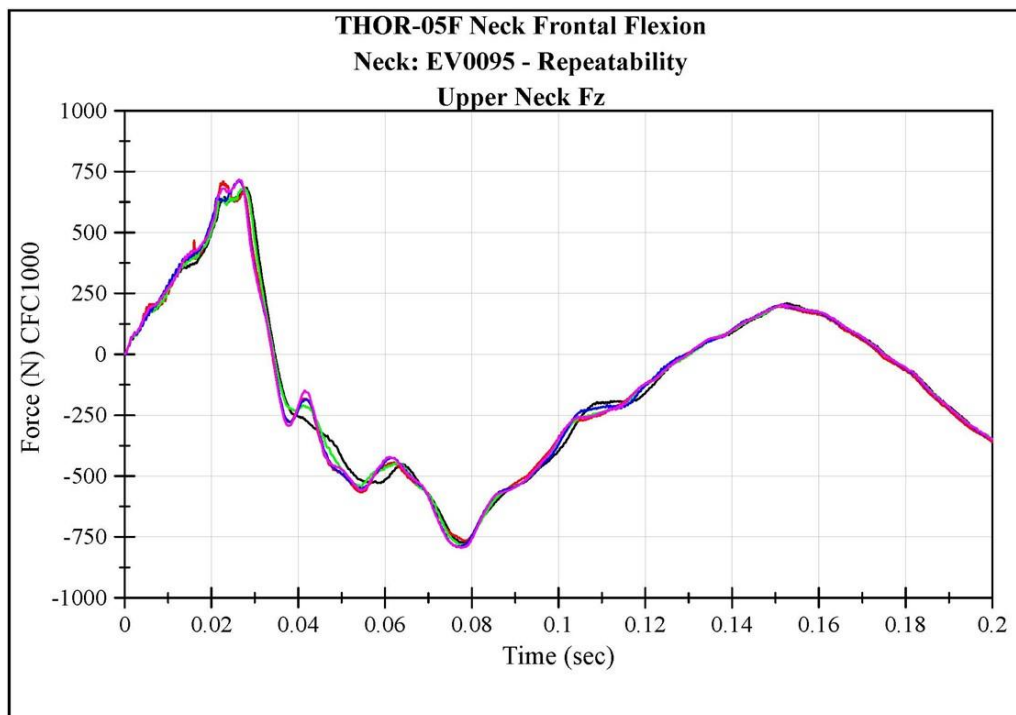


Figure 6-15. Humanetics neck frontal flexion upper neck force F_z repeatability for Neck EV0095

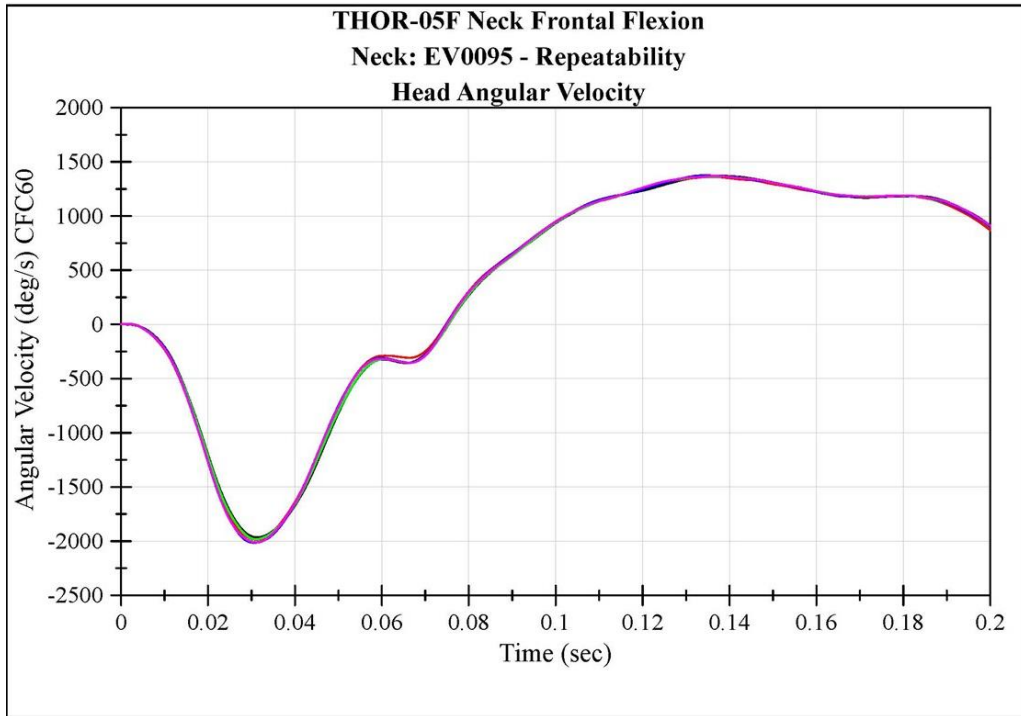


Figure 6-16. Humanetics neck frontal flexion angular velocity ω_y repeatability for Neck EV0095

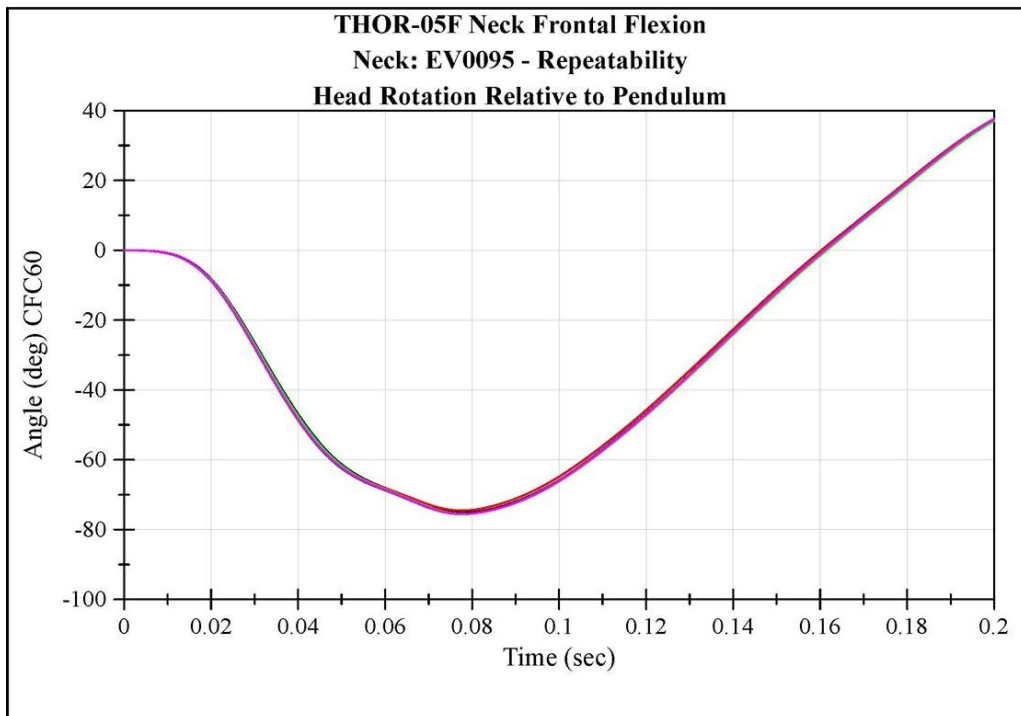


Figure 6-17. Humanetics neck frontal flexion head rotation θ_y repeatability for Neck EV0095

6.2.5 THOR-05F Neck EV0095 Testing at Calspan

Repeatability results at Calspan for neck flexion testing on Neck EV0095 (removed from ATD EV4675) displayed CV values below 5 percent (Table 6-9 through Table 6-10, Figure 6-18 through Figure 6-21).

Table 6-9. Calspan EV0095 Neck 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)
2025_03_26 12_17	1.78	3.72	5.18
2025_03_26 12_49	1.78	3.78	5.20
2025_03_26 13_22	1.81	3.80	5.18
2025_03_26 14_04	1.73	3.64	5.15
2025_03_26 14_38	1.74	3.66	5.15
Mean	1.77	3.72	5.17
Standard Deviation	0.03	0.07	0.02
CV	1.9%	1.9%	0.4%

Table 6-10. Calspan EV0095 Neck Flexion Repeatability Results

Test Number	Maximum Upper Neck M_y (N-m)	Maximum Upper Neck F_z Prior to 40 ms (N)	Minimum Head ω_y (deg/s)	Minimum Head θ_y (deg)
2025_03_26 12_17	18.1	882	-2,217	-79.4
2025_03_26 12_49	18.4	909	-2,239	-78.7
2025_03_26 13_22	18.3	912	-2,254	-79.1
2025_03_26 14_04	17.9	891	-2,226	-79.2
2025_03_26 14_38	18.1	862	-2,213	-79.0
Mean	18.1	891	-2,230	-79.1
Standard Deviation	0.21	20.7	17.1	0.25
CV	1.1%	2.3%	0.8%	0.3%

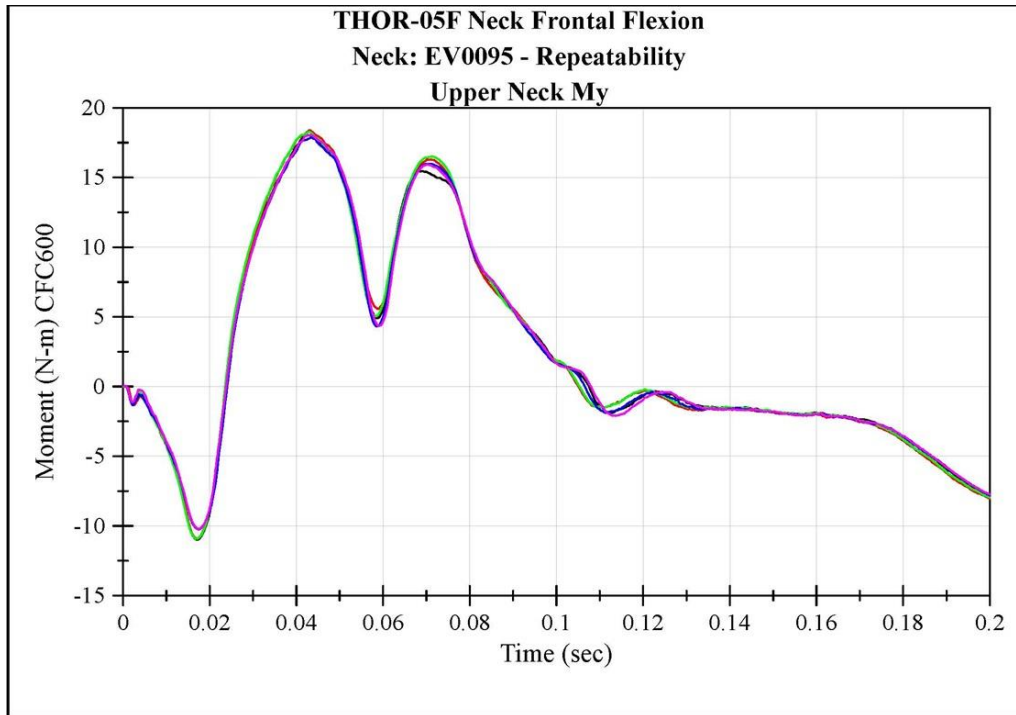


Figure 6-18. Calspan neck frontal flexion upper neck moment M_y repeatability for Neck EV0095

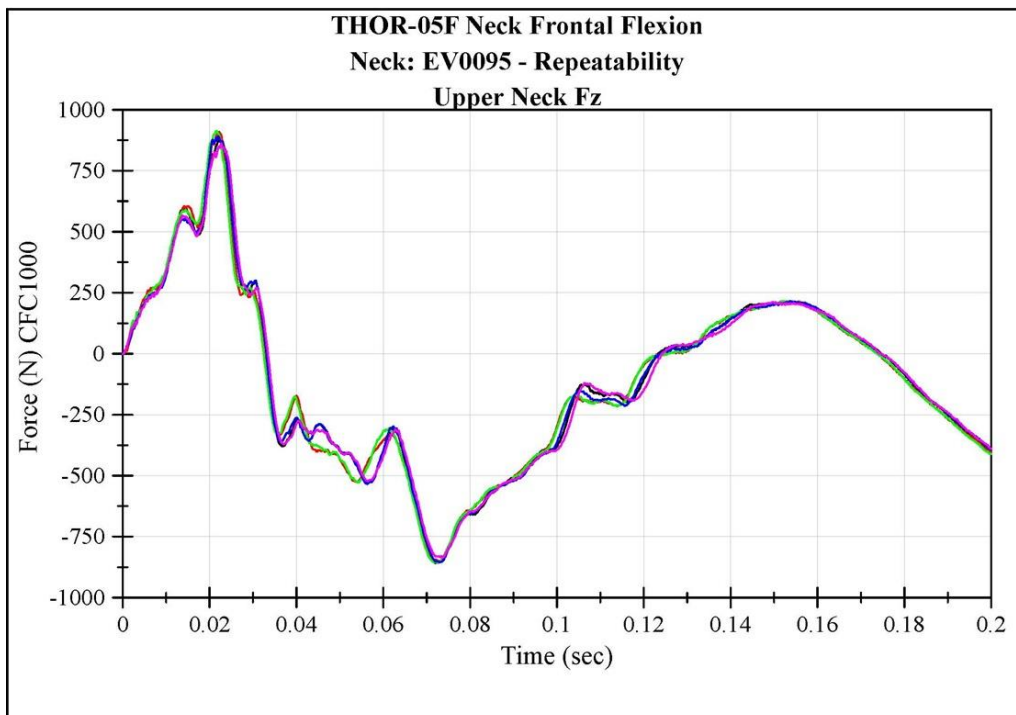


Figure 6-19. Calspan neck frontal flexion upper neck force F_z repeatability for Neck EV0095

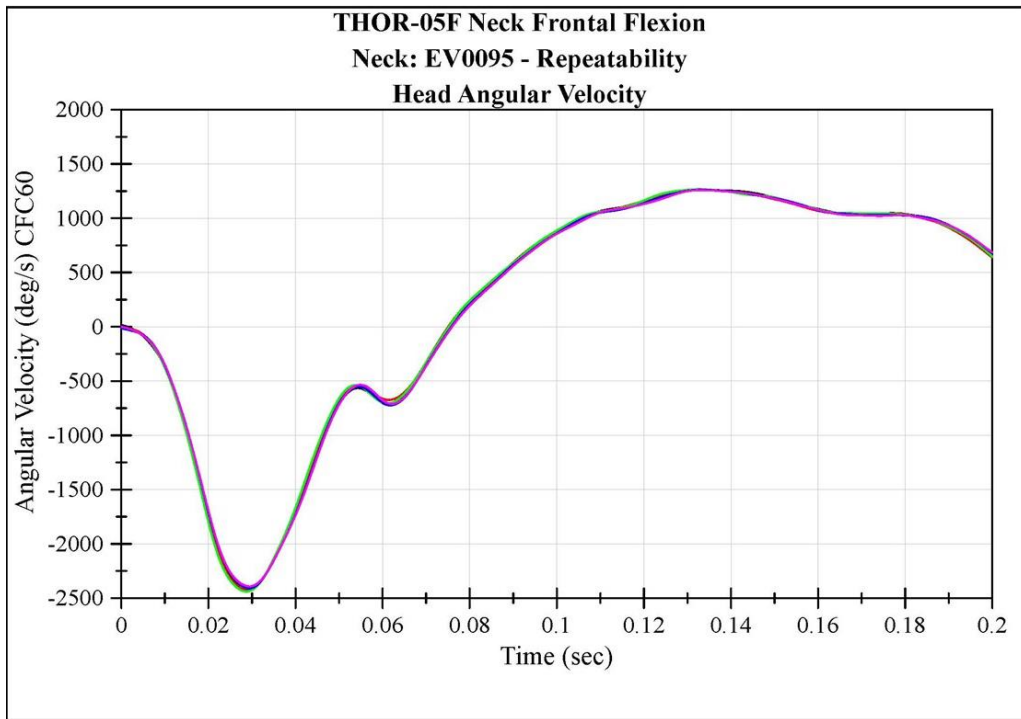


Figure 6-20. Calspan neck frontal flexion angular velocity ω_y repeatability for Neck EV0095

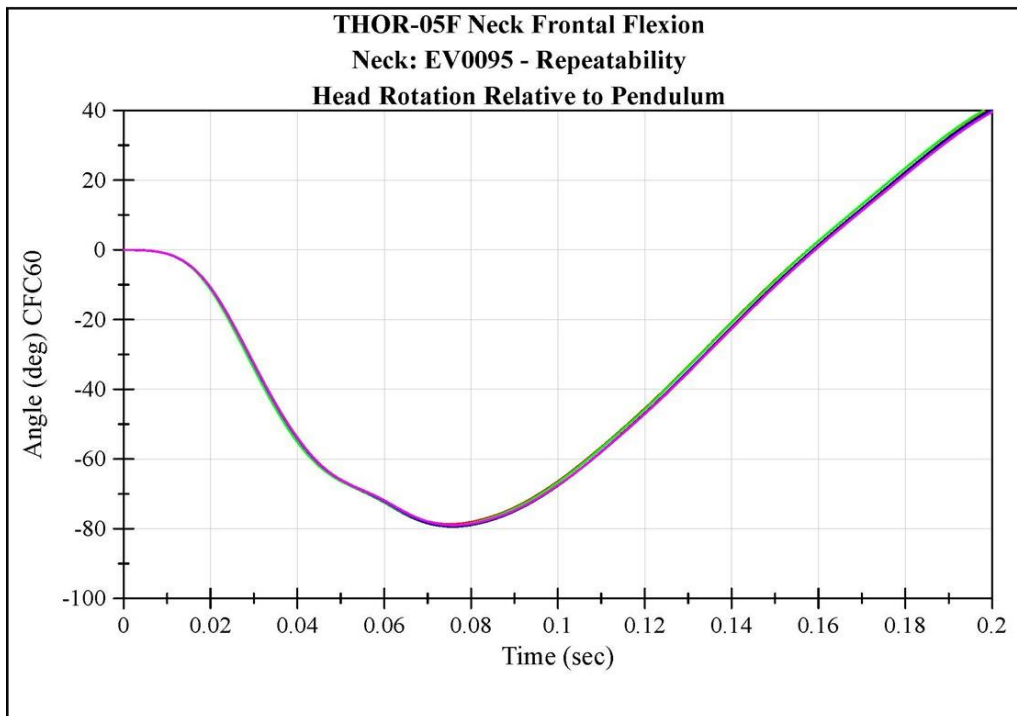


Figure 6-21. Calspan neck frontal flexion head rotation θ_y repeatability for Neck EV0095

6.2.6 THOR-05F Neck EV0095 Testing at TRC

Repeatability results at TRC for neck flexion testing on Neck EV0095 (removed from ATD EV4675) displayed CV values below 5 percent (Table 6-11 through Table 6-12, Figure 6-22 through Figure 6-25).

Table 6-11. TRC EV0095 Neck 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)
2025_04_30 13_36	1.66	3.37	4.85
2025_04_30 14_47	1.67	3.39	4.88
2025_05_01 08_11	1.59	3.30	4.80
2025_05_01 08_32	1.61	3.33	4.94
2025_05_01 09_04	1.67	3.43	4.93
Mean	1.64	3.36	4.88
Standard Deviation	0.04	0.05	0.06
CV	2.3%	1.5%	1.2%

Table 6-12. TRC EV0095 Neck Flexion Repeatability Results

Test Number	Maximum Upper Neck M_y (N-m)	Maximum Upper Neck F_z Prior to 40 ms (N)	Minimum Head ω_y (deg/s)	Minimum Head θ_y (deg)
2025_04_30 13_36	17.7	718	-2,059	-75.9
2025_04_30 14_47	17.3	728	-2,071	-77.3
2025_05_01 08_11	17.5	719	-2,032	-75.9
2025_05_01 08_32	17.4	779	-2,076	-77.1
2025_05_01 09_04	17.2	732	-2,067	-77.1
Mean	17.4	735	-2,061	-76.6
Standard Deviation	0.19	25.2	17.5	0.69
CV	1.1%	3.4%	0.8%	0.9%

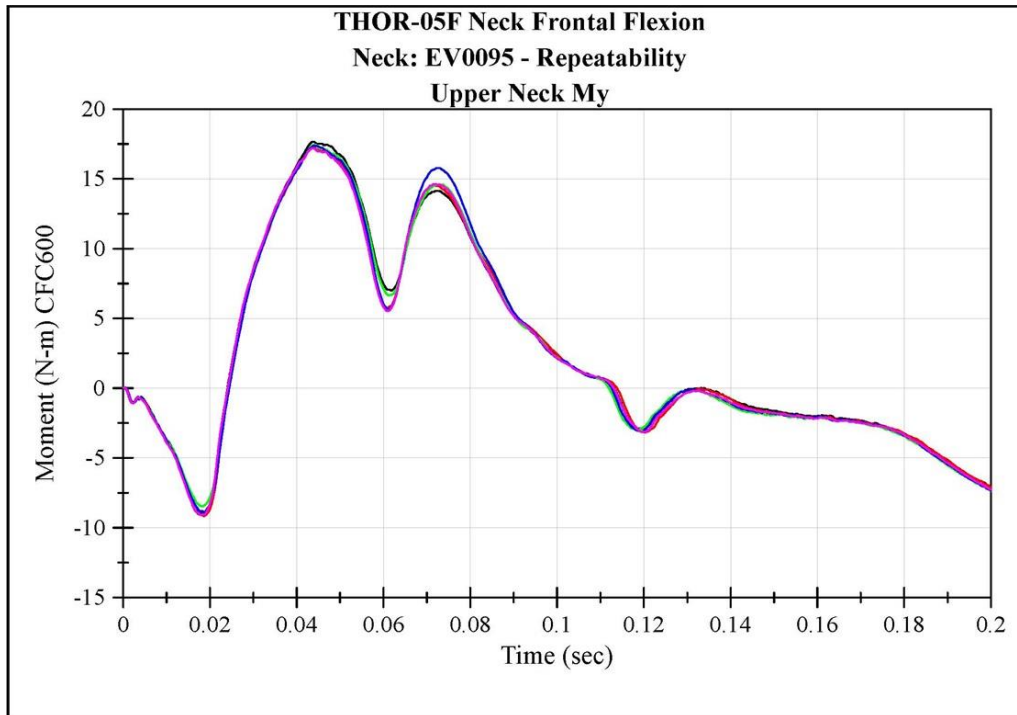


Figure 6-22. TRC neck frontal flexion upper neck moment M_y repeatability for Neck EV0095

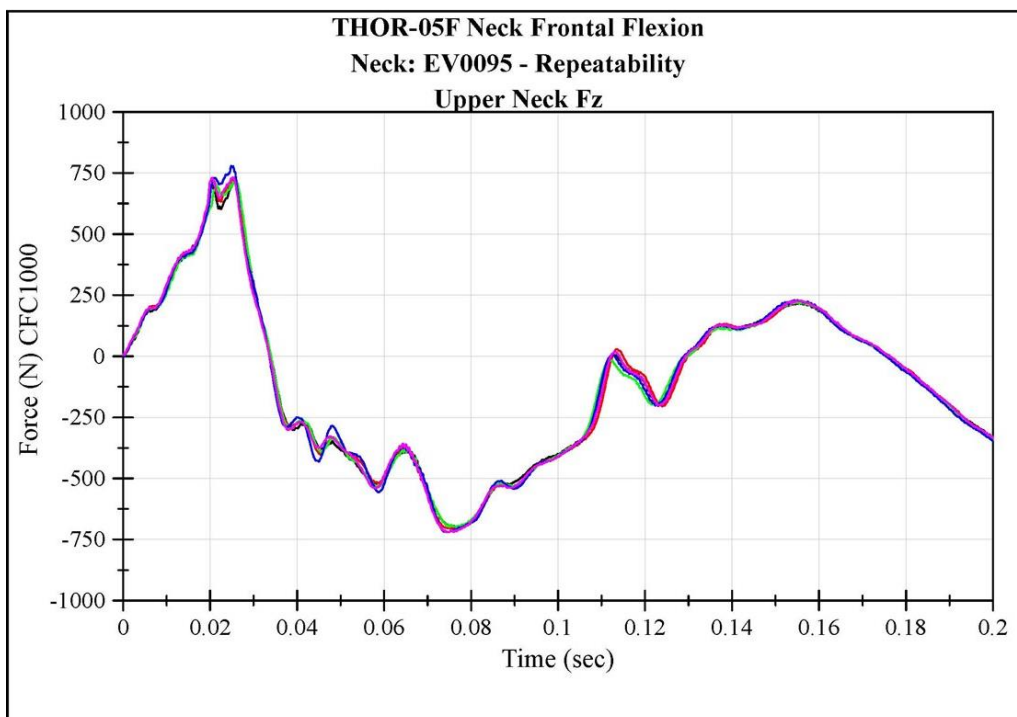


Figure 6-23. TRC neck frontal flexion upper neck force F_z repeatability for Neck EV0095

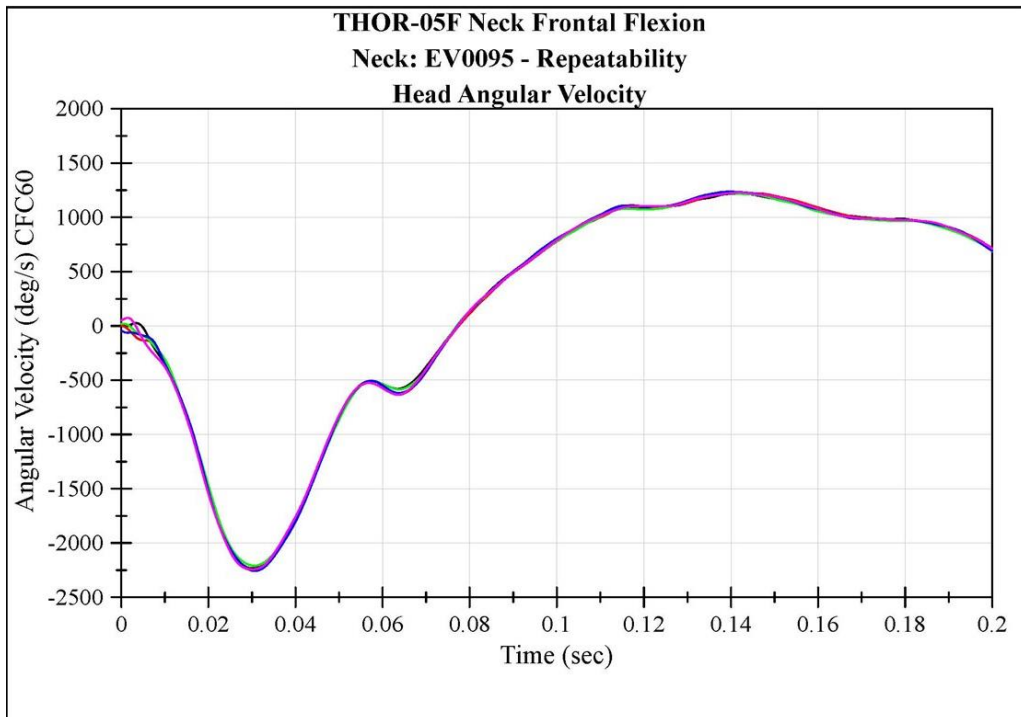


Figure 6-24. TRC neck frontal flexion angular velocity ω_y repeatability for Neck EV0095

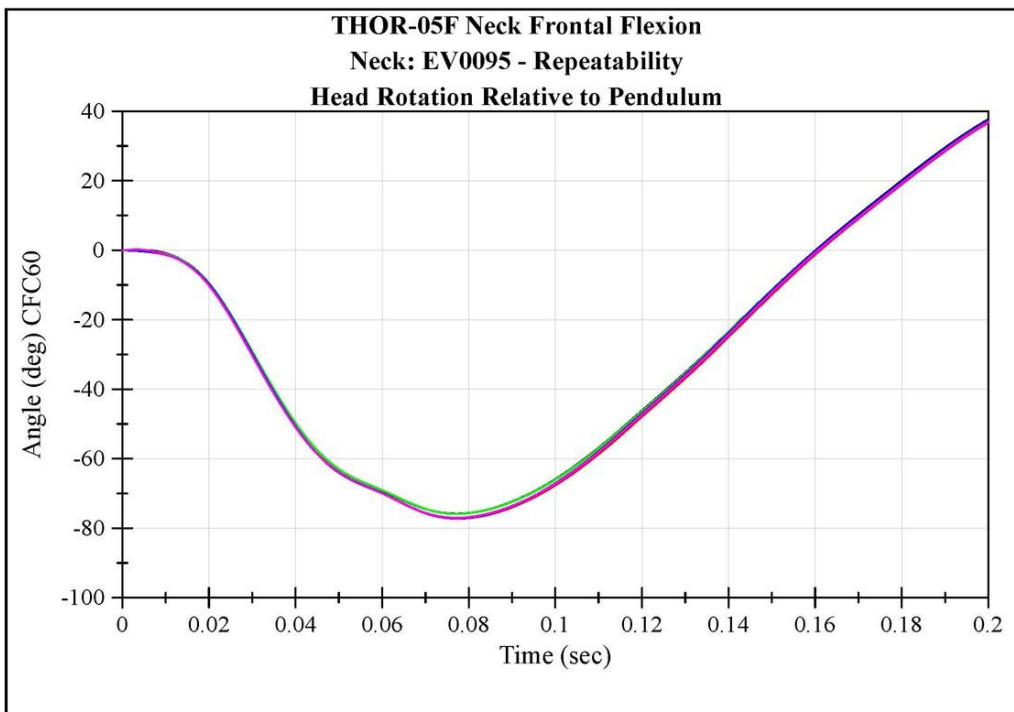


Figure 6-25. TRC neck frontal flexion head rotation repeatability θ_y for Neck EV0095

6.3 Neck Flexion Dummy Reproducibility Results

Dummy Reproducibility results at VRTC for the three THOR-05F necks displayed CV values below 5 percent for all test specifications (Table 6-13 and Table 6-14).

Table 6-13. THOR-05F Neck Flexion Pulse 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 EU9734	240326-8	1.69	3.38	4.84
	240326-9	1.75	3.57	4.97
	240326-10	1.81	3.61	5.08
	240326-11	1.76	3.56	5.01
	240327-1	1.77	3.56	5.02
VRTC Neck EV1357	240529-17	1.71	3.41	4.84
	240529-18	1.72	3.39	4.86
	240529-19	1.68	3.35	4.84
	240529-20	1.73	3.36	4.80
	240529-22	1.72	3.44	4.92
VRTC Neck EV0095	241202-4	1.82	3.57	5.04
	241202-6	1.79	3.57	5.08
	241202-7	1.82	3.63	5.08
	241203-2	1.80	3.59	5.08
	241203-4	1.89	3.70	5.08
Mean		1.76	3.51	4.97
Standard Deviation		0.06	0.11	0.11
CV		3.2%	3.2%	2.2%

Table 6-14. THOR-05F Neck Flexion Reproducibility Results

Neck Number	Test Number	Maximum Upper Neck M_y (N-m)	Maximum Upper Neck F_z Prior to 40 ms (N)	Minimum Head ω_y (deg/s)	Minimum Head θ_y (deg)
VRTC Neck EU9734	240326-8	17.5	741	-2,157	-79.8
	240326-9	17.6	760	-2,196	-80.2
	240326-10	17.8	812	-2,250	-80.5
	240326-11	17.4	767	-2,208	-81.3
	240327-1	18.2	771	-2,175	-78.8
VRTC Neck EV1357	240529-17	18.1	738	-2,079	-78.0
	240529-18	18.2	756	-2,094	-78.6
	240529-19	18.2	756	-2,089	-78.3
	240529-20	18.1	727	-2,075	-78.0
	240529-22	18.2	761	-2,125	-78.5
VRTC Neck EV0095	241202-4	18.6	752	-2,230	-78.9
	241202-6	18.2	772	-2,234	-80.1
	241202-7	17.8	797	-2,260	-80.9
	241203-2	18.1	769	-2,227	-79.6
	241203-4	17.9	786	-2,278	-80.7
Mean		18.0	764	-2,178	-79.5
Standard Deviation		0.31	22.2	70.7	1.10
CV		1.7%	2.9%	3.2%	1.4%

6.4 Lab-to-Lab Variability Analysis

The results of the neck flexion qualification tests from each lab are presented in Table 6-15 and Table 6-16. The last three rows of the tables show the *Test Reproducibility* results when data from all four labs are combined. *Test Reproducibility* results at VRTC, Humanetics, Calspan, and TRC for the neck flexion tests displayed CV values below 5 percent for velocity at 24 milliseconds and between 5 and 10 percent for velocity at 8 and 16 milliseconds (Table 6-15). The results yielded CV values below 5 percent for upper neck moment and rotation and between 5 and 10 percent for angular velocity and upper neck force prior to 40 ms (Table 6-16).

Table 6-15. THOR-05F Neck Flexion Pulse 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 EV0095	241202-4	1.82	3.57	5.04
	241202-6	1.79	3.57	5.08
	241202-7	1.82	3.63	5.08
	241203-2	1.80	3.59	5.08
	241203-4	1.89	3.70	5.08
Humanetics Neck EV0095	686837	1.59	3.14	4.54
	686932	1.64	3.24	4.69
	686938	1.60	3.18	4.59
	686942	1.65	3.31	4.73
	686950	1.66	3.28	4.74
Calspan Neck EV0095	2025_03_26_12_17	1.78	3.72	5.18
	2025_03_26_12_49	1.78	3.78	5.20
	2025_03_26_13_22	1.81	3.80	5.18
	2025_03_26_14_04	1.73	3.64	5.15
	2025_03_26_14_38	1.74	3.66	5.15
TRC Neck EV0095	2025_04_30_13_36	1.66	3.37	4.85
	2025_04_30_14_47	1.67	3.39	4.88
	2025_05_01_08_11	1.59	3.30	4.80
	2025_05_01_08_32	1.61	3.33	4.94
	2025_05_01_09_04	1.67	3.43	4.93
Test Reproducibility Neck EV0095				
Mean		1.71	3.48	4.95
Standard Deviation		0.09	0.21	0.21
CV		5.3%	6.0%	4.2%

Table 6-16. THOR-05F Neck Flexion Reproducibility Results

Neck Number	Test Number	Maximum Upper Neck M_y (N-m)	Maximum Upper Neck F_z Prior to 40 ms (N)	Minimum Head ω_y (deg/s)	Minimum Head θ_y (deg)
VRTC Neck EV0095	240326-8	18.6	752	-2,230	-78.9
	240326-9	18.2	772	-2,234	-80.1
	240326-10	17.8	797	-2,260	-80.9
	240326-11	18.1	769	-2,227	-79.6
	240327-1	17.9	786	-2,278	-80.7
Humanetics Neck EV0095	240326-8	17.0	685	-1,965	-75.1
	240326-9	17.3	710	-1,987	-74.6
	240326-10	16.9	688	-1,983	-75.5
	240326-11	17.1	713	-2,014	-75.6
	240327-1	16.9	717	-2,011	-75.6
Calspan Neck EV0095	2025_03_26 12_17	18.1	882	-2,217	-79.4
	2025_03_26 12_49	18.4	909	-2,239	-78.7
	2025_03_26 13_22	18.3	912	-2,254	-79.1
	2025_03_26 14_04	17.9	891	-2,226	-79.2
	2025_03_26 14_38	18.1	862	-2,213	-79.0
TRC Neck EV0095	2025_04_30 13_36	17.7	718	-2,059	-75.9
	2025_04_30 14_47	17.3	728	-2,071	-77.3
	2025_05_01 08_11	17.5	719	-2,032	-75.9
	2025_05_01 08_32	17.4	779	-2,076	-77.1
	2025_05_01 09_04	17.2	732	-2,067	-77.1
Test Reproducibility Neck EV0095					
Mean		17.7	776	-2,132	-77.8
Standard Deviation		0.53	75.4	113	2.02
CV		3.0%	9.7%	5.3%	2.6%

6.5 Corridor Development

All the data used to determine the neck frontal flexion qualification corridors is shown in Table 6-17 through Table 6-18. The qualification corridors were calculated using the mean plus or minus 10 percent of the peak for the specified measured or calculated channels (Table 6-19).

Table 6-17. THOR-05F Neck 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 EU9734	240326-8	1.69	3.38	4.84
	240326-9	1.75	3.57	4.97
	240326-10	1.81	3.61	5.08
	240326-11	1.76	3.56	5.01
	240327-1	1.77	3.56	5.02
VRTC Neck EV1357	240529-17	1.71	3.41	4.84
	240529-18	1.72	3.39	4.86
	240529-19	1.68	3.35	4.84
	240529-20	1.73	3.36	4.80
	240529-22	1.72	3.44	4.92
VRTC Neck EV0095	241202-4	1.82	3.57	5.04
	241202-6	1.79	3.57	5.08
	241202-7	1.82	3.63	5.08
	241203-2	1.80	3.59	5.08
	241203-4	1.89	3.70	5.08
Humanetics Neck EV0095	686837	1.59	3.14	4.54
	686932	1.64	3.24	4.69
	686938	1.60	3.18	4.59
	686942	1.65	3.31	4.73
	686950	1.66	3.28	4.74
Calspan Neck EV0095	2025_03_26 12_17	1.78	3.72	5.18
	2025_03_26 12_49	1.78	3.78	5.20
	2025_03_26 13_22	1.81	3.80	5.18
	2025_03_26 14_04	1.73	3.64	5.15
	2025_03_26 14_38	1.74	3.66	5.15
TRC Neck EV0095	2025_04_30 13_36	1.66	3.37	4.85
	2025_04_30 14_47	1.67	3.39	4.88
	2025_05_01 08_11	1.59	3.30	4.80
	2025_05_01 08_32	1.61	3.33	4.94
	2025_05_01 09_04	1.67	3.43	4.93
Mean		1.72	3.48	4.94
Standard Deviation		0.07	0.18	0.18
CV		4.3%	5.1%	3.7%

Table 6-18. THOR-05F Neck Flexion Qualification Corridor Results
(Highlighted values fell outside average $\pm 10\%$.)

Neck Number	Test Number	Maximum Upper Neck M_y (N-m)	Maximum Upper Neck F_z Prior to 40 ms (N)	Minimum Head ω_y (deg/s)	Minimum Head θ_y (deg)
VRTC Neck EU9734	240326-8	17.5	741	-2,157	-79.8
	240326-9	17.6	760	-2,196	-80.2
	240326-10	17.8	812	-2,250	-80.5
	240326-11	17.4	767	-2,208	-81.3
	240327-1	18.2	771	-2,175	-78.8
VRTC Neck EV1357	240529-17	18.1	738	-2,079	-78.0
	240529-18	18.2	756	-2,094	-78.6
	240529-19	18.2	756	-2,089	-78.3
	240529-20	18.1	727	-2,075	-78.0
	240529-22	18.2	761	-2,125	-78.5
VRTC Neck EV0095	241202-4	18.6	752	-2,230	-78.9
	241202-6	18.2	772	-2,234	-80.1
	241202-7	17.8	797	-2,260	-80.9
	241203-2	18.1	769	-2,227	-79.6
	241203-4	17.9	786	-2,278	-80.7
Humanetics Neck EV0095	240326-8	17.0	685	-1,965	-75.1
	240326-9	17.3	710	-1,987	-74.6
	240326-10	16.9	688	-1,983	-75.5
	240326-11	17.1	713	-2,014	-75.6
	240327-1	16.9	717	-2,011	-75.6
Calspan Neck EV0095	2025_03_26 12_17	18.1	882	-2,217	-79.4
	2025_03_26 12_49	18.4	909	-2,239	-78.7
	2025_03_26 13_22	18.3	912	-2,254	-79.1
	2025_03_26 14_04	17.9	891	-2,226	-79.2
	2025_03_26 14_38	18.1	862	-2,213	-79.0
TRC Neck EV0095	2025_04_30 13_36	17.7	718	-2,059	-75.9
	2025_04_30 14_47	17.3	728	-2,071	-77.3
	2025_05_01 08_11	17.5	719	-2,032	-75.9
	2025_05_01 08_32	17.4	779	-2,076	-77.1
	2025_05_01 09_04	17.2	732	-2,067	-77.1
Mean		17.8	770	-2,136	-78.2
Standard Deviation		0.50	60.1	100	1.92
CV		2.8%	7.8%	4.7%	2.5%

Table 6-19. Neck Flexion Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Pendulum Velocity at 8 ms after T0	m/s	1.55	1.89	1.72	10
Pendulum Velocity at 16 ms after T0	m/s	3.13	3.82	3.48	10
Pendulum Velocity at 24 ms after T0	m/s	4.44	5.43	4.94	10
Impact Velocity	m/s	4.95	5.05	5.00	
Maximum Upper Neck M_y	N-m	16.0	19.5	17.8	10
Maximum Upper Neck F_z prior to 40 ms	N	693	847	770	10
Minimum Head Angular Velocity ω_y (relative to earth)	deg/s	-2,350	-1,923	-2,136	10
Minimum Head Rotation θ_y (relative to pendulum)	deg	-86.1	-70.4	-78.2	10

Discussion. Highlighted cells in Table 6-18 indicate test values that did not achieve their respective target response $\pm 10\%$. Two Humanetics' tests showed results slightly under the range for upper neck force data and all upper neck force data from Calspan were elevated and above the corridors.

Repeatability (Table 6-1 through Table 6-12) showed all CV values below 5 percent.

Dummy Reproducibility (Table 6-13 and Table 6-14) showed all CV values below 5 percent.

In the case of *Test Reproducibility*, for pendulum velocities from lab-to-lab tests, CV values were over 5 percent, but under 10 percent for velocities at 8 ms and 16 ms. At 24 ms, the CV was under 5 percent. The moment and head rotation CV values were below 5 percent, while angular velocity and upper neck force CV values were between 5 and 10 percent; the upper neck force was nearly 10 percent, likely due to the five elevated tests at Calspan and the two under range tests at Humanetics.

7 NECK EXTENSION

7.1 Methodology

Repeatability and reproducibility tests were performed using the neck extension qualification procedures described in the *THOR-05F Qualification Procedures and Requirements*. The extension tests resemble the Hybrid III head-neck pendulum test defined in CFR Title 49, Part 572, Subpart E with 152.4 mm 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 via the neck mounting plate (TF-200-2357); and the pendulum was decelerated from the specified speed during contact with a Hexcel aluminum honeycomb (or equivalent). During these tests, the upper neck moment (M_y), upper neck force (F_z), head angular velocity, and head rotation were measured.

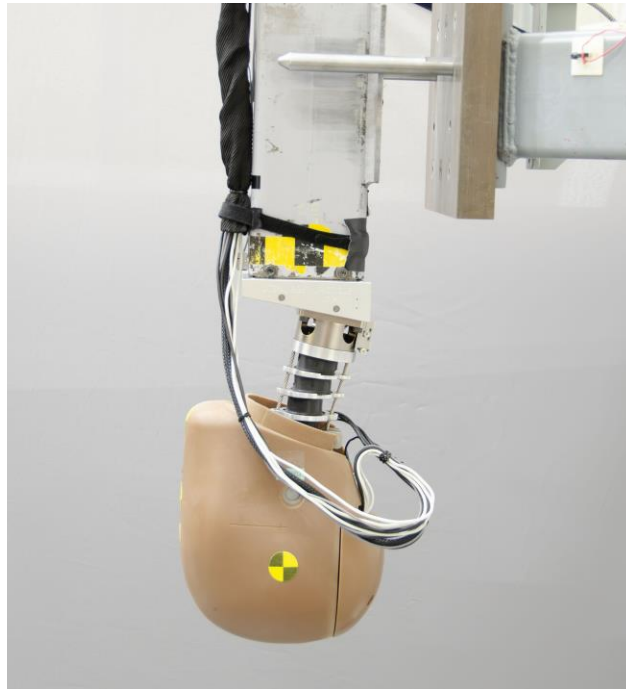


Figure 7-1. Neck extension test setup

7.2 Neck Extension Repeatability Results

Sections 7.2.1 through 7.2.6 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 four 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-05F Neck EU9734 Testing at VRTC

Repeatability results for neck extension testing on Neck EU9734 (removed from ATD EU9863) at VRTC yielded CV values below 5 percent for all measurements, except for upper neck moment, which was above 10 percent (Table 7-1 through Table 7-2, Figure 7-2 through Figure 7-5).

Table 7-1. VRTC EU9734 Neck Extension 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)
240326-1	1.69	3.43	4.89
240326-2	1.71	3.43	4.86
240326-3	1.59	3.29	4.74
240326-4	1.61	3.33	4.78
240326-5	1.58	3.20	4.62
Mean	1.64	3.34	4.78
Standard Deviation	0.06	0.10	0.11
CV	3.7%	2.9%	2.3%

Table 7-2. VRTC EU9734 Neck Extension Repeatability Results

Test Number	Minimum Upper Neck M_y (N-m)	Minimum Upper Neck F_z (N)	Maximum Head Angular Velocity ω_y (deg/s)	Maximum Head Rotation θ_y (deg)
240326-1	-22.9	-1,512	2,457	87.3
240326-2	-19.4	-1,560	2,444	88.9
240326-3	-17.3	-1,554	2,419	88.3
240326-4	-17.5	-1,555	2,426	88.6
240326-5	-16.4	-1,554	2,382	89.0
Mean	-18.7	-1,547	2,426	88.4
Standard Deviation	2.59	19.5	28.8	0.68
CV	13.9%	1.3%	1.2%	0.8%

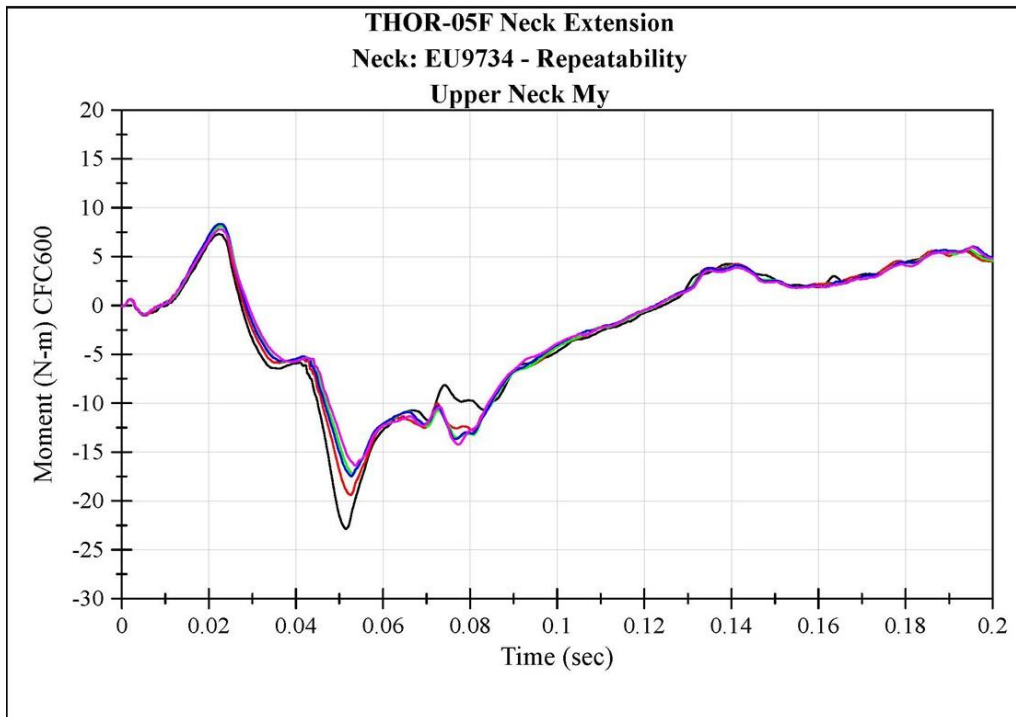


Figure 7-2. VRTC neck extension upper neck moment My repeatability for Neck EU9734

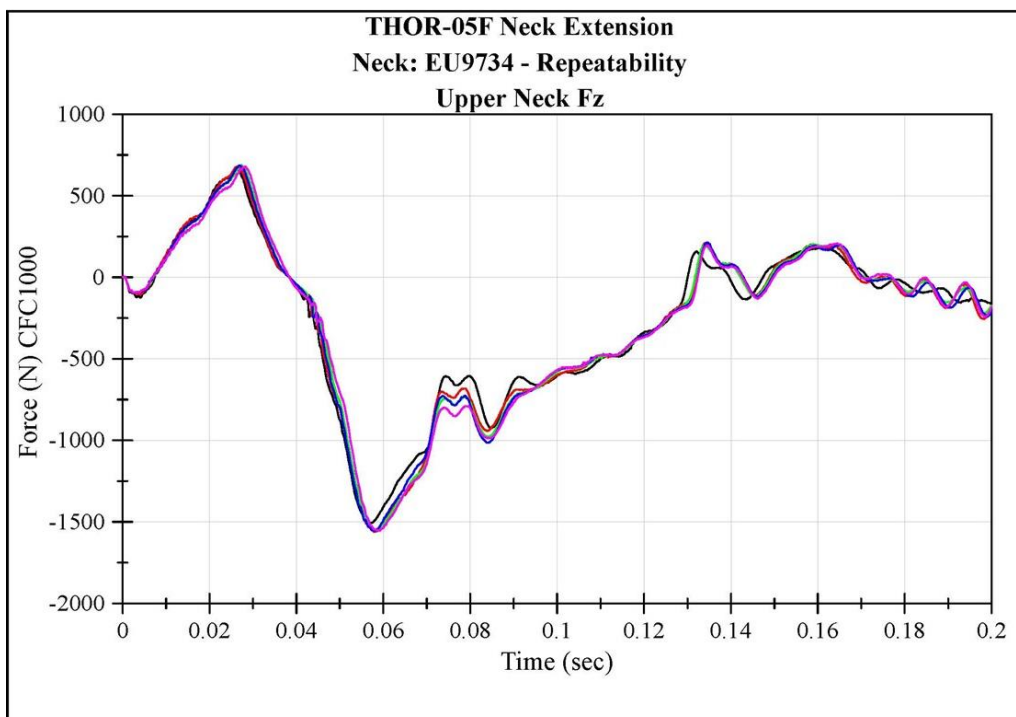


Figure 7-3. VRTC neck extension upper neck force Fz repeatability for Neck EU9734

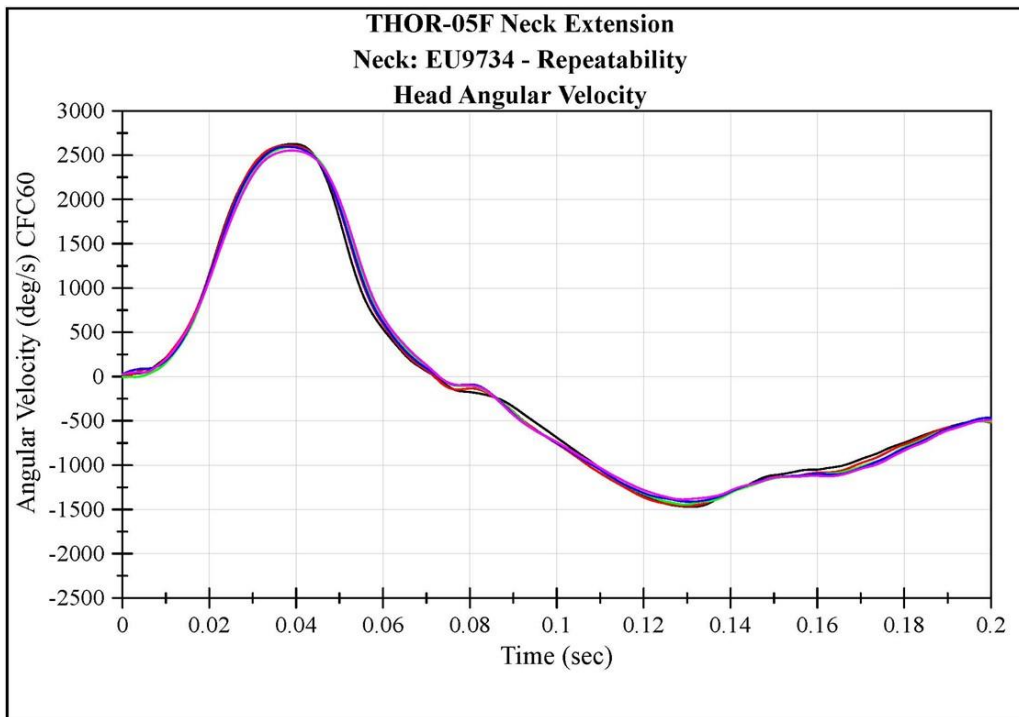


Figure 7-4. VRTC neck extension head angular velocity about Y repeatability for THOR-05F Neck EU9734

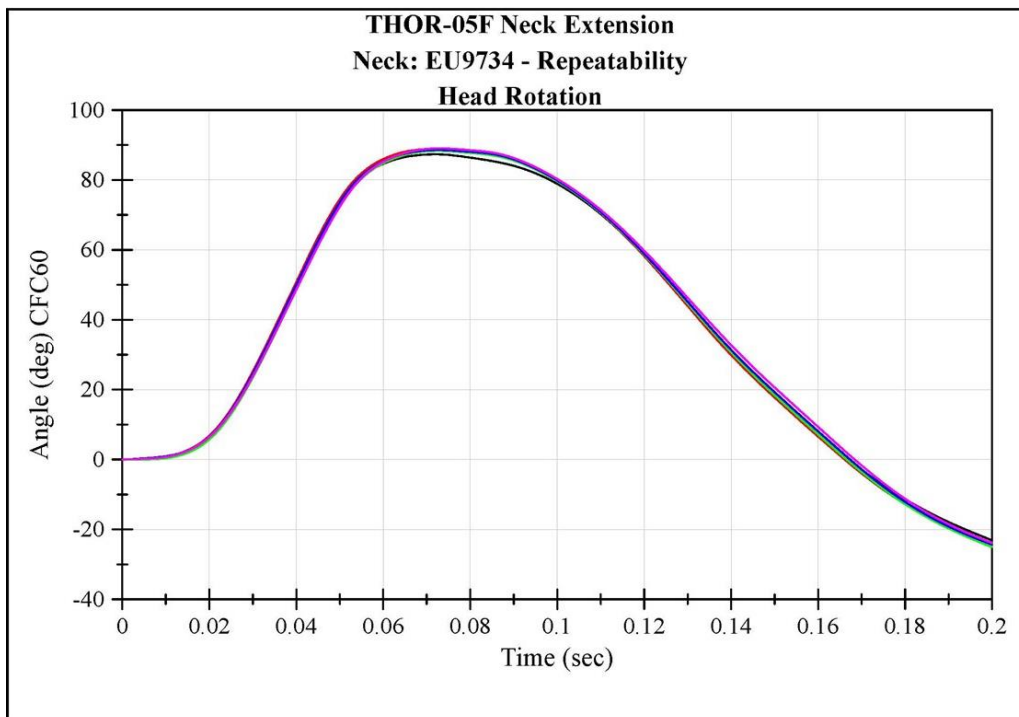


Figure 7-5. VRTC neck extension head rotation repeatability for THOR-05F Neck EU9734

7.2.2 THOR-05F Neck EV1357 Testing at VRTC

Repeatability results for neck extension testing on Neck EV1357 (removed from ATD EV0674) at VRTC yielded CV values below 5 percent (Table 7-3 through Table 7-4, Figure 7-6 through Figure 7-9).

Table 7-3. VRTC EV1357 Neck Extension 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)
240530-11	1.71	3.40	4.92
240530-13	1.75	3.48	4.95
240530-14	1.75	3.49	4.92
240530-15	1.72	3.43	4.92
240530-16	1.74	3.44	4.85
Mean	1.73	3.45	4.91
Standard Deviation	0.02	0.04	0.04
CV	1.0%	1.0%	0.8%

Table 7-4. VRTC EV1357 Neck Extension Repeatability Results

Test Number	Minimum Upper Neck M_y (N-m)	Minimum Upper Neck F_z (N)	Maximum Head Angular Velocity ω_y (deg/s)	Maximum Head Rotation θ_y (deg)
240530-11	-22.0	-1,281	2,365	84.4
240530-13	-21.0	-1,354	2,394	84.6
240530-14	-21.0	-1,320	2,392	86.2
240530-15	-21.2	-1,308	2,392	85.7
240530-16	-20.9	-1,322	2,382	86.5
Mean	-21.2	-1,317	2,385	85.5
Standard Deviation	0.45	26.2	12.2	0.93
CV	2.1%	2.0%	0.5%	1.1%

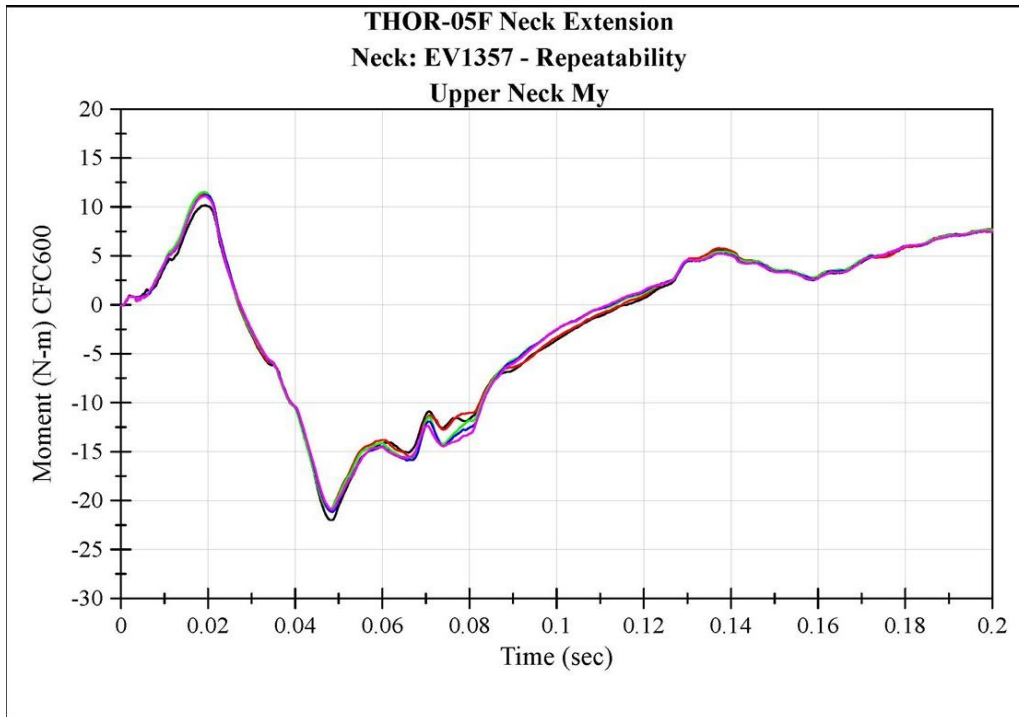


Figure 7-6. VRTC neck extension upper neck moment My repeatability for Neck EV1357

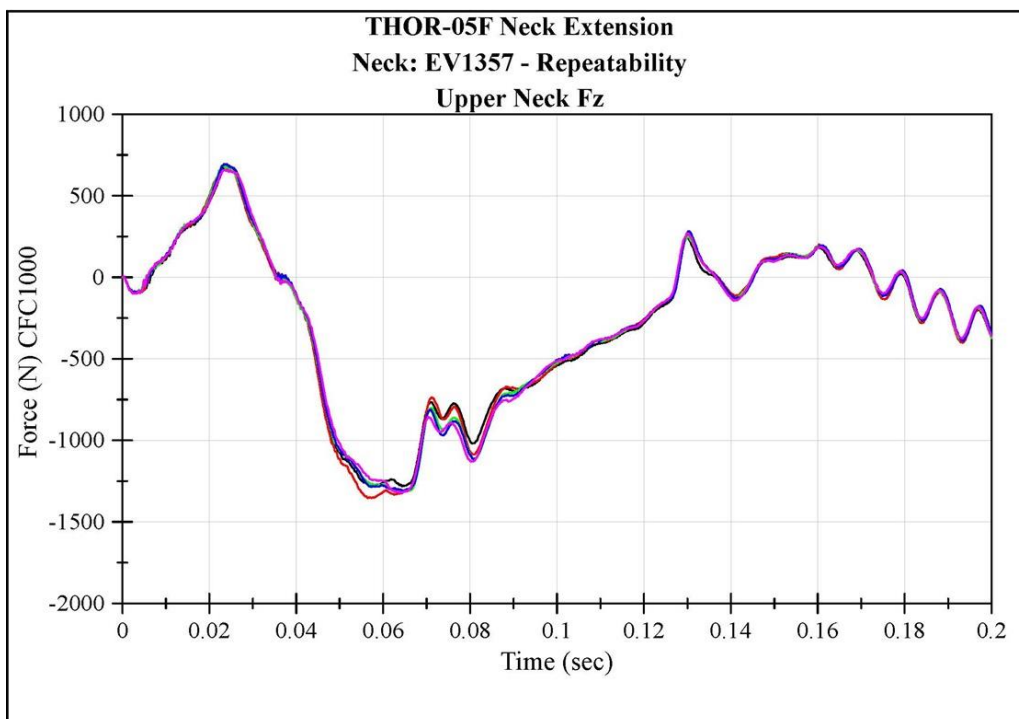


Figure 7-7. VRTC neck extension upper neck force Fz repeatability for Neck EV1357

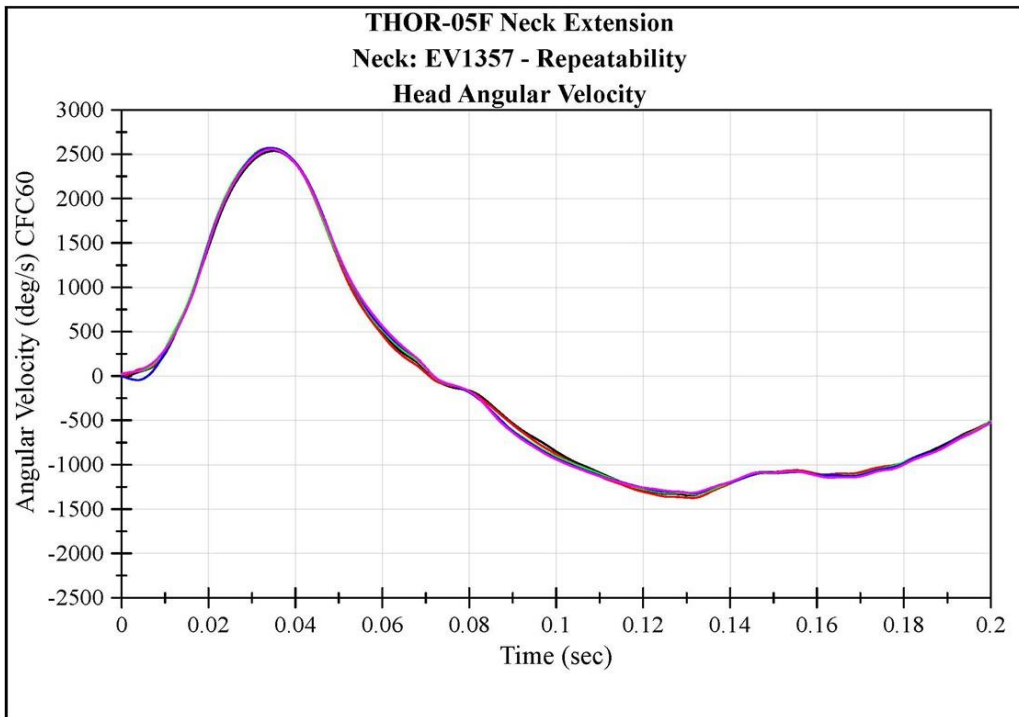


Figure 7-8. VRTC neck extension head angular velocity about Y repeatability for Neck EV1357

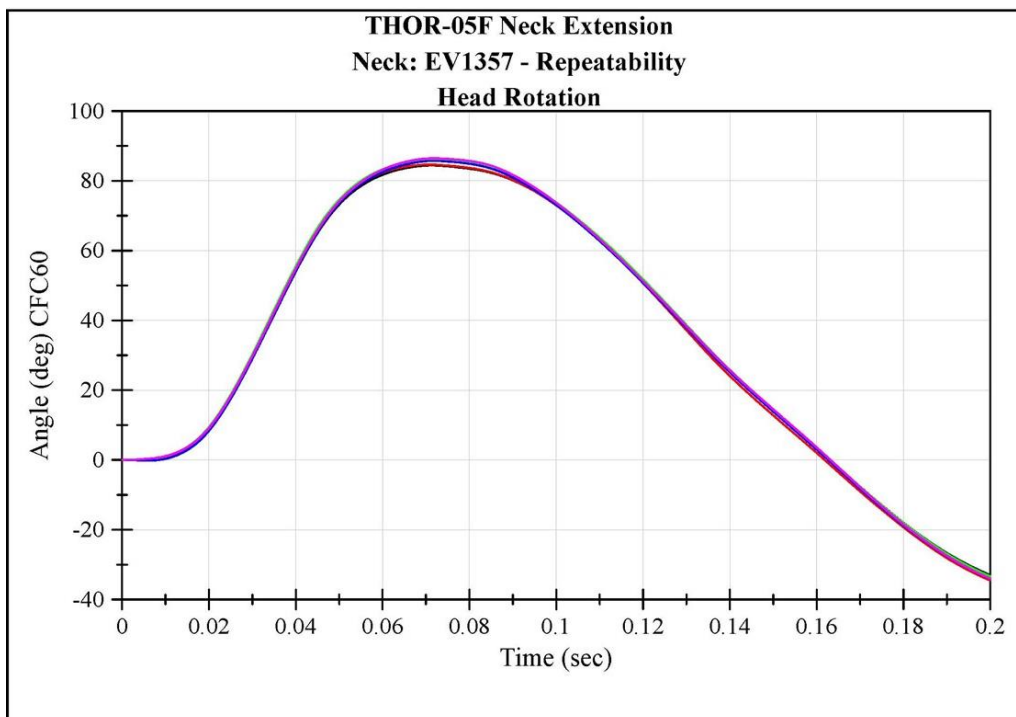


Figure 7-9. VRTC neck extension head rotation repeatability for Neck EV1357

7.2.3 THOR-05F Neck EV0095 Testing at VRTC

Repeatability results for neck extension testing on Neck EV0095 (removed from ATD EV4675) at VRTC yielded CV values below 5 percent (Table 7-5 through Table 7-6, Figure 7-10 through Figure 7-13)

Table 7-5. VRTC EV0095 Neck Extension 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)
241127-6	1.77	3.52	5.04
241127-7	1.73	3.48	4.93
241127-8	1.81	3.60	5.03
241202-1	1.81	3.61	5.04
241202-2	1.72	3.57	5.03
Mean	1.77	3.56	5.01
Standard Deviation	0.04	0.06	0.05
CV	2.4%	1.5%	0.9%

Table 7-6. VRTC EV0095 Neck Extension Repeatability Results

Test Number	Minimum Upper Neck M_y (N-m)	Minimum Upper Neck F_z (N)	Maximum Head Angular Velocity ω_y (deg/s)	Maximum Head Rotation θ_y (deg)
241127-6	-21.0	-1,314	2,508	90.0
241127-7	-19.7	-1,394	2,472	88.8
241127-8	-19.4	-1,448	2,503	88.6
241202-1	-20.7	-1,436	2,487	87.9
241202-2	-19.5	-1,467	2,497	88.2
Mean	-20.1	-1,412	2,493	88.7
Standard Deviation	0.74	60.9	14.3	0.81
CV	3.7%	4.3%	0.6%	0.9%

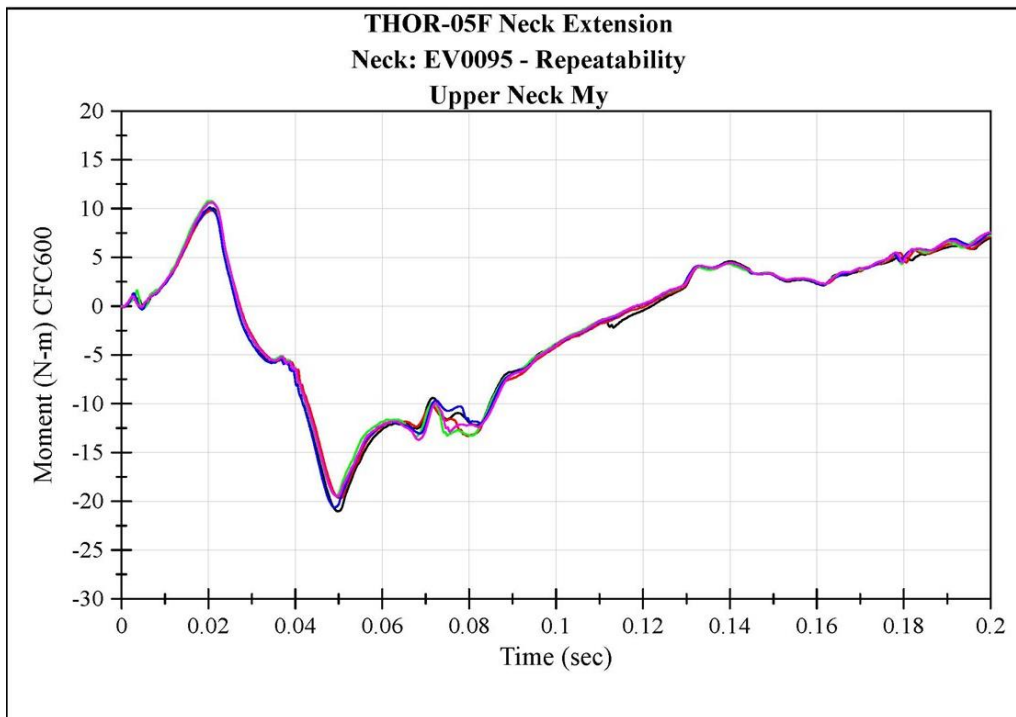


Figure 7-10. VRTC neck extension upper neck moment My repeatability for Neck EV0095

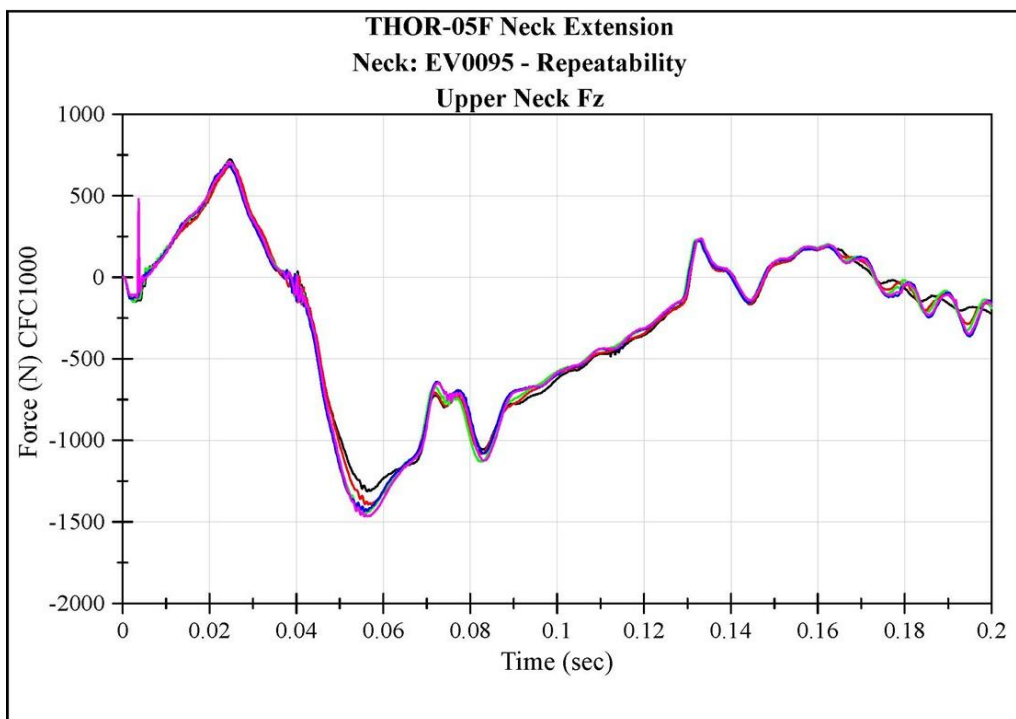


Figure 7-11. VRTC neck extension upper neck force Fz repeatability for Neck EV0095

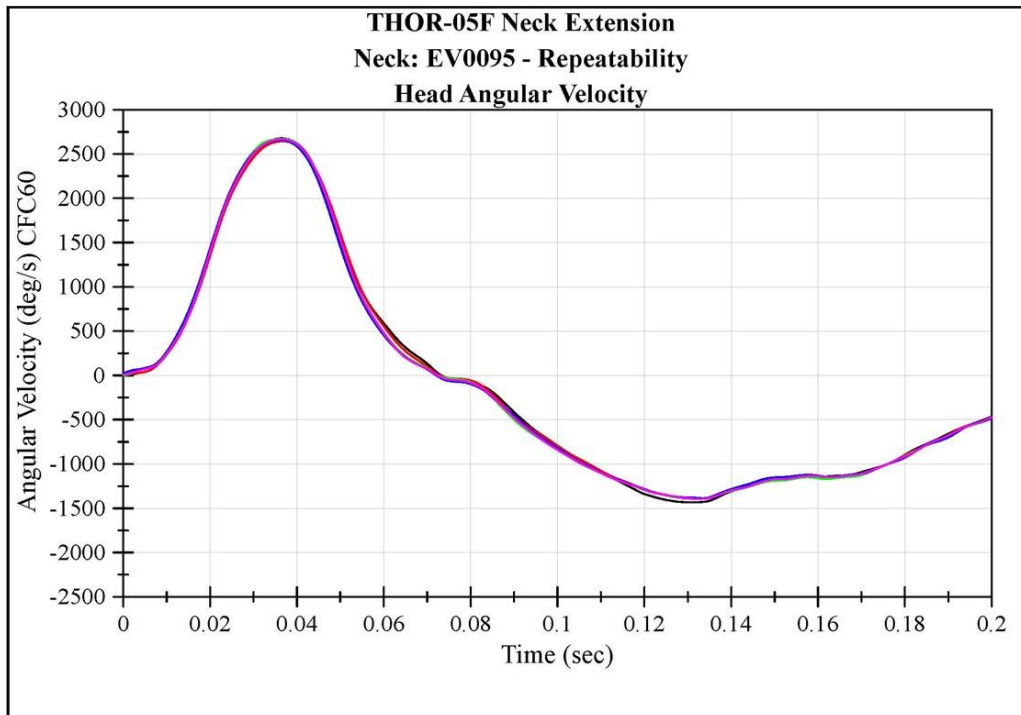


Figure 7-12. VRTC neck extension head angular velocity about Y repeatability for Neck EV0095

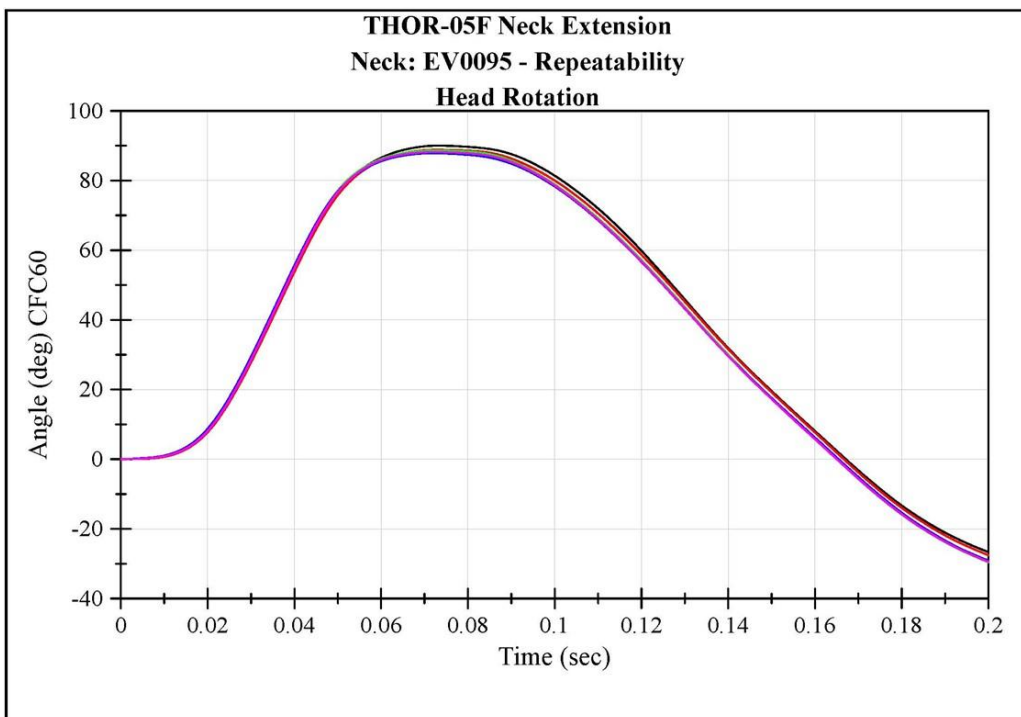


Figure 7-13. VRTC neck extension head rotation repeatability for Neck EV0095

7.2.4 THOR-05F Neck EV0095 Testing at Humanetics

Repeatability results for neck extension testing on Neck EV0095 (removed from ATD EV4675) at Humanetics yielded CV values below 5 percent (Table 7-7 through Table 7-8, Figure 7-14 through Figure 7-17).

Table 7-7. Humanetics EV0095 Neck Extension 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)
686778	1.66	3.35	4.88
686769	1.64	3.31	4.75
686792	1.66	3.33	4.77
686757	1.65	3.30	4.75
686786	1.67	3.32	4.77
Mean	1.66	3.32	4.78
Standard Deviation	0.01	0.02	0.05
CV	0.7%	0.6%	1.1%

Table 7-8. Humanetics EV0095 Neck Extension Repeatability Results

Test Number	Minimum Upper Neck M_y (N-m)	Minimum Upper Neck F_z (N)	Maximum Head Angular Velocity ω_y (deg/s)	Maximum Head Rotation θ_y (deg)
686778	-18.1	-1,171	2,389	87.6
686769	-17.9	-1,183	2,355	87.3
686792	-17.7	-1,163	2,364	87.8
686757	-17.7	-1,211	2,353	86.7
686786	-17.8	-1,175	2,356	87.4
Mean	-17.9	-1,181	2,363	87.4
Standard Deviation	0.18	18.7	15.0	0.41
CV	1.0%	1.6%	0.6%	0.5%

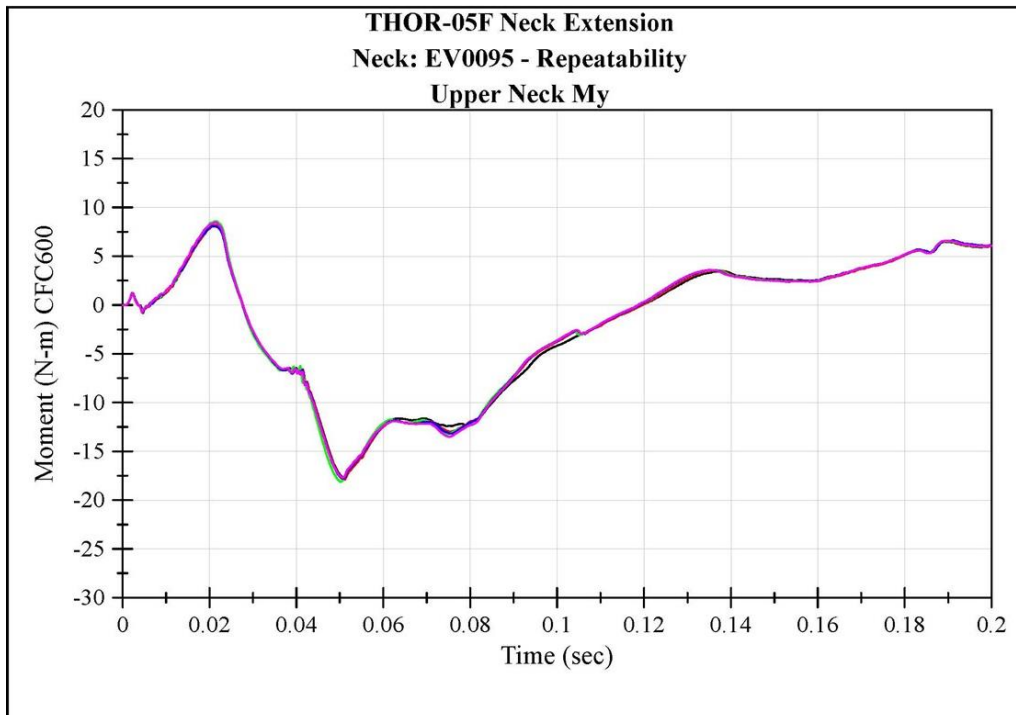


Figure 7-14. Humanetics neck extension upper neck moment My repeatability for Neck EV0095

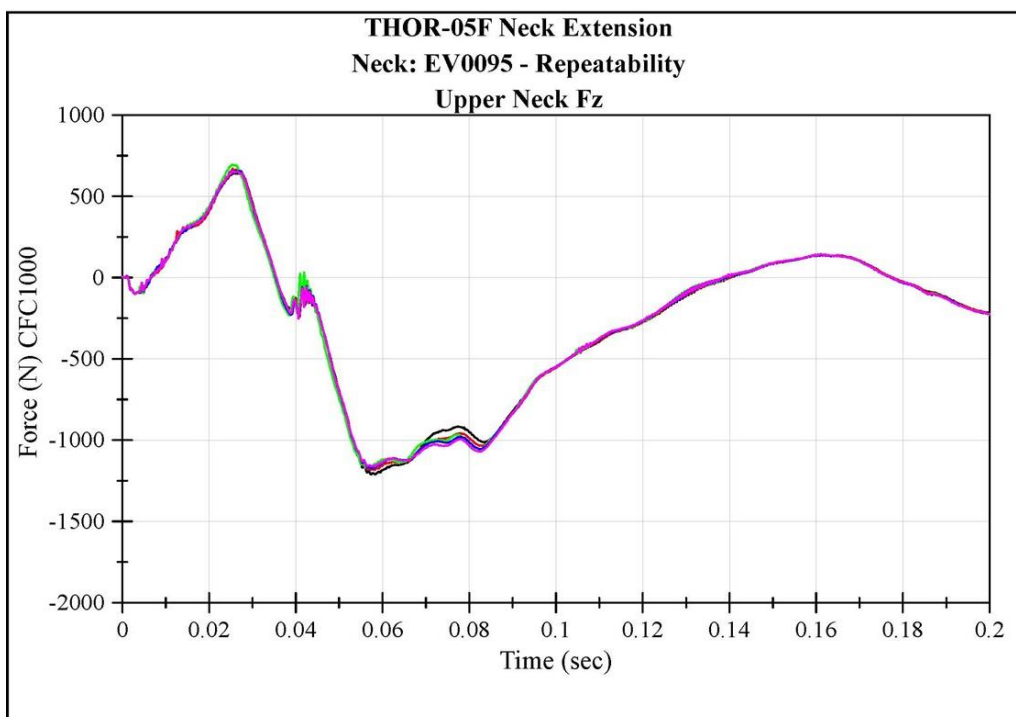


Figure 7-15. Humanetics neck extension upper neck force Fz repeatability for Neck EV0095

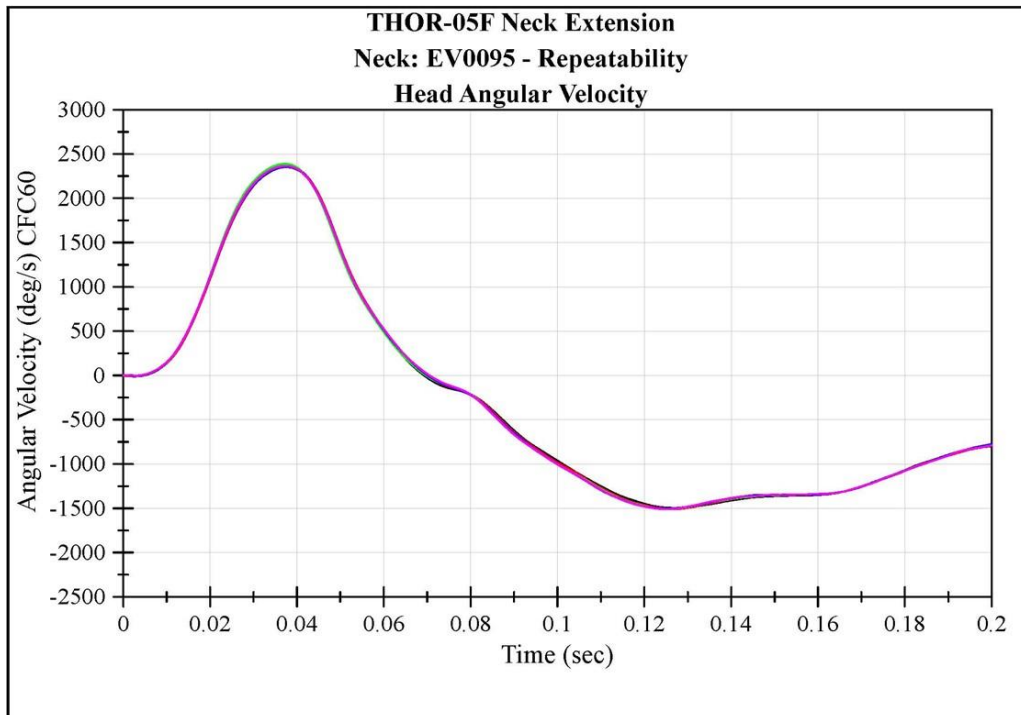


Figure 7-16. Humanetics neck extension head angular velocity about Y repeatability for Neck EV0095

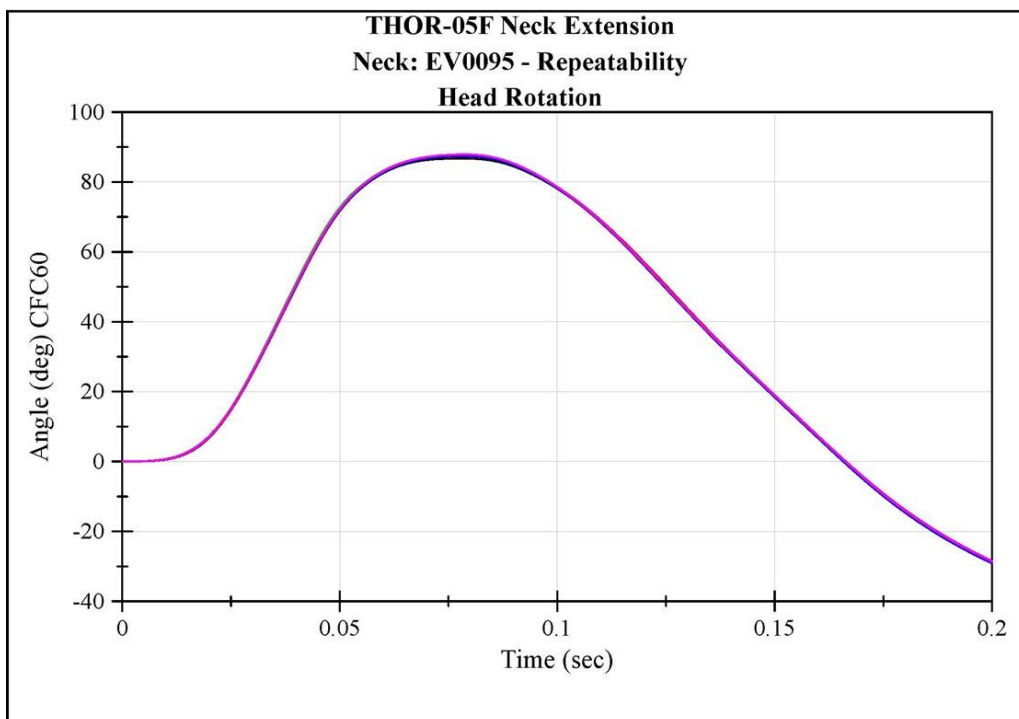


Figure 7-17. Humanetics neck extension head rotation repeatability for Neck EV0095

7.2.5 THOR-05F Neck EV0095 Testing at Calspan

Repeatability results for neck extension testing on Neck EV0095 (removed from ATD EV4675) at Calspan yielded CV values below 5 percent (Table 7-9 through Table 7-10, Figure 7-18 through Figure 7-21).

Table 7-9. Calspan EV0095 Neck Extension 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)
2025_03_26 15_50	1.80	3.69	5.20
2025_03_26 16_23	1.81	3.71	5.24
2025_03_26 16_56	1.81	3.72	5.20
2025_03_26 17_28	1.80	3.67	5.19
2025_03_26 18_01	1.83	3.71	5.23
Mean	1.81	3.70	5.21
Standard Deviation	0.01	0.02	0.02
CV	0.7%	0.5%	0.4%

Table 7-10. Calspan EV0095 Neck Extension Repeatability Results

Test Number	Minimum Upper Neck M_y (N-m)	Minimum Upper Neck F_z (N)	Maximum Head Angular Velocity ω_y (deg/s)	Maximum Head Rotation θ_y (deg)
2025_03_26 15_50	-17.0	-1,324	2,301	87.3
2025_03_26 16_23	-17.4	-1,298	2,309	89.3
2025_03_26 16_56	-17.2	-1,306	2,299	89.6
2025_03_26 17_28	-17.8	-1,289	2,296	89.6
2025_03_26 18_01	-17.3	-1,294	2,312	90.2
Mean	-17.3	-1,302	2,303	89.2
Standard Deviation	0.27	13.7	6.7	1.10
CV	1.6%	1.1%	0.3%	1.2%

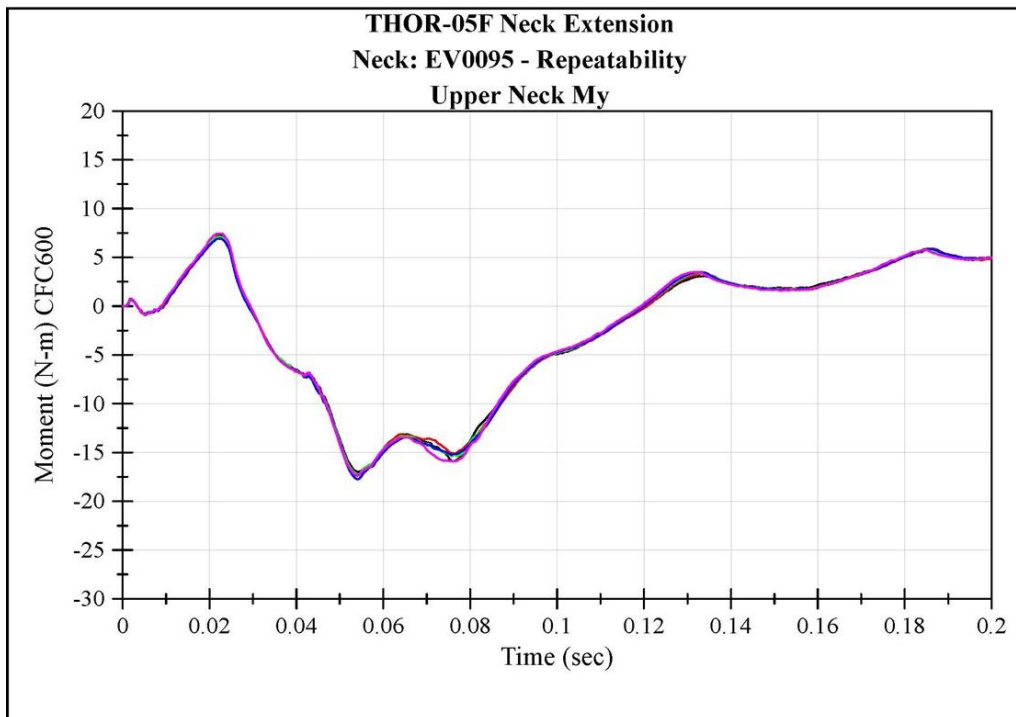


Figure 7-18. Calspan neck extension upper neck moment My repeatability for Neck EV0095

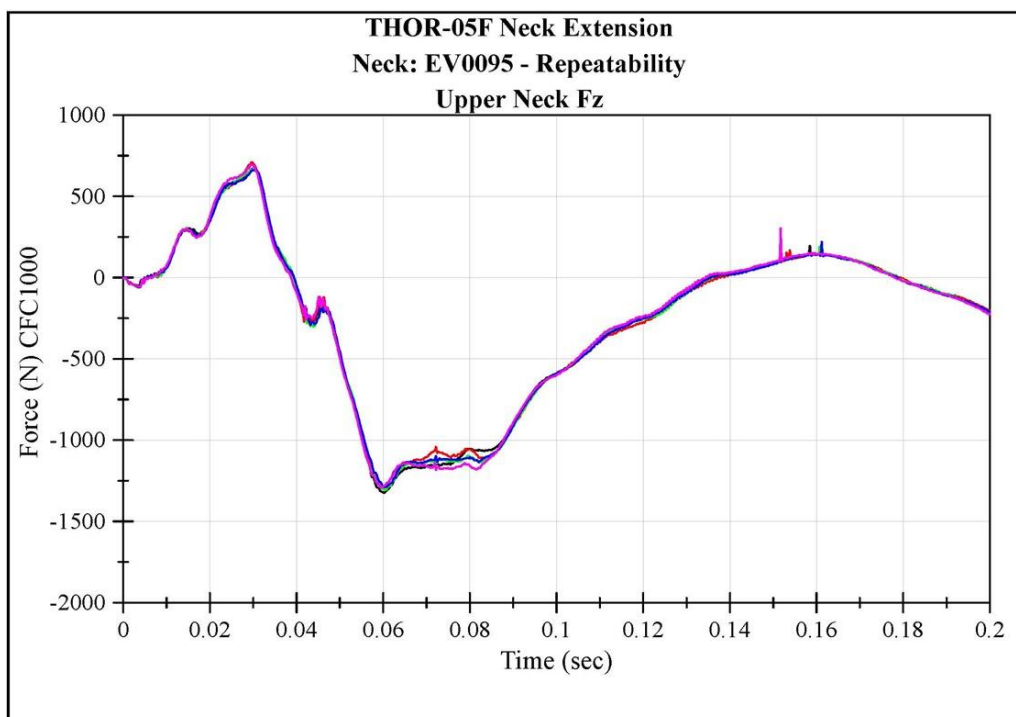


Figure 7-19. Calspan neck extension upper neck force Fz repeatability for Neck EV0095

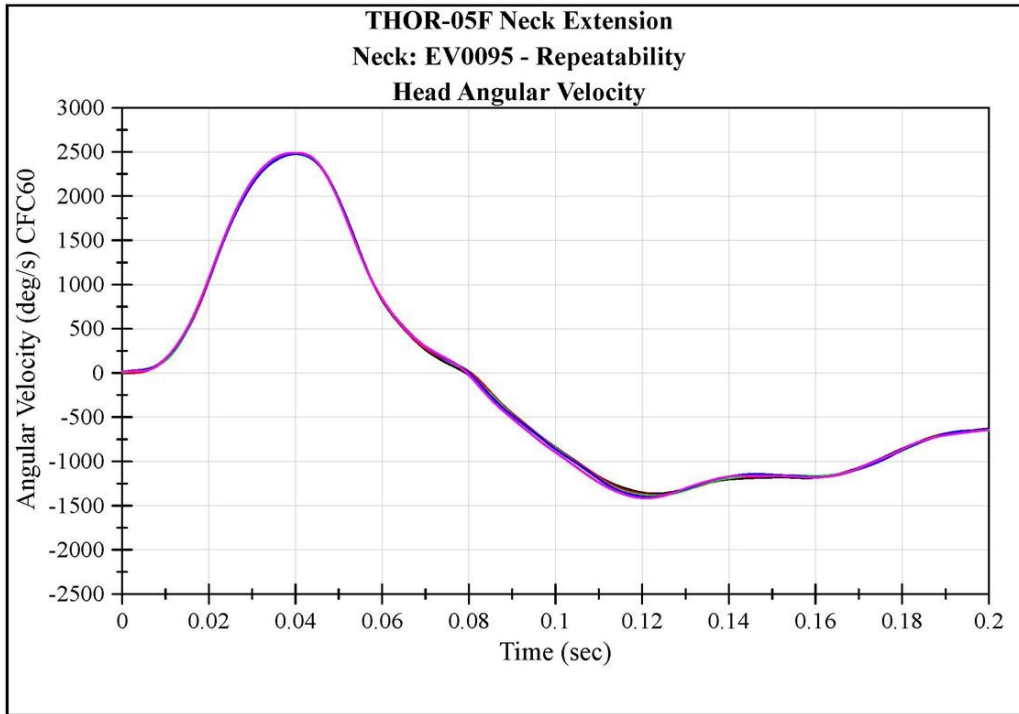


Figure 7-20. Calspan neck extension head angular velocity about Y repeatability for Neck EV0095

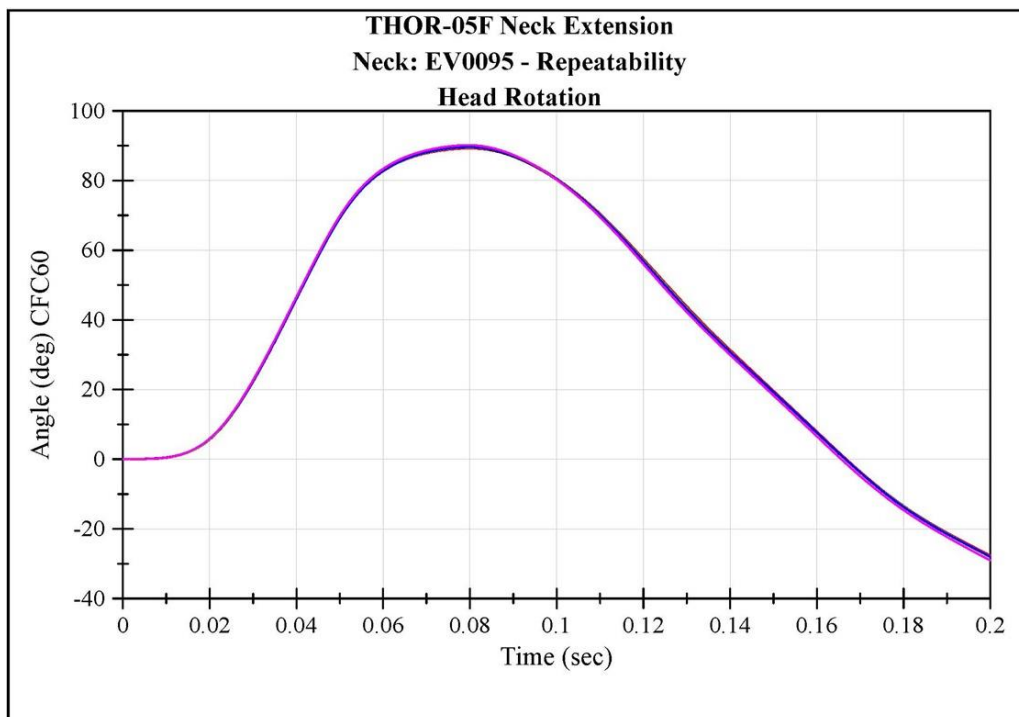


Figure 7-21. Calspan neck extension head rotation repeatability for Neck EV0095

7.2.6 THOR-05F Neck EV0095 Testing at TRC

Repeatability results for neck extension testing on Neck EV0095 (removed from ATD EV4675) at TRC yielded CV values below 5 percent (Table 7-11 through Table 7-12, Figure 7-22 through Figure 7-25).

Table 7-11. TRC EV0095 Neck Extension 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)
2025_04_29_15_10	1.62	3.35	4.89
2025_04_30_08_31	1.64	3.42	5.03
2025_04_30_11_19	1.65	3.40	4.91
2025_04_30_12_54	1.63	3.37	4.90
2025_05_02_10_42	1.65	3.63	4.80
Mean	1.64	3.43	4.91
Standard Deviation	0.01	0.11	0.08
CV	0.8%	3.3%	1.7%

Table 7-12. TRC EV0095 Neck Extension Repeatability Results

Test Number	Minimum Upper Neck M_y (N-m)	Minimum Upper Neck F_z (N)	Maximum Head Angular Velocity ω_y (deg/s)	Maximum Head Rotation θ_y (deg)
2025_04_29_15_10	-18.0	-1,233	2,354	87.7
2025_04_30_08_31	-18.1	-1,237	2,415	89.4
2025_04_30_11_19	-18.1	-1,183	2,390	88.4
2025_04_30_12_54	-17.8	-1,204	2,386	88.1
2025_05_02_10_42	-18.3	-1,262	2,376	87.2
Mean	-18.1	-1,224	2,384	88.2
Standard Deviation	0.17	30.7	22.2	0.83
CV	1.0%	2.5%	0.9%	0.9%

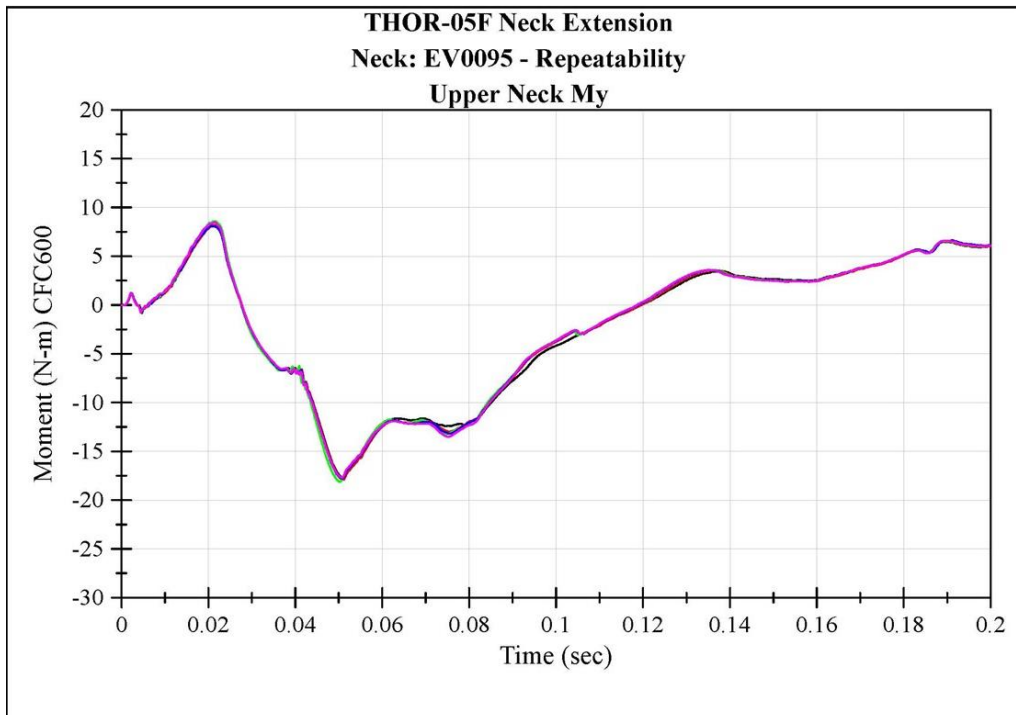


Figure 7-22. TRC neck extension upper neck moment My repeatability for Neck EV0095

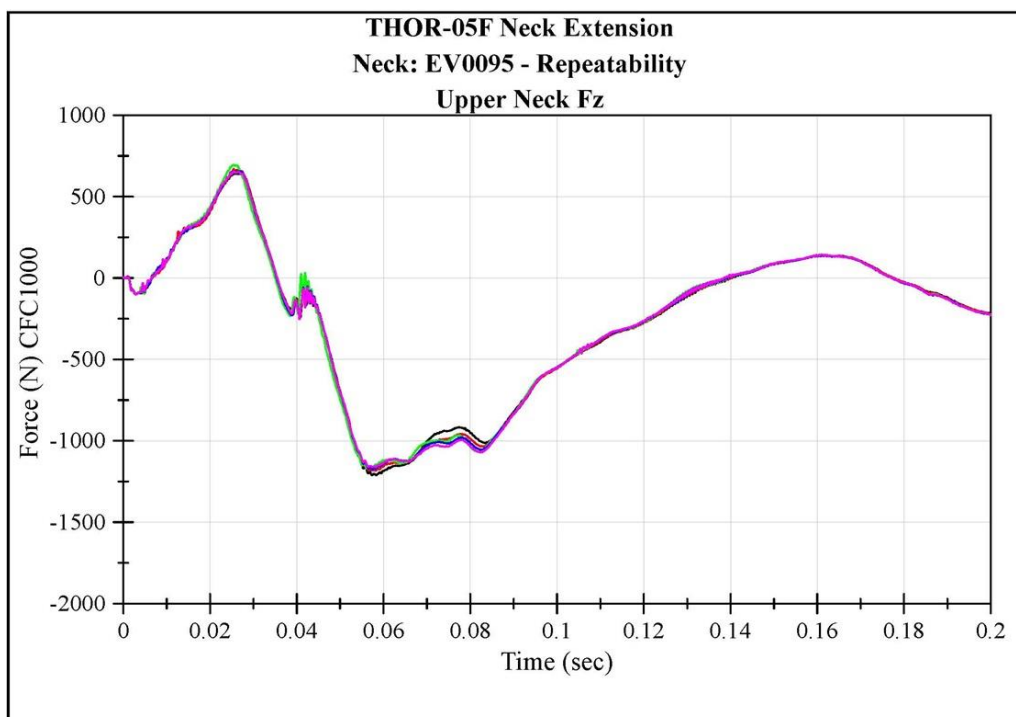


Figure 7-23. TRC neck extension upper neck force Fz repeatability for Neck EV0095

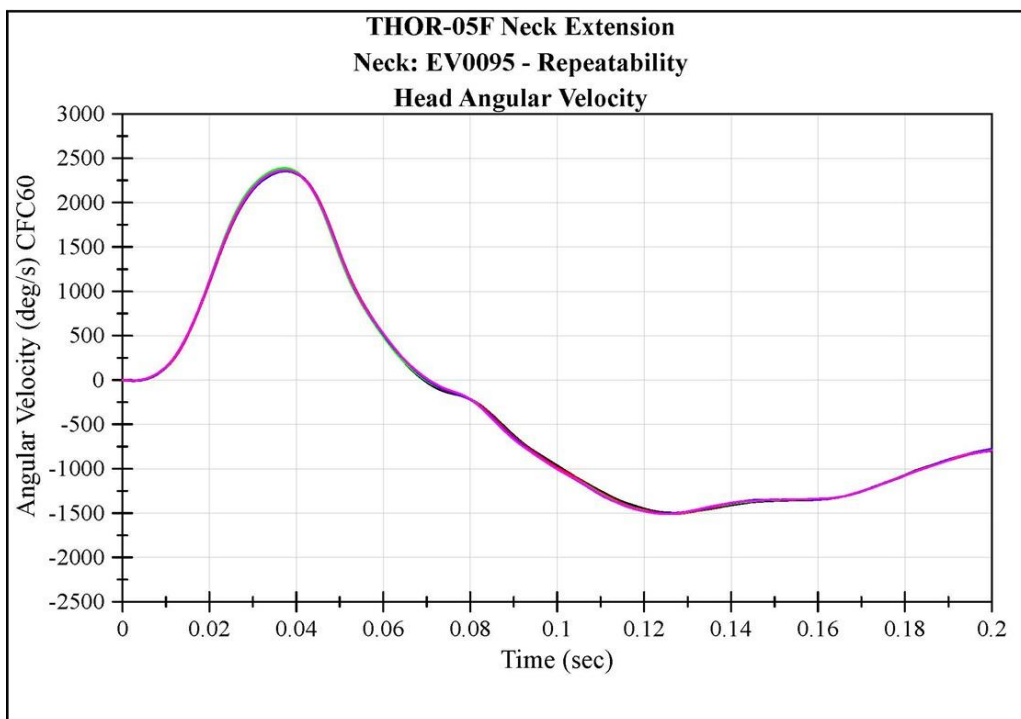


Figure 7-24. TRC neck extension head angular velocity about Y repeatability for Neck EV0095

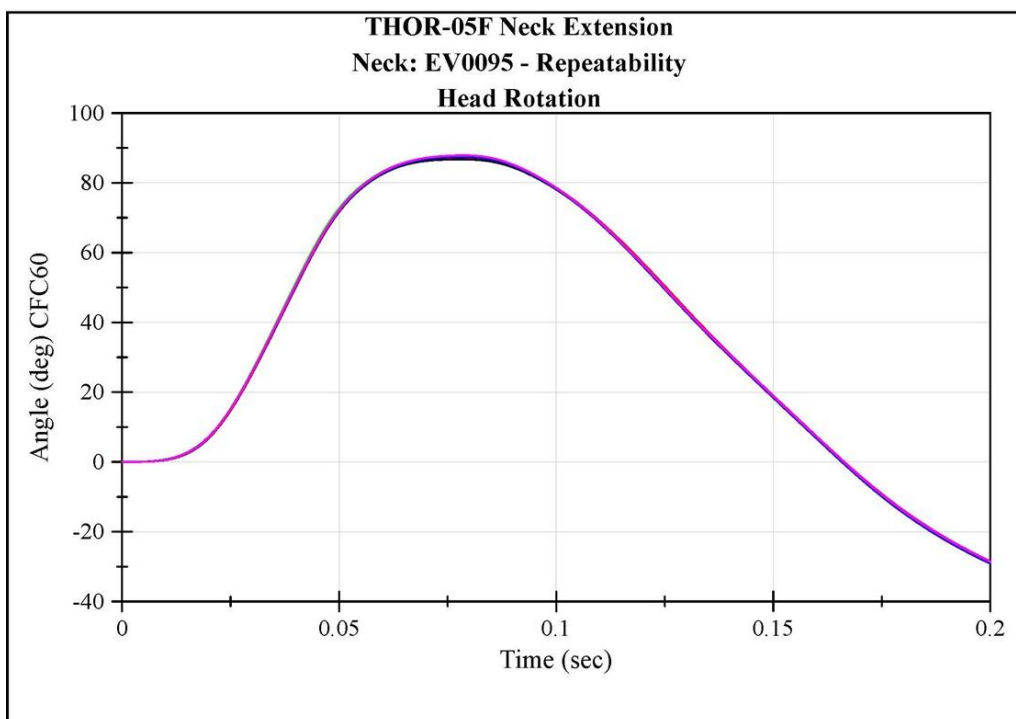


Figure 7-25. TRC neck extension head rotation repeatability for Neck EV0095

7.3 Neck Extension Dummy Reproducibility Results

Dummy Reproducibility results for neck extension qualification at VRTC yielded CV values below 5 percent for all velocities (Table 7-13). Results yielded CV values below 5 percent for head angular velocity and rotation, whereas upper neck moment and force were above 5 percent, but under 10 percent (Table 7-14).

Table 7-13. THOR-05F Neck Extension Pulse Reproducibility 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 EU9734	240326-1	1.69	3.43	4.89
	240326-2	1.71	3.43	4.86
	240326-3	1.59	3.29	4.74
	240326-4	1.61	3.33	4.78
	240326-5	1.58	3.20	4.62
VRTC Neck EV1357	240530-11	1.71	3.40	4.92
	240530-13	1.75	3.48	4.95
	240530-14	1.75	3.49	4.92
	240530-15	1.72	3.43	4.92
	240530-16	1.74	3.44	4.85
VRTC Neck EV0095	241127-6	1.77	3.52	5.04
	241127-7	1.73	3.48	4.93
	241127-8	1.81	3.60	5.03
	241202-1	1.81	3.61	5.04
	241202-2	1.72	3.57	5.03
Mean		1.71	3.45	4.90
Standard Deviation		0.07	0.11	0.12
CV		4.1%	3.2%	2.5%

Table 7-14. THOR-05F Neck Extension Reproducibility Corridors Results

Neck Number	Test Number	Minimum Upper Neck M_y (N-m)	Minimum Upper Neck F_z (N)	Maximum Head Angular Velocity ω_y (deg/s)	Maximum Head Rotation θ_y (deg)
VRTC Neck EU9734	240326-1	-22.9	-1,512	2,457	87.3
	240326-2	-19.4	-1,560	2,444	88.9
	240326-3	-17.3	-1,554	2,419	88.3
	240326-4	-17.5	-1,555	2,426	88.6
	240326-5	-16.4	-1,554	2,382	89.0
VRTC Neck EV1357	240530-11	-22.0	-1,281	2,365	84.4
	240530-13	-21.0	-1,354	2,394	84.6
	240530-14	-21.0	-1,320	2,392	86.2
	240530-15	-21.2	-1,308	2,392	85.7
	240530-16	-20.9	-1,322	2,382	86.5
VRTC Neck EV0095	241127-6	-21.0	-1,314	2,508	90.0
	241127-7	-19.7	-1,394	2,472	88.8
	241127-8	-19.4	-1,448	2,503	88.6
	241202-1	-20.7	-1,436	2,487	87.9
	241202-2	-19.5	-1,467	2,497	88.2
Mean		-20.0	-1,425	2,435	87.5
Standard Deviation		1.81	104	49.8	1.69
CV		9.0%	7.3%	2.0%	1.9%

7.4 Lab-to-Lab Variability Analysis

The results of the neck extension qualification tests from each lab are presented in Table 7-15 and Table 7-16. The last three rows of the tables show the *Test Reproducibility* results when data from VRTC, Humanetics, Calspan, and TRC are combined. *Test Reproducibility* results for the neck extension tests at all four labs yielded CV values below 5 percent for all pendulum velocities (Table 7-15). The results yielded CV values below 5 percent for head angular velocity and rotation, whereas upper neck moment and force were above 5 percent, but under 10 percent (Table 7-16).

Table 7-15. THOR-05F Neck Extension Pulse Reproducibility 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 EV0095	241127-6	1.77	3.52	5.04
	241127-7	1.73	3.48	4.93
	241127-8	1.81	3.60	5.03
	241202-1	1.81	3.61	5.04
	241202-2	1.72	3.57	5.03
Humanetics Neck EV0095	686778	1.66	3.35	4.88
	686769	1.64	3.31	4.75
	686792	1.66	3.33	4.77
	686757	1.65	3.30	4.75
	686786	1.67	3.32	4.77
Calspan Neck EV0095	2025_03_26 15_50	1.80	3.69	5.20
	2025_03_26 16_23	1.81	3.71	5.24
	2025_03_26 16_56	1.81	3.72	5.20
	2025_03_26 17_28	1.80	3.67	5.19
	2025_03_26 18_01	1.83	3.71	5.23
TRC Neck EV0095	2025_04_29 15_10	1.62	3.35	4.89
	2025_04_30 08_31	1.64	3.42	5.03
	2025_04_30 11_19	1.65	3.40	4.91
	2025_04_30 12_54	1.63	3.37	4.90
	2025_05_02 10_42	1.65	3.63	4.80
Test Reproducibility Neck EV0095				
Mean		1.72	3.50	4.98
Standard Deviation		0.08	0.16	0.17
CV		4.5%	4.5%	3.4%

Table 7-16. THOR-05F Neck Extension Reproducibility Corridors Results

Neck Number	Test Number	Minimum Upper Neck M_y (N-m)	Minimum Upper Neck F_z (N)	Maximum Head Angular Velocity ω_y (deg/s)	Maximum Head Rotation θ_y (deg)
VRTC Neck EV0095	241127-6	-21.0	-1,314	2,508	90.0
	241127-7	-19.7	-1,394	2,472	88.8
	241127-8	-19.4	-1,448	2,503	88.6
	241202-1	-20.7	-1,436	2,487	87.9
	241202-2	-19.5	-1,467	2,497	88.2
Humanetics Neck EV0095	686778	-18.1	-1,171	2,389	87.6
	686769	-17.9	-1,183	2,355	87.3
	686792	-17.7	-1,163	2,364	87.8
	686757	-17.7	-1,211	2,353	86.7
	686786	-17.8	-1,175	2,356	87.4
Calspan Neck EV0095	2025_03_26 15_50	-17.0	-1,324	2,301	87.3
	2025_03_26 16_23	-17.4	-1,298	2,309	89.3
	2025_03_26 16_56	-17.2	-1,306	2,299	89.6
	2025_03_26 17_28	-17.8	-1,289	2,296	89.6
	2025_03_26 18_01	-17.3	-1,294	2,312	90.2
TRC Neck EV0095	2025_04_29 15_10	-18.0	-1,233	2,354	87.7
	2025_04_30 08_31	-18.1	-1,237	2,415	89.4
	2025_04_30 11_19	-18.1	-1,183	2,390	88.4
	2025_04_30 12_54	-17.8	-1,204	2,386	88.1
	2025_05_02 10_42	-18.3	-1,262	2,376	87.2
Test Reproducibility Neck EV0095					
Mean		-18.3	-1,280	2,386	88.4
Standard Deviation		1.13	96.1	71.9	1.02
CV		6.2%	7.5%	3.0%	1.2%

7.5 Corridor Development

All the data used to determine the neck extension qualification corridors is shown in Table 7-17 and Table 7-18. The qualification corridors were calculated using the mean plus or minus 10 percent of the peak for the specified measured or calculated channels (Table 7-19).

Table 7-17. THOR-05F Neck Extension 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 EU9734	240326-1	1.69	3.43	4.89
	240326-2	1.71	3.43	4.86
	240326-3	1.59	3.29	4.74
	240326-4	1.61	3.33	4.78
	240326-5	1.58	3.20	4.62
VRTC Neck EV1357	240530-11	1.71	3.40	4.92
	240530-13	1.75	3.48	4.95
	240530-14	1.75	3.49	4.92
	240530-15	1.72	3.43	4.92
	240530-16	1.74	3.44	4.85
VRTC Neck EV0095	241127-6	1.77	3.52	5.04
	241127-7	1.73	3.48	4.93
	241127-8	1.81	3.60	5.03
	241202-1	1.81	3.61	5.04
	241202-2	1.72	3.57	5.03
Humanetics Neck EV0095	686778	1.66	3.35	4.88
	686769	1.64	3.31	4.75
	686792	1.66	3.33	4.77
	686757	1.65	3.30	4.75
	686786	1.67	3.32	4.77
Calspan Neck EV0095	2025_03_26 15_50	1.80	3.69	5.20
	2025_03_26 16_23	1.81	3.71	5.24
	2025_03_26 16_56	1.81	3.72	5.20
	2025_03_26 17_28	1.80	3.67	5.19
	2025_03_26 18_01	1.83	3.71	5.23
TRC Neck EV0095	2025_04_29 15_10	1.62	3.35	4.89
	2025_04_30 08_31	1.64	3.42	5.03
	2025_04_30 11_19	1.65	3.40	4.91
	2025_04_30 12_54	1.63	3.37	4.90
	2025_05_02 10_42	1.65	3.63	4.80
Mean		1.71	3.47	4.94
Standard Deviation		0.07	0.14	0.16
CV		4.3%	4.1%	3.2%

Table 7-18. THOR-05F Neck Extension Qualification Corridor Results
(Highlighted values fell outside average $\pm 10\%$.)

Neck Number	Test Number	Minimum Upper Neck M_y (N-m)	Minimum Upper Neck F_z (N)	Maximum Head Angular Velocity ω_y (deg/s)	Maximum Head Rotation θ_y (deg)
VRTC Neck EU9734	240326-1	-22.9	-1,512	2,457	87.3
	240326-2	-19.4	-1,560	2,444	88.9
	240326-3	-17.3	-1,554	2,419	88.3
	240326-4	-17.5	-1,555	2,426	88.6
	240326-5	-16.4	-1,554	2,382	89.0
VRTC Neck EV1357	240530-11	-22.0	-1,281	2,365	84.4
	240530-13	-21.0	-1,354	2,394	84.6
	240530-14	-21.0	-1,320	2,392	86.2
	240530-15	-21.2	-1,308	2,392	85.7
	240530-16	-20.9	-1,322	2,382	86.5
VRTC Neck EV0095	241127-6	-21.0	-1,314	2,508	90.0
	241127-7	-19.7	-1,394	2,472	88.8
	241127-8	-19.4	-1,448	2,503	88.6
	241202-1	-20.7	-1,436	2,487	87.9
	241202-2	-19.5	-1,467	2,497	88.2
Humanetics Neck EV0095	686778	-18.1	-1,171	2,389	87.6
	686769	-17.9	-1,183	2,355	87.3
	686792	-17.7	-1,163	2,364	87.8
	686757	-17.7	-1,211	2,353	86.7
	686786	-17.8	-1,175	2,356	87.4
Calspan Neck EV0095	2025_03_26 15_50	-17.0	-1,324	2,301	87.3
	2025_03_26 16_23	-17.4	-1,298	2,309	89.3
	2025_03_26 16_56	-17.2	-1,306	2,299	89.6
	2025_03_26 17_28	-17.8	-1,289	2,296	89.6
	2025_03_26 18_01	-17.3	-1,294	2,312	90.2
TRC Neck EV0095	2025_04_29 15_10	-18.0	-1,233	2,354	87.7
	2025_04_30 08_31	-18.1	-1,237	2,415	89.4
	2025_04_30 11_19	-18.1	-1,183	2,390	88.4
	2025_04_30 12_54	-17.8	-1,204	2,386	88.1
	2025_05_02 10_42	-18.3	-1,262	2,376	87.2
Mean		-18.9	-1,335	2,393	87.9
Standard Deviation		1.7	127	60	1.4
CV		8.9%	9.5%	2.5%	1.6%

Table 7-19. Neck Extension Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width $\pm\%$
Pendulum Velocity at 8 ms after T0	m/s	1.54	1.88	1.71	10.0%
Pendulum Velocity at 16 ms after T0	m/s	3.12	3.81	3.47	10.0%
Pendulum Velocity at 24 ms after T0	m/s	4.44	5.43	4.94	10.0%
Impact Velocity	m/s	4.95	5.05	5.00	
Minimum Upper Neck M_y	N-m	-20.8	-17.0	-18.9	10.0%
Minimum Upper Neck F_z	N	-1,469	-1,202	-1,335	10.0%
Maximum Head Angular Velocity ω_y (relative to earth)	deg/s	2,154	2,632	2,393	10.0%
Maximum Head Rotation θ_y (relative to pendulum)	deg	79.1	96.7	87.9	10.0%

Discussion. Highlighted cells in Table 7-18 indicate test values that did not achieve their respective target response $\pm 10\%$. All such test non-conformities were either due to the upper neck moment or upper neck Z-axis force. All upper neck Z-axis force results from VRTC test on EU9734 and four of five tests from the Humanetics tests on neck EV0095 were outside of the specification range. As a result, the CV values for these two specifications were all above 5 percent, and closer to 10 percent. VRTC tests on neck EV1357 exceeded the upper neck Y moment range in all tests. The head angular velocity and rotation were both below 5 percent.

Repeatability (Table 7-1 and Table 7-12) displayed CV values below 5 percent for all test responses for all dummies, with the exception of neck EU9734 tested at VRTC; this neck yielded a CV over 10 percent for upper neck Y-axis moment, likely due to the high value outlier on the first test.

Dummy Reproducibility pendulum velocity displayed CV values all below 5 percent (Table 7-13). Head angular velocity and head rotation produced CV values that were less than 5 percent (Table 7-14). However, upper neck moment and Z-axis force produced CV values above 5 percent, but under 10 percent. All upper neck moment on neck EV1357 and all upper neck forces on neck EU934 were out of range, so these tests elevated the CV.

Test Reproducibility results showed all pendulum velocity, head angular velocity, and head rotation CV values were below 5 percent. (Table 7-15 and Table 7-16). Like the *Dummy Reproducibility* trends, upper neck moment and Z-axis force CV values were above 5 percent, but under 10 percent.

8 NECK LATERAL FLEXION

8.1 Methodology

Repeatability and reproducibility tests were performed using the neck lateral flexion qualification procedures described in the *THOR-05F Qualification Procedures and Requirements*. 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. For lateral neck flexion tests, the lower neck load cell is attached rigidly to the bottom of the head-neck pendulum via the neck mounting plate (TF-200-2357); and the pendulum is decelerated from the specified speed during contact with a Hexcel aluminum honeycomb (or equivalent) (Figure 8-1). During these tests, the upper neck moment (M_x), head angular velocity, and head rotation were measured.

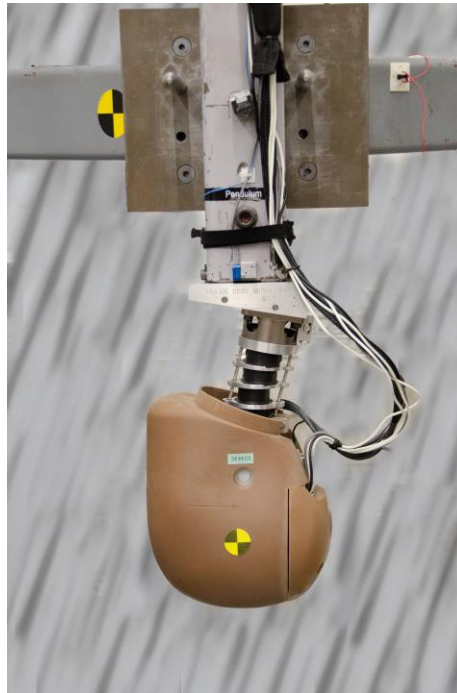


Figure 8-1. Neck lateral flexion test setup (left)

8.2 Neck Lateral Flexion Repeatability Results

Sections 8.2.1 through 8.2.12 illustrate the results of the neck lateral flexion repeatability tests. For this study, the left and right sides were tested to confirm symmetrical responses. Each section contains a table providing the quantified test data, followed by plot overlays of the five repeat tests conducted at all four 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-05F Neck EU9734 Left Testing at VRTC

Repeatability results for neck left lateral flexion testing on Neck EU9734 (removed from ATD EU9863) at VRTC yielded CV values below 5 percent (Table 8-1 through Table 8-2, Figure 8-2 through Figure 8-4).

Table 8-1. VRTC EU9734 Left Lateral Flexion Pulse Repeatability Results

Test Number	Pendulum Velocity at 5 ms after T0 (m/s)	Pendulum Velocity at 10 ms after T0 (m/s)	Pendulum Velocity at 15 ms after T0 (m/s)
240327-5	0.94	2.00	2.93
240327-6	0.98	2.07	3.00
240327-7	1.01	2.10	2.95
240327-8	1.02	2.08	3.01
240327-9	0.99	2.03	2.98
Mean	0.99	2.05	2.97
Standard Deviation	0.03	0.04	0.03
CV	3.0%	2.1%	1.1%

Table 8-2. VRTC EU9734 Left Lateral Flexion Repeatability Results

Test Number	Maximum Upper Neck M_x after 40 ms (Nm)	Minimum Head ω_x (deg/s)	Minimum Head θ_x (deg)
240327-5	29.4	-1,355	-51.7
240327-6	28.6	-1,373	-53.1
240327-7	28.1	-1,349	-53.9
240327-8	28.3	-1,385	-54.8
240327-9	28.2	-1,380	-54.4
Mean	28.5	-1,368	-53.6
Standard Deviation	0.50	15.7	1.23
CV	1.8%	1.1%	2.3%

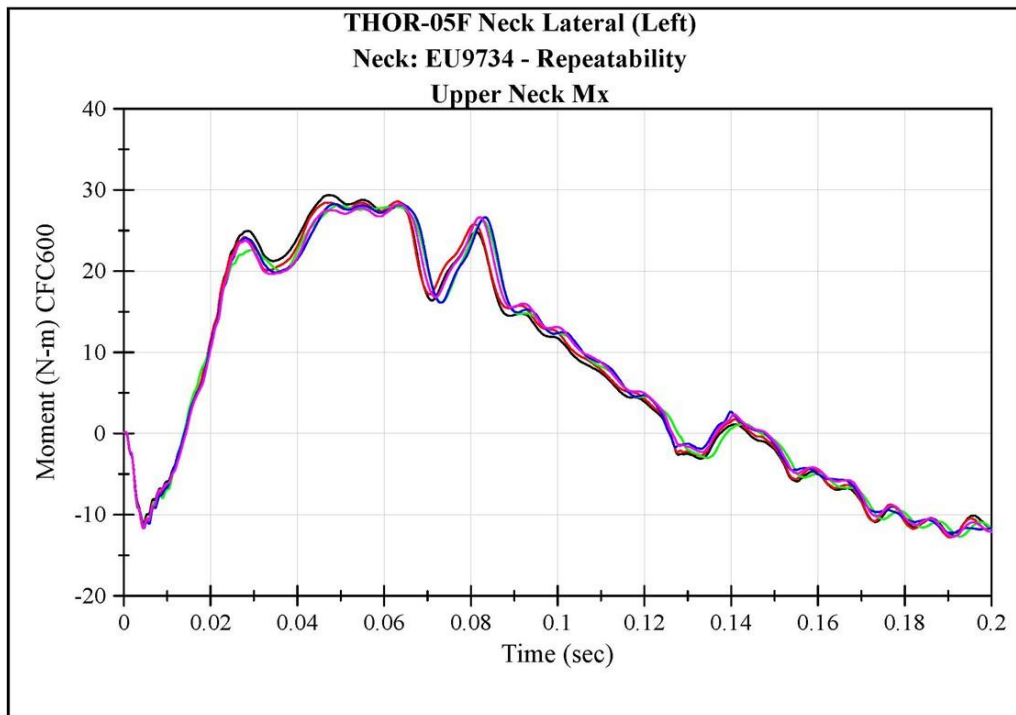


Figure 8-2. VRTC neck left lateral flexion upper neck moment Mx repeatability for THOR-05F Neck EU9734

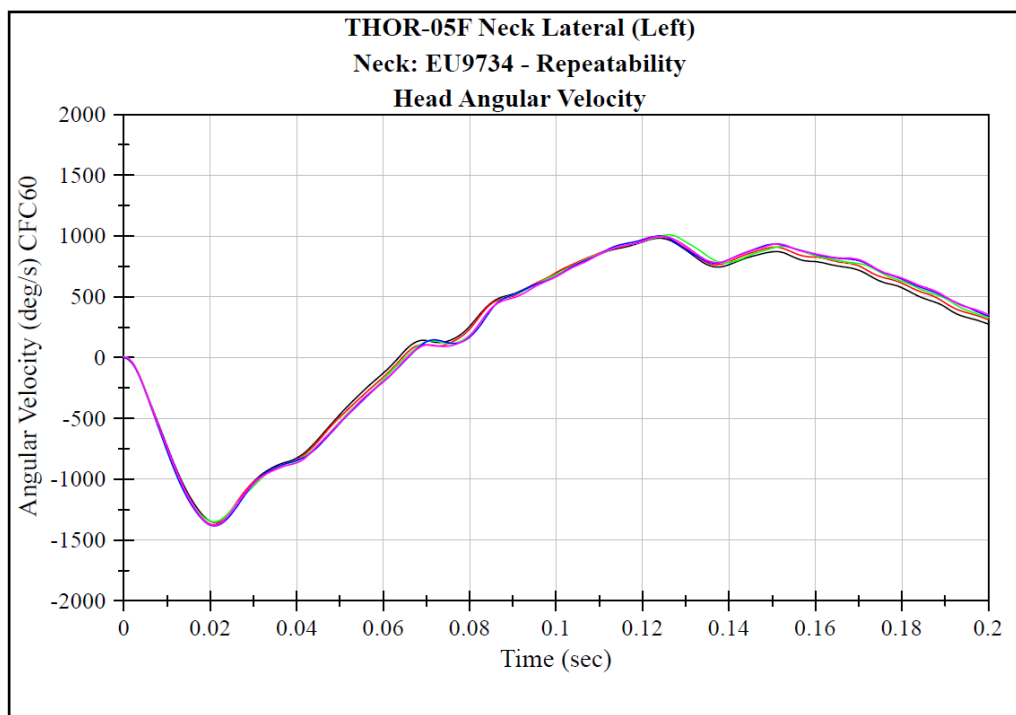


Figure 8-3. VRTC neck left lateral flexion head angular velocity about X repeatability for THOR-05F Neck EU9734

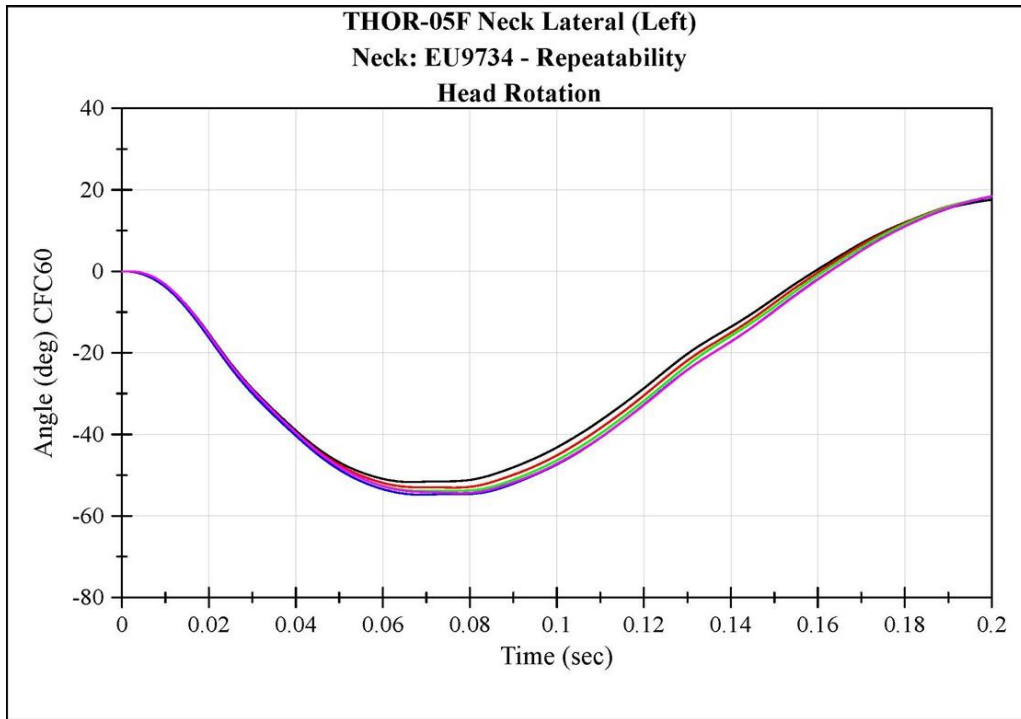


Figure 8-4. VRTC neck left lateral head rotation repeatability for THOR-05F Neck EU9734

8.2.2 THOR-05F Neck EU9734 Right Testing at VRTC

Repeatability results for neck right lateral flexion testing on Neck EU9734 (removed from ATD EU9863) at VRTC yielded CV values below 5 percent (Table 8-3 and Table 8-4, Figure 8-5 through Figure 8-7).

Table 8-3. VRTC EU9734 Right Lateral Flexion Pulse Repeatability Results

Test Number	Pendulum Velocity at 5 ms after T0 (m/s)	Pendulum Velocity at 10 ms after T0 (m/s)	Pendulum Velocity at 15 ms after T0 (m/s)
240327-10	1.03	2.09	3.05
240327-11	1.02	2.14	3.10
240327-12	0.99	2.03	2.92
240327-13	1.00	2.12	3.07
240327-14	0.98	2.03	2.92
Mean	1.00	2.09	3.01
Standard Deviation	0.02	0.05	0.09
CV	2.1%	2.4%	2.9%

Table 8-4. VRTC THOR-05F Neck EU9734 Right Lateral Flexion Repeatability Results

Test Number	Minimum Upper Neck M_x after 40 ms (Nm)	Maximum Head ω_x (deg/s)	Maximum Head θ_x (deg)
240327-10	-29.2	1,390	53.6
240327-11	-28.8	1,396	54.5
240327-12	-28.3	1,350	54.5
240327-13	-28.4	1,389	54.9
240327-14	-28.1	1,355	54.6
Mean	-28.6	1,376	54.4
Standard Deviation	0.45	21.5	0.51
CV	1.6%	1.6%	0.9%

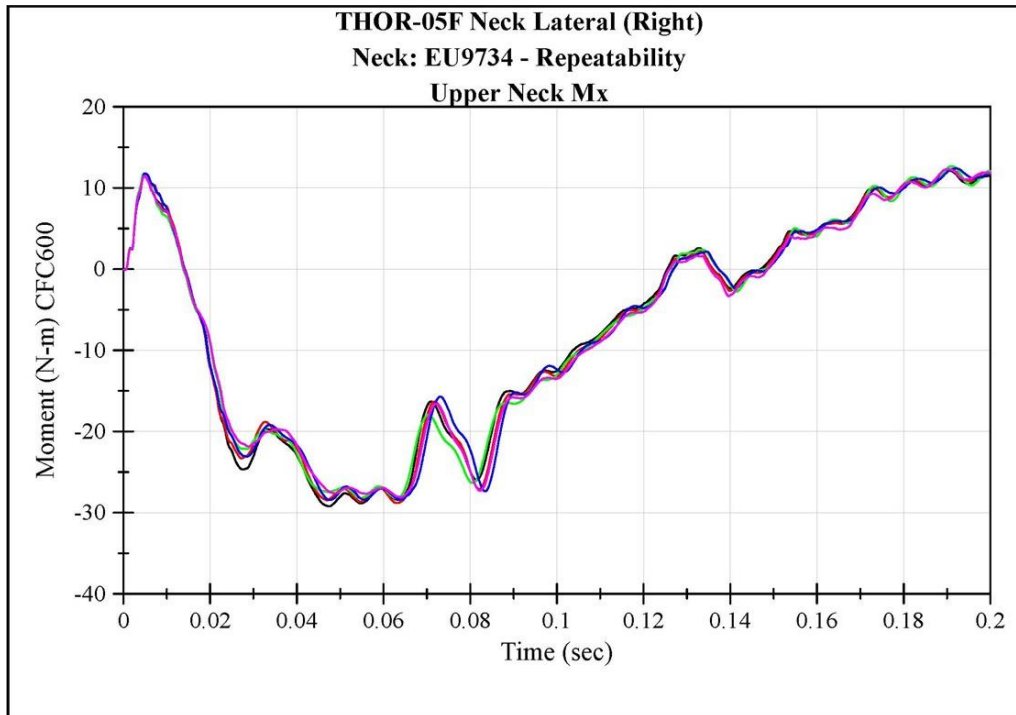


Figure 8-5. VRTC neck right lateral flexion upper neck moment Mx repeatability for THOR-05F Neck EU9734

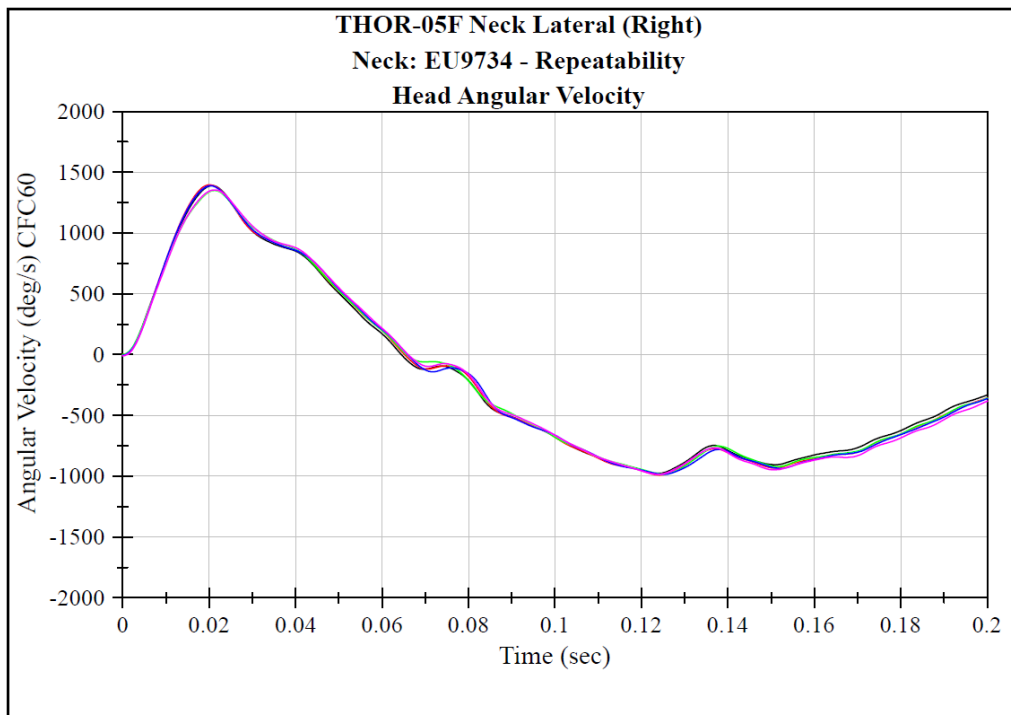


Figure 8-6. VRTC neck right lateral flexion head angular velocity about X repeatability for THOR-05F Neck EU9734

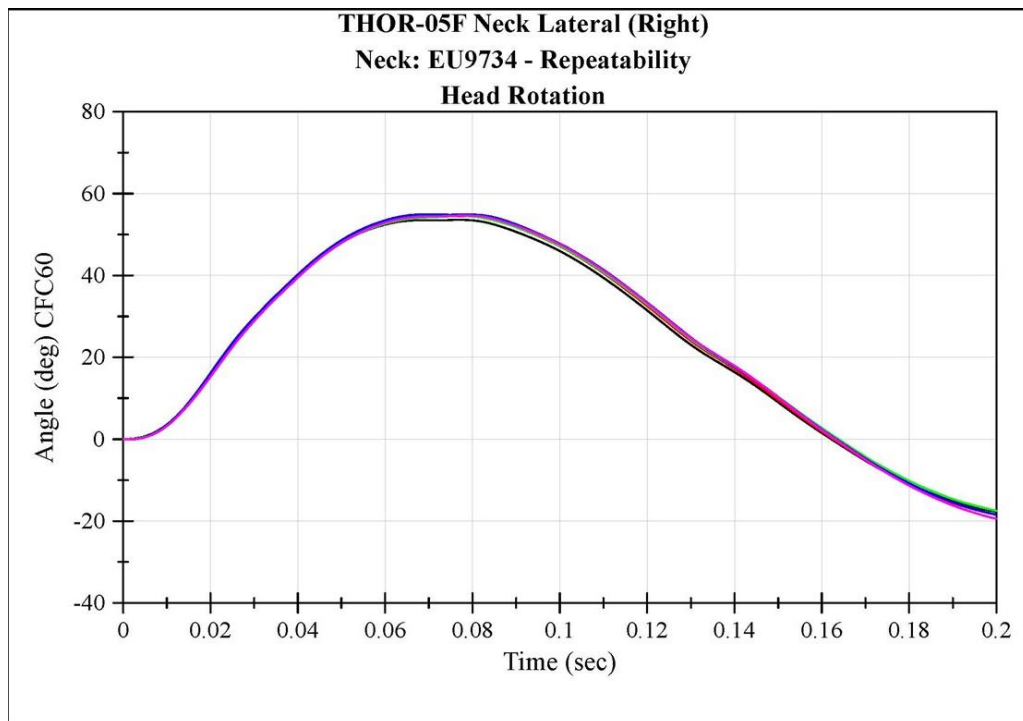


Figure 8-7. VRTC neck right lateral flexion head rotation repeatability for THOR-05F Neck EU9734

8.2.3 THOR-05F Neck EV1357 Left Testing at VRTC

Repeatability results for neck left lateral flexion testing on Neck EV1357 (removed from ATD EV0674) at VRTC yielded CV values below 5 percent (Table 8-5 through Table 8-6, Figure 8-8 through Figure 8-10).

Table 8-5. VRTC THOR-05F Neck EV1357 Left Lateral Flexion Pulse Repeatability Results

Test Number	Pendulum Velocity at 5 ms after T0 (m/s)	Pendulum Velocity at 10 ms after T0 (m/s)	Pendulum Velocity at 15 ms after T0 (m/s)
240531-2	0.99	2.05	2.97
240531-3	0.98	2.03	2.98
240531-4	1.04	2.11	3.03
240531-5	0.97	2.00	2.87
240531-6	0.95	1.99	2.85
Mean	0.99	2.04	2.94
Standard Deviation	0.03	0.05	0.08
CV	3.3%	2.3%	2.6%

Table 8-6. VRTC THOR-05F Neck EV1357 Left Lateral Flexion Repeatability Results

Test Number	Maximum Upper Neck M_x after 40 ms (Nm)	Minimum Head ω_x (deg/s)	Minimum Head θ_x (deg)
240531-2	31.2	-1,309	-50.4
240531-3	31.2	-1,317	-50.3
240531-4	31.0	-1,318	-50.8
240531-5	30.7	-1,303	-50.6
240531-6	30.2	-1,282	-50.7
Mean	30.9	-1,306	-50.5
Standard Deviation	0.43	14.9	0.20
CV	1.4%	1.1%	0.4%

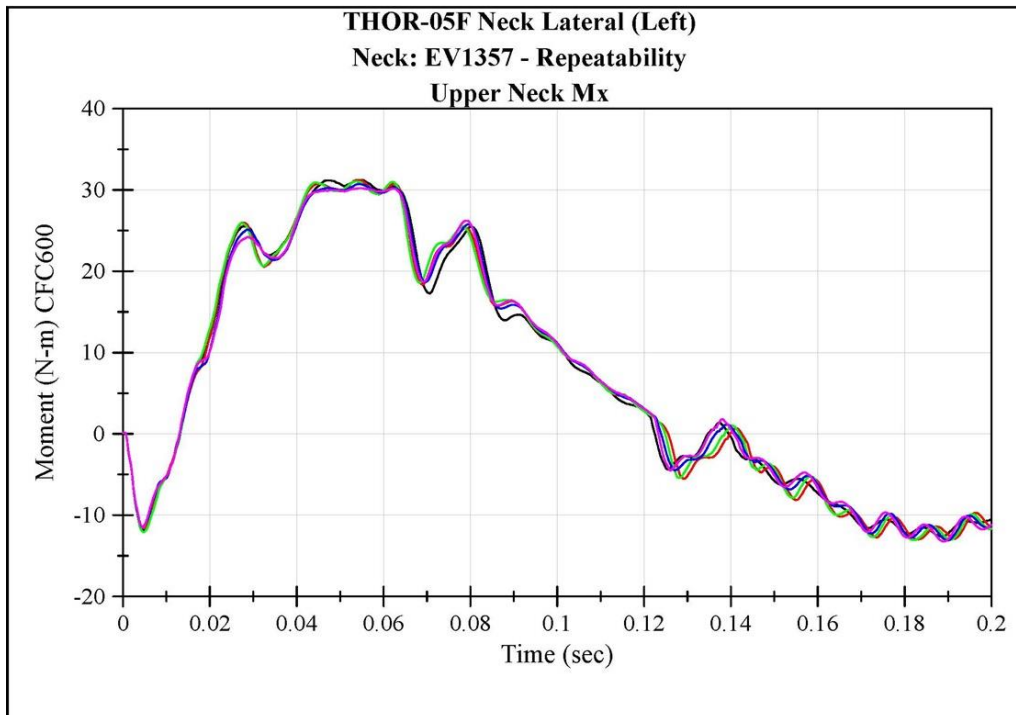


Figure 8-8. VRTC neck left lateral flexion upper neck moment Mx repeatability for THOR-05F Neck EV1357

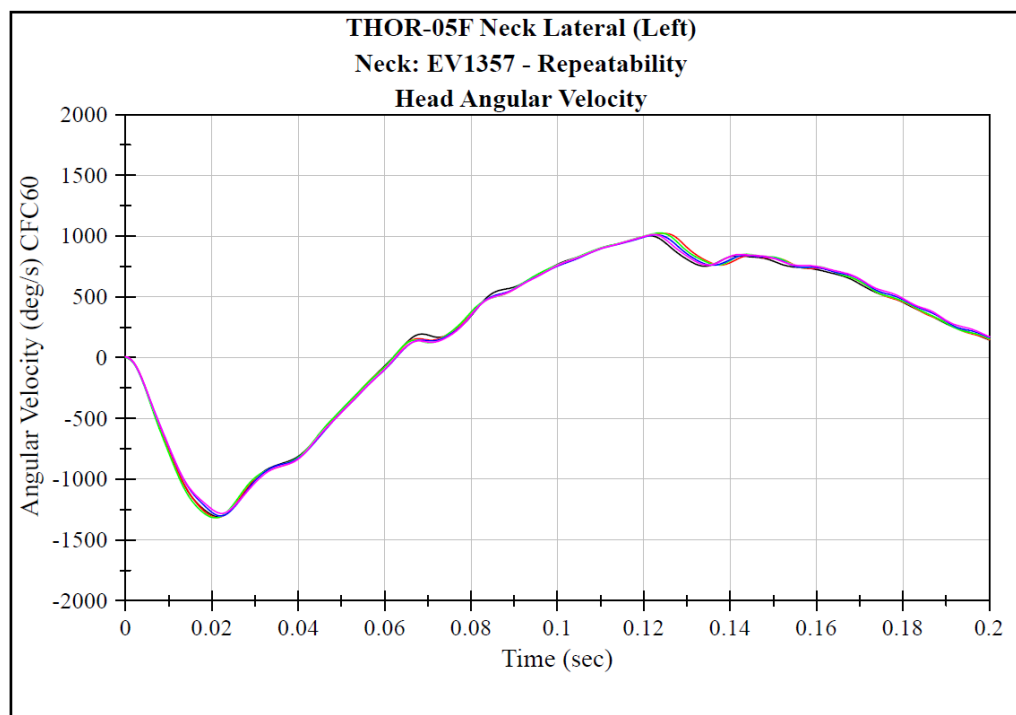


Figure 8-9. VRTC neck left lateral flexion head angular velocity about X repeatability for THOR-05F Neck EV1357

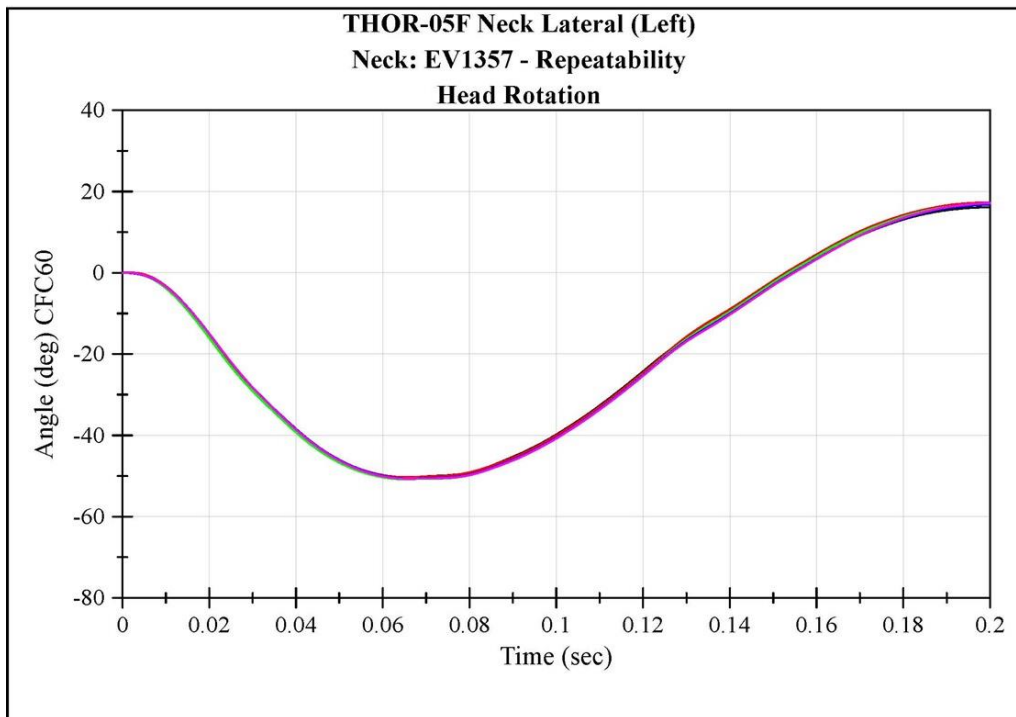


Figure 8-10. VRTC neck left lateral head rotation repeatability for THOR-05F Neck EV1357

8.2.4 THOR-05F Neck EV1357 Right Testing at VRTC

Repeatability results for neck right lateral flexion testing on Neck EV1357 (removed from ATD EV0674) at VRTC yielded CV values below 5 percent (Table 8-7 through Table 8-8, Figure 8-11 through Figure 8-13).

Table 8-7. VRTC THOR-05F Neck EV1357 Right Lateral Flexion Pulse Repeatability Results

Test Number	Pendulum Velocity at 5 ms after T0 (m/s)	Pendulum Velocity at 10 ms after T0 (m/s)	Pendulum Velocity at 15 ms after T0 (m/s)
240531-7	0.98	2.05	3.01
240605-13	0.99	2.02	2.93
240605-14	0.97	2.02	2.95
240605-15	1.04	2.15	3.10
240605-16	0.95	1.98	2.90
Mean	0.99	2.05	2.98
Standard Deviation	0.03	0.07	0.08
CV	3.4%	3.2%	2.7%

Table 8-8. VRTC THOR-05F Neck EV1357 Right Lateral Flexion Repeatability Results

Test Number	Minimum Upper Neck M _x after 40 ms (Nm)	Maximum Head ω _x (deg/s)	Maximum Head θ _x (deg)
240531-7	-31.2	1,315	49.3
240605-13	-31.2	1,292	49.5
240605-14	-31.1	1,305	50.7
240605-15	-31.5	1,319	50.7
240605-16	-30.7	1,298	50.6
Mean	-31.1	1,306	50.2
Standard Deviation	0.29	11.2	0.69
CV	0.9%	0.9%	1.4%

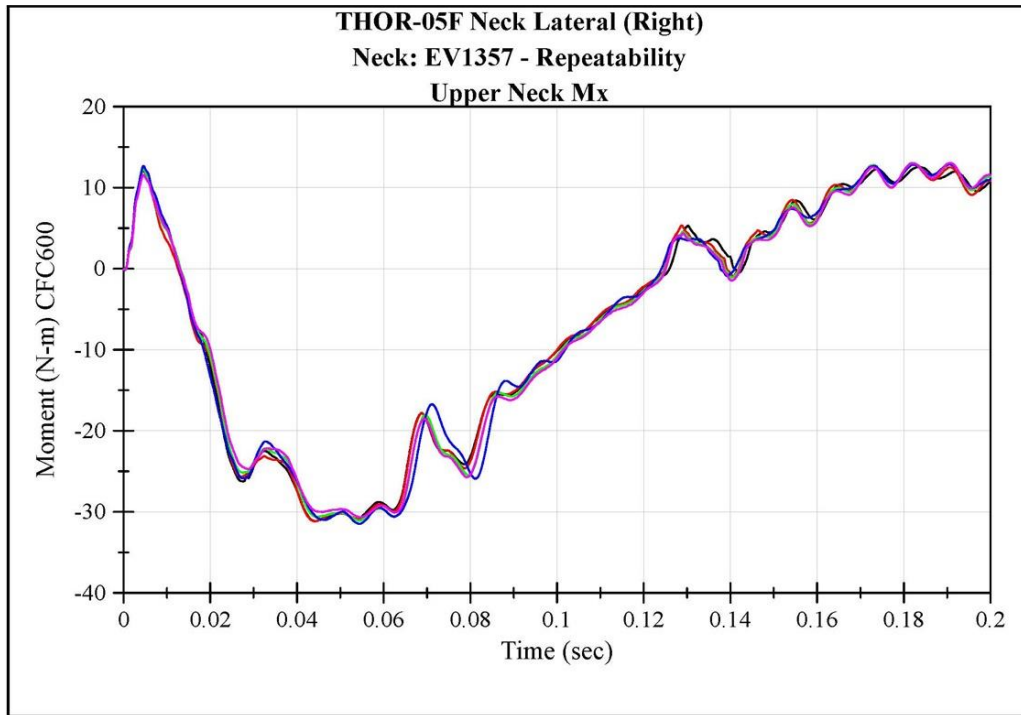


Figure 8-11. VRTC neck right lateral flexion upper neck moment Mx repeatability for THOR-05F Neck EV1357

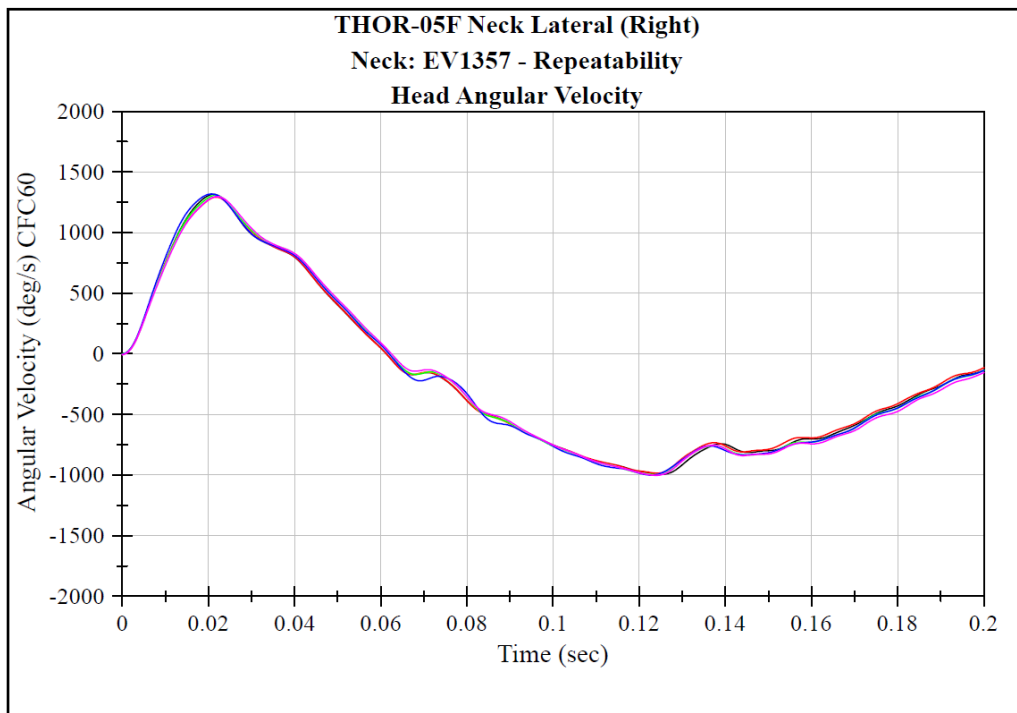


Figure 8-12. VRTC neck right lateral flexion head angular velocity about X repeatability for THOR-05F Neck EV1357

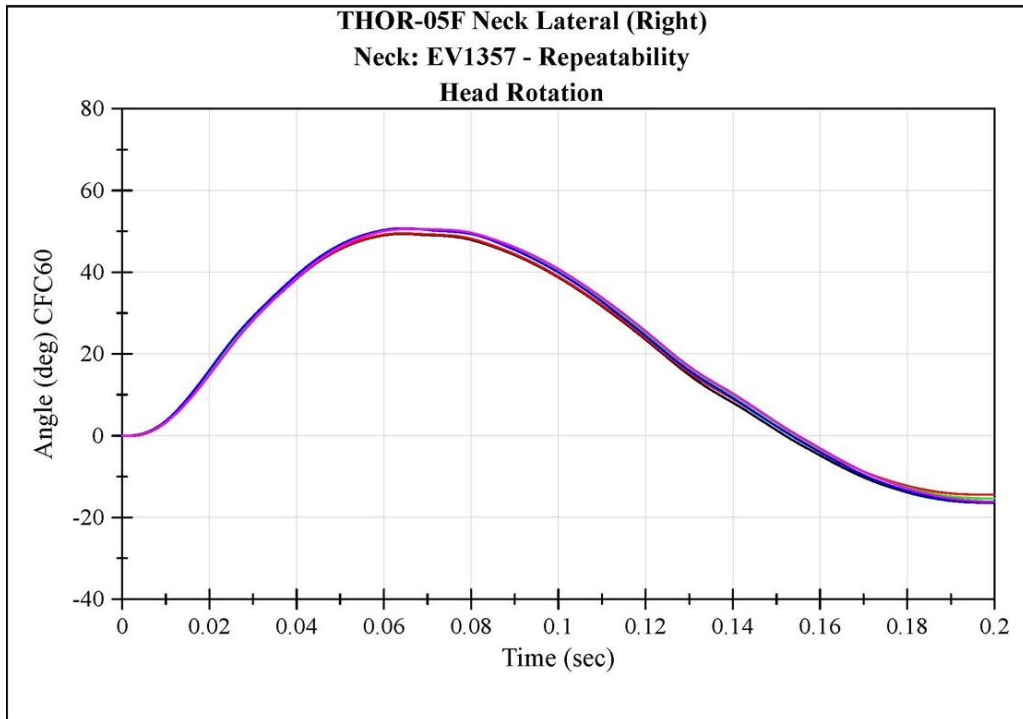


Figure 8-13. VRTC neck right lateral flexion head rotation repeatability for THOR-05F Neck EV1357

8.2.5 THOR-05F Neck EV0095 Left Testing at VRTC

Repeatability results for neck left lateral flexion testing on Neck EV0095 (removed from ATD EV4675) at VRTC yielded CV values below 5 percent (Table 8-9 through Table 8-10, Figure 8-14 through Figure 8-16).

Table 8-9. VRTC EV0095 Left Lateral Flexion Pulse Repeatability Results

Test Number	Pendulum Velocity at 5 ms after T0 (m/s)	Pendulum Velocity at 10 ms after T0 (m/s)	Pendulum Velocity at 15 ms after T0 (m/s)
241126-11	0.95	2.05	2.96
241126-12	0.99	2.02	2.94
241126-13	0.96	1.96	2.81
241126-14	0.93	1.95	2.78
241126-15	0.97	2.02	2.91
Mean	0.96	2.00	2.88
Standard Deviation	0.02	0.05	0.08
CV	2.2%	2.3%	2.8%

Table 8-10. VRTC EV0095 Left Lateral Flexion Repeatability Results

Test Number	Maximum Upper Neck M_x after 40 ms (Nm)	Minimum Head ω_x (deg/s)	Minimum Head θ_x (deg)
241126-11	29.6	-1,333	-49.6
241126-12	29.3	-1,334	-50.8
241126-13	29.0	-1,305	-51.0
241126-14	28.7	-1,287	-51.0
241126-15	29.0	-1,338	-51.4
Mean	29.1	-1,319	-50.8
Standard Deviation	0.34	22.5	0.68
CV	1.2%	1.7%	1.3%

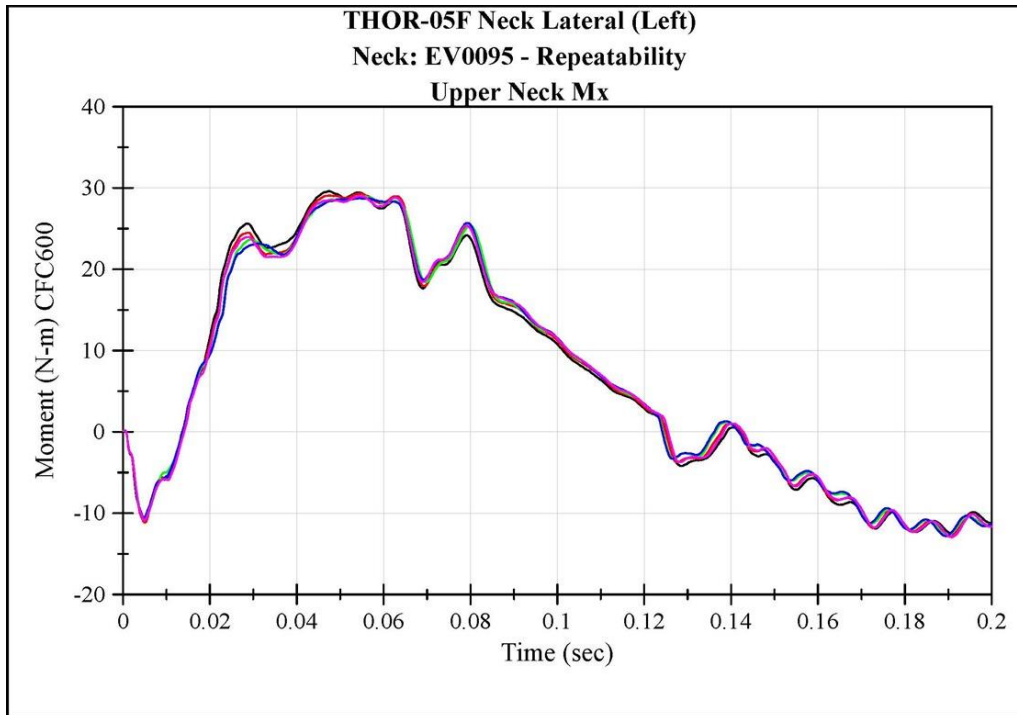


Figure 8-14. VRTC neck left lateral flexion upper neck moment Mx repeatability for THOR-05F Neck EV0095

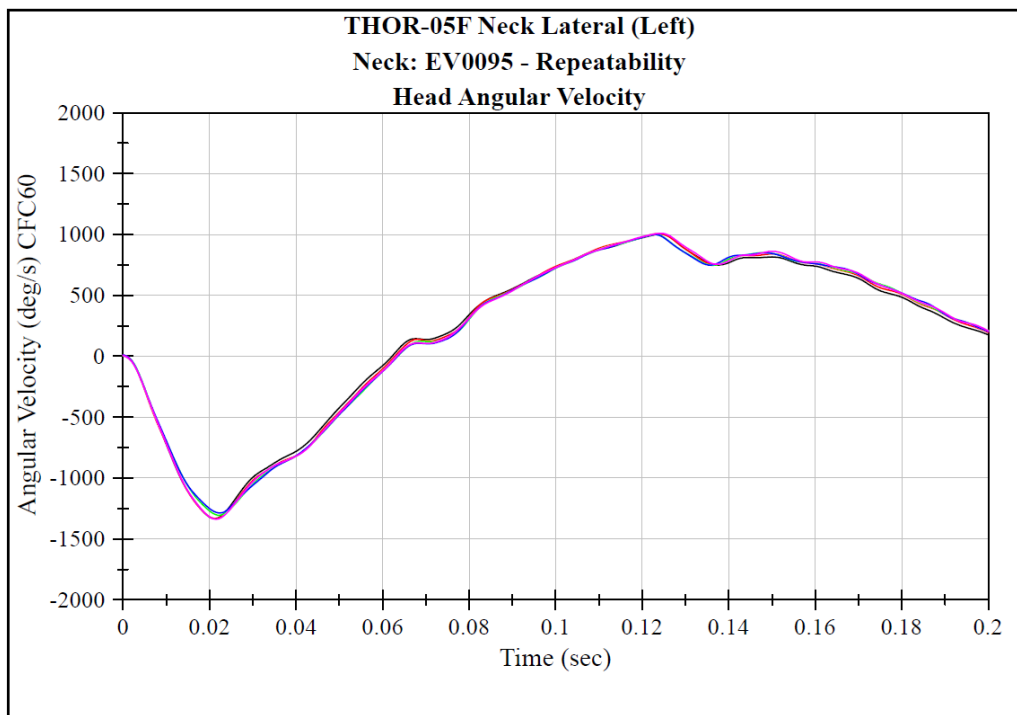


Figure 8-15. VRTC neck left lateral flexion head angular velocity about X repeatability for THOR-05F Neck EV0095

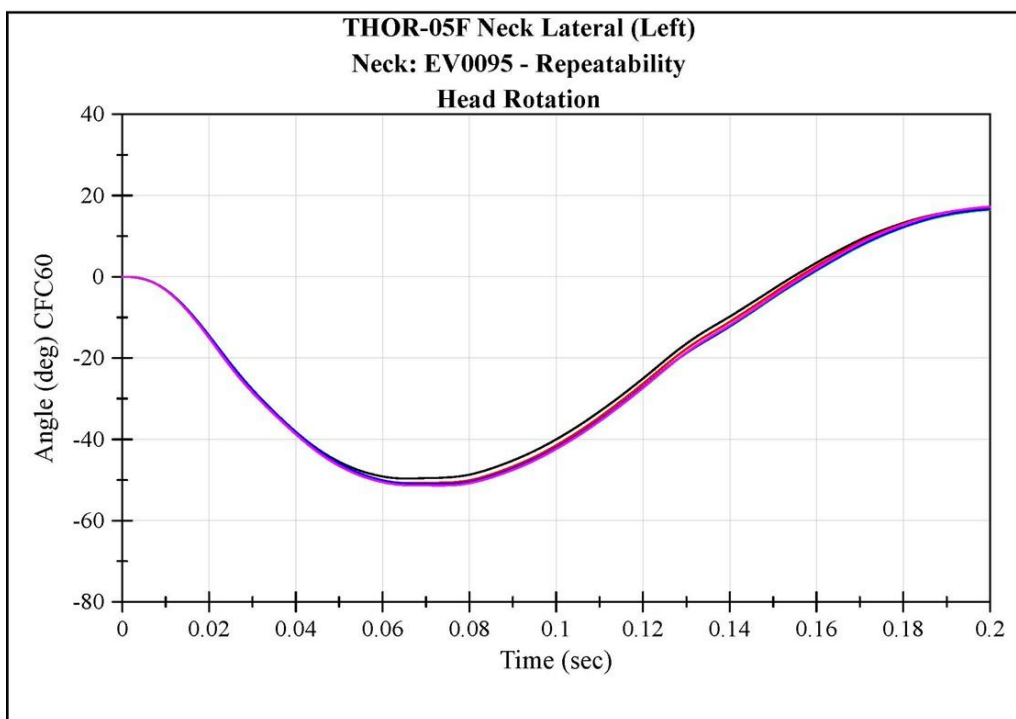


Figure 8-16. VRTC neck left lateral head rotation repeatability for THOR-05F Neck EV0095

8.2.6 THOR-05F Neck EV0095 Right Testing at VRTC

Repeatability results for right neck lateral flexion testing on Neck EV0095 (removed from ATD EV4675) at VRTC yielded CV values below 5 percent (Table 8-11 through Table 8-12, Figure 8-17 through Figure 8-19).

Table 8-11. VRTC EV0095 Right Lateral Flexion Pulse Repeatability Results

Test Number	Pendulum Velocity at 5 ms after T0 (m/s)	Pendulum Velocity at 10 ms after T0 (m/s)	Pendulum Velocity at 15 ms after T0 (m/s)
241127-1	0.99	2.07	3.02
241127-2	0.98	2.02	2.90
241127-3	0.98	2.11	3.04
241127-4	1.01	2.11	3.00
241127-5	1.01	2.15	3.03
Mean	0.99	2.09	3.00
Standard Deviation	0.02	0.05	0.06
CV	1.5%	2.3%	1.9%

Table 8-12. VRTC EV0095 Right Lateral Flexion Repeatability Results

Test Number	Minimum Upper Neck M _x after 40 ms (Nm)	Maximum Head ω _x (deg/s)	Maximum Head θ _x (deg)
241127-1	-30.1	1,325	50.3
241127-2	-29.1	1,303	51.3
241127-3	-29.5	1,329	51.7
241127-4	-29.4	1,313	51.2
241127-5	-29.4	1,325	51.5
Mean	-29.5	1,319	51.2
Standard Deviation	0.36	10.5	0.54
CV	1.2%	0.8%	1.0%

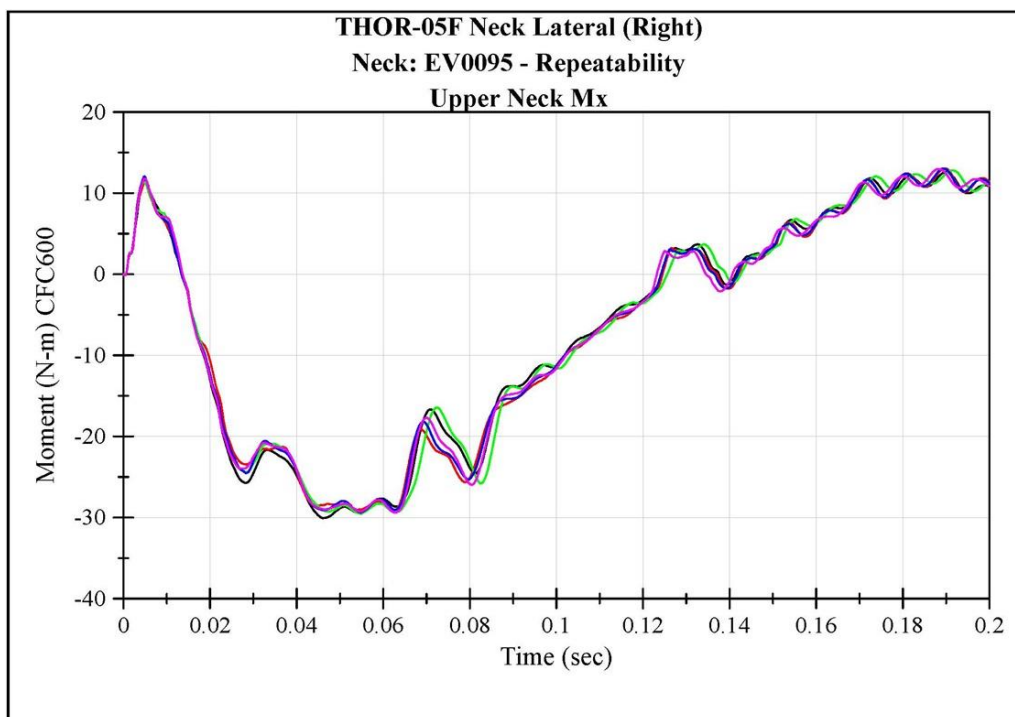


Figure 8-17. VRTC neck right lateral flexion upper neck moment Mx repeatability for THOR-05F Neck EV0095

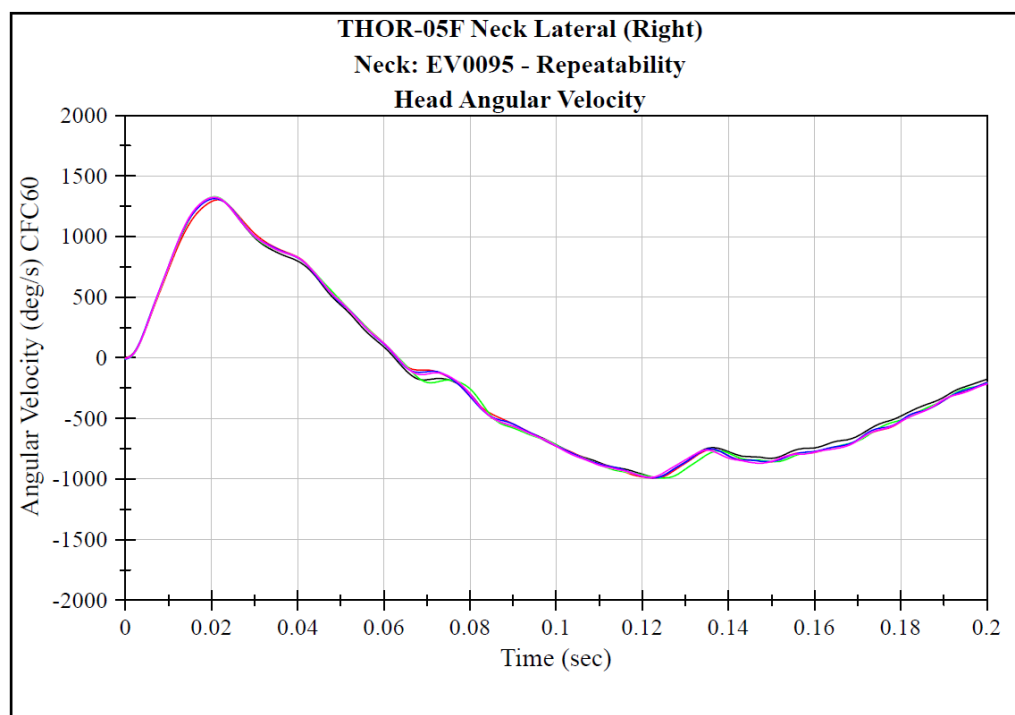


Figure 8-18. VRTC neck right lateral flexion head angular velocity about X repeatability for THOR-05F Neck EV0095

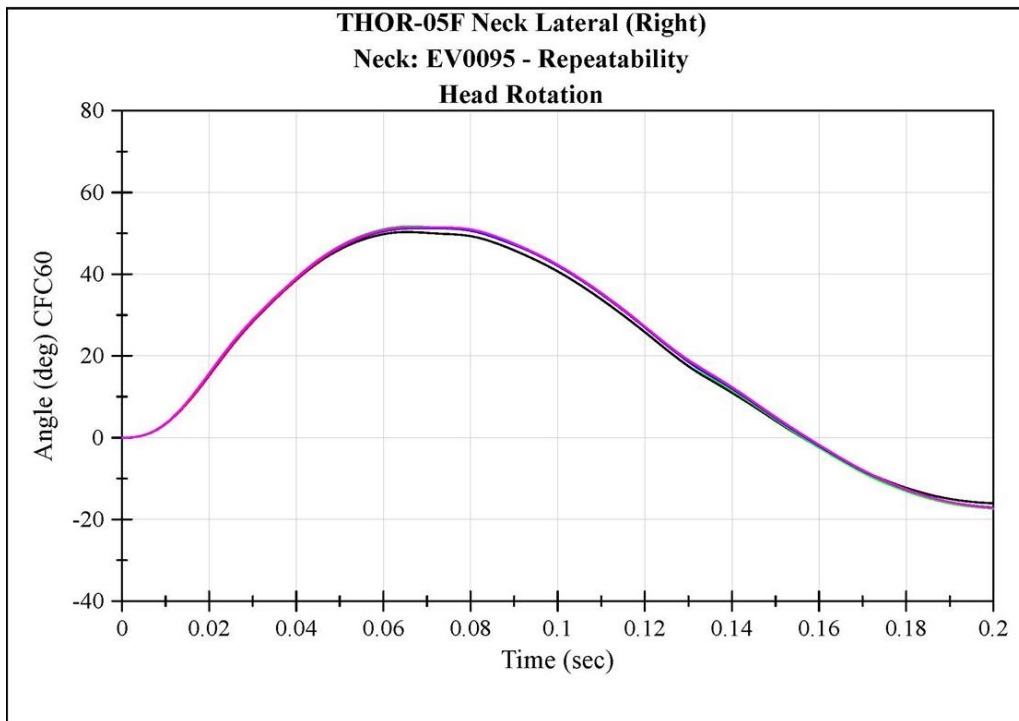


Figure 8-19. VRTC neck right lateral flexion head rotation repeatability for THOR-05F Neck EV0095

8.2.7 THOR-05F Neck EV0095 Left Testing at Humanetics

Repeatability results for neck left lateral flexion testing on Neck EV0095 (removed from ATD EV4675) at Humanetics yielded CV values below 5 percent for upper neck moment, head angular velocity, and rotation, and above 5 percent, but under 10 percent for all velocities (Table 8-13 through Table 8-14, Figure 8-20 through Figure 8-22).

Table 8-13. Humanetics THOR-05F Neck EV0095 Left Lateral Flexion Pulse Repeatability Results

Test Number	Pendulum Velocity at 5 ms after T0 (m/s)	Pendulum Velocity at 10 ms after T0 (m/s)	Pendulum Velocity at 15 ms after T0 (m/s)
686129	1.01	2.09	3.08
686057	0.94	1.95	2.90
686096	0.91	1.94	2.84
686111	1.04	2.18	3.23
686105	1.08	2.24	3.26
Mean	1.00	2.08	3.06
Standard Deviation	0.07	0.13	0.19
CV	7.0%	6.5%	6.2%

Table 8-14. Humanetics THOR-05F Neck EV0095 Left Lateral Flexion Repeatability Results

Test Number	Maximum Upper Neck M_x after 40 ms (Nm)	Minimum Head ω_x (deg/s)	Minimum Head θ_x (deg)
686129	31.9	-1,330	-50.1
686057	30.8	-1,307	-49.7
686096	30.1	-1,289	-48.8
686111	33.1	-1,360	-50.1
686105	32.5	-1,358	-49.7
Mean	31.7	-1,329	-49.7
Standard Deviation	1.20	31.0	0.52
CV	3.8%	2.3%	1.1%

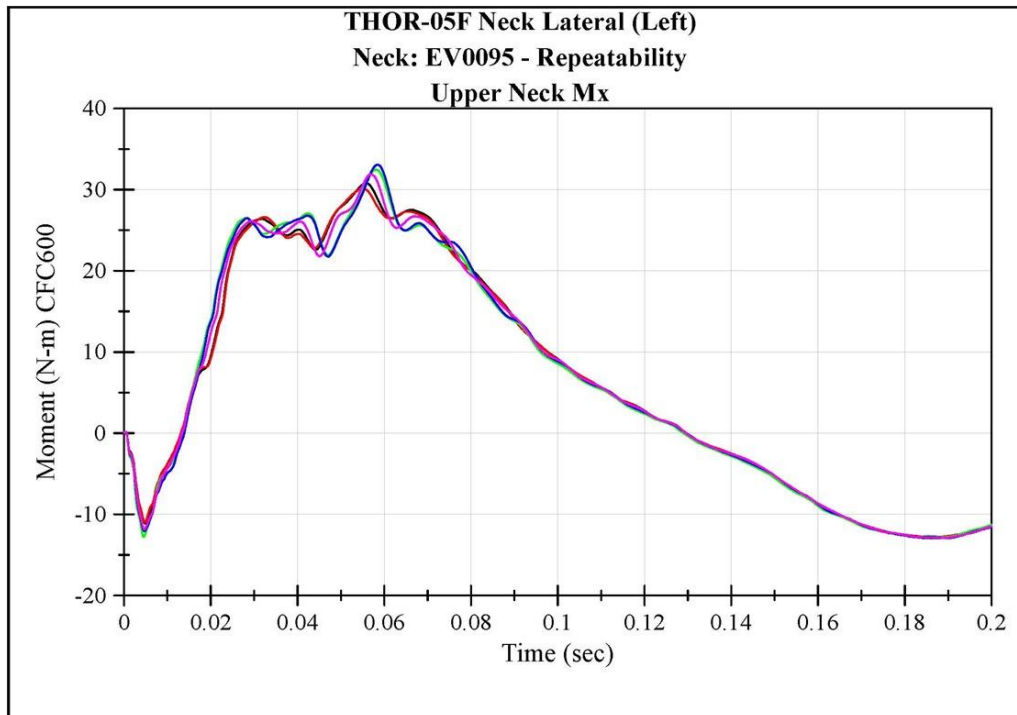


Figure 8-20. Humanetics neck left lateral flexion upper neck moment Mx repeatability for THOR-05F Neck EV0095

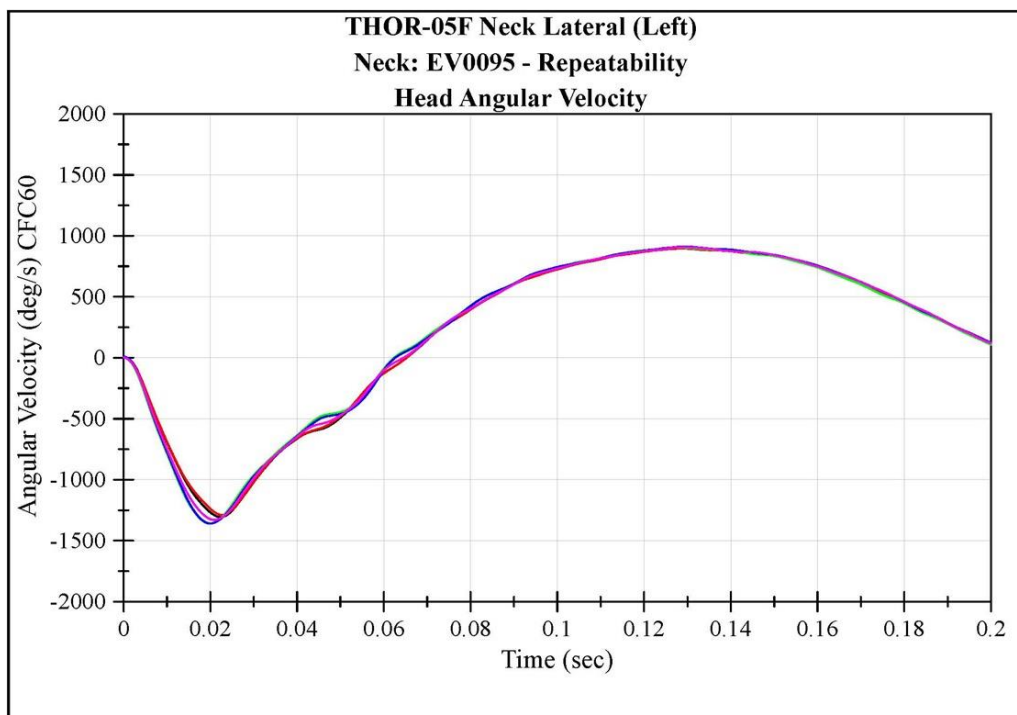


Figure 8-21. Humanetics neck left lateral flexion head angular velocity about X repeatability for THOR-05F Neck EV0095

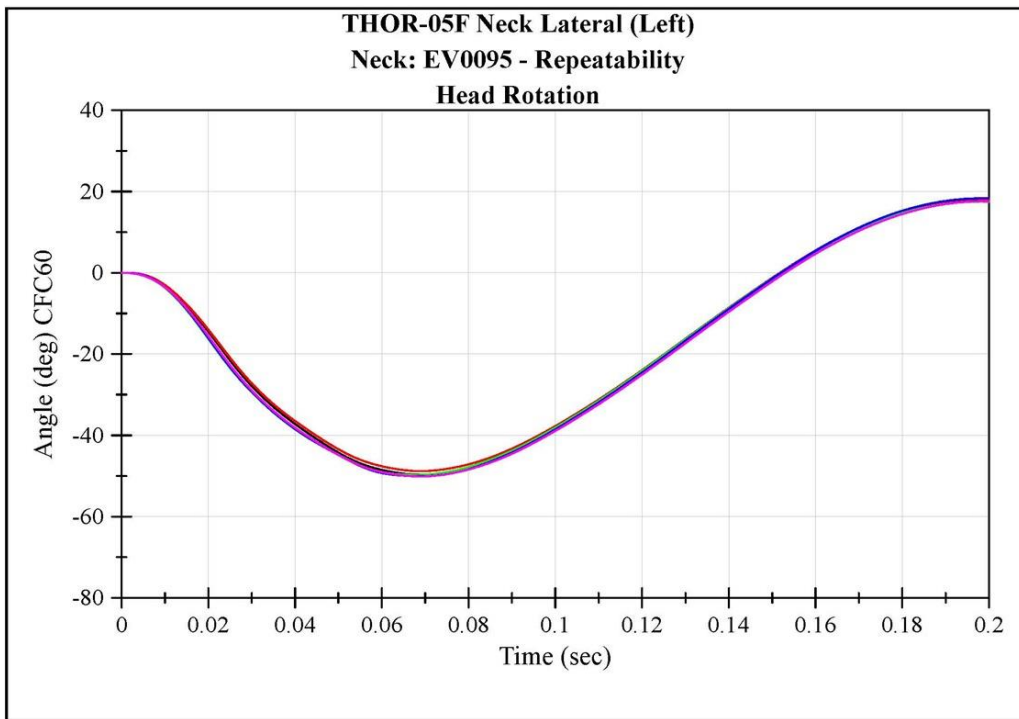


Figure 8-22. Humanetics neck left lateral head rotation repeatability for THOR-05F Neck EV0095

8.2.8 THOR-05F Neck EV0095 Right Testing at Humanetics

Repeatability results for neck right lateral flexion testing on Neck EV0095 (removed from ATD EV4675) at Humanetics for right lateral flexion yielded CV values below 5 percent (Table 8-15 through Table 8-16, Figure 8-23 through Figure 8-25).

Table 8-15. Humanetics THOR-05F Neck EV0095 Right Lateral Flexion Pulse Repeatability Results

Test Number	Pendulum Velocity at 5 ms after T0 (m/s)	Pendulum Velocity at 10 ms after T0 (m/s)	Pendulum Velocity at 15 ms after T0 (m/s)
686407	0.95	1.97	2.88
686403	0.99	2.04	2.97
686398	0.98	2.04	2.97
686395	0.99	2.01	2.97
686314	1.01	2.07	3.06
Mean	0.98	2.03	2.97
Standard Deviation	0.02	0.04	0.06
CV	2.2%	1.9%	2.1%

Table 8-16. Humanetics THOR-05F Neck EV0095 Right Lateral Flexion Repeatability Results

Test Number	Minimum Upper Neck M _x after 40 ms (Nm)	Maximum Head ω _x (deg/s)	Maximum Head θ _x (deg)
686407	-30.0	1,290	50.0
686403	-30.7	1,298	50.1
686398	-31.2	1,315	50.2
686395	-30.6	1,297	49.9
686314	-31.5	1,331	48.4
Mean	-30.8	1,306	49.7
Standard Deviation	0.57	16.8	0.75
CV	1.8%	1.3%	1.5%

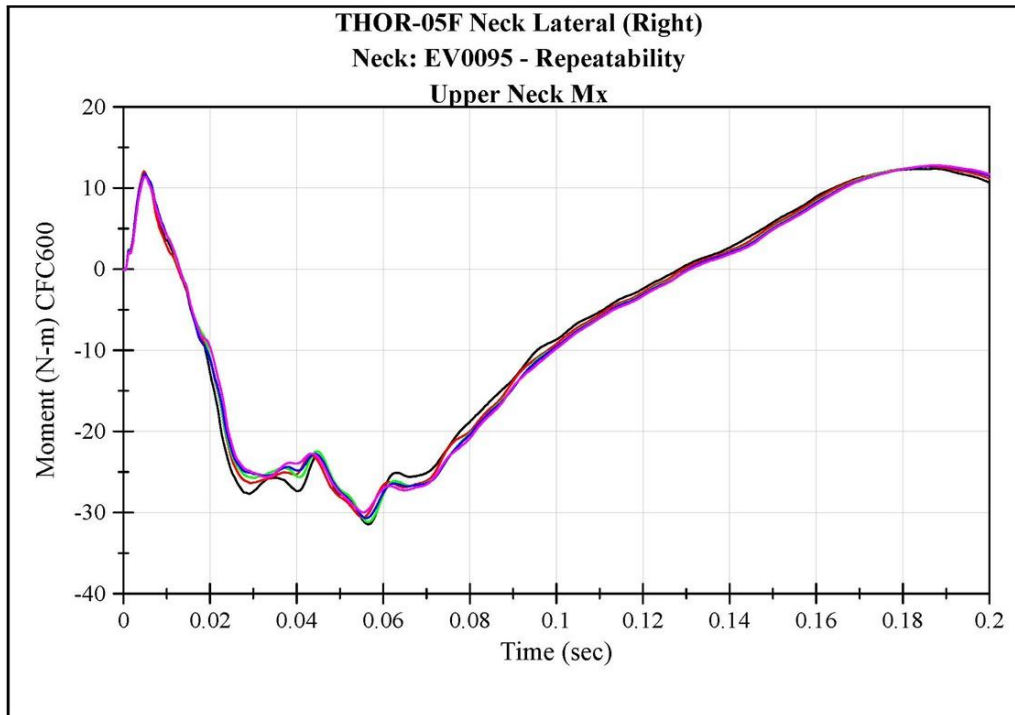


Figure 8-23. Humanetics neck right lateral flexion upper neck moment Mx repeatability for THOR-05F Neck EV0095

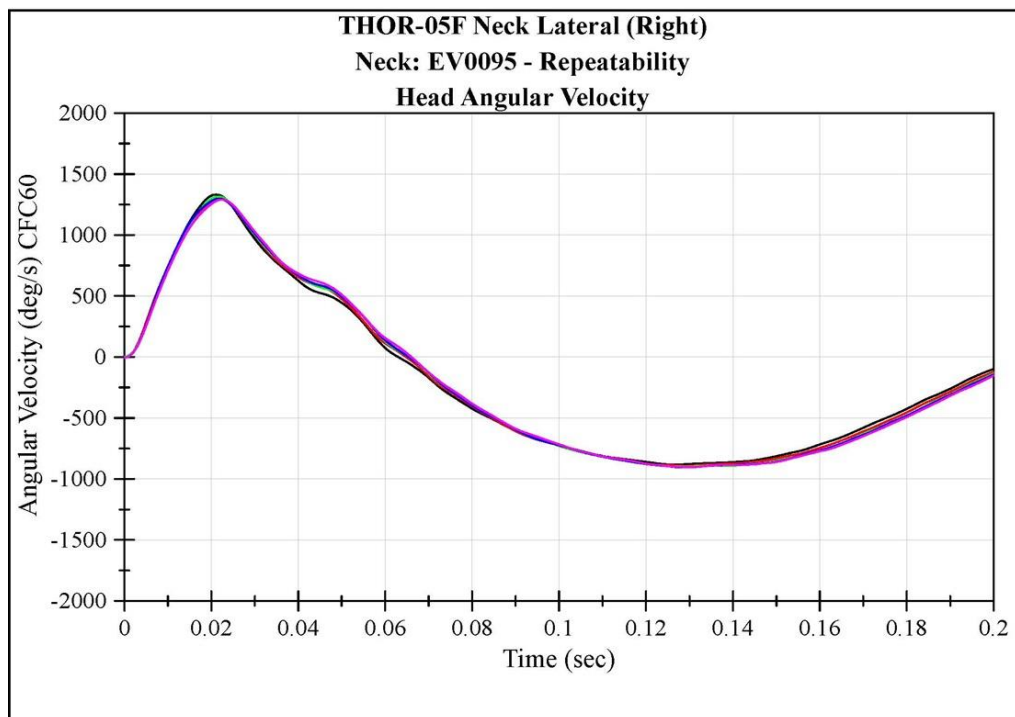


Figure 8-24. Humanetics neck right lateral flexion head angular velocity about X repeatability for THOR-05F Neck EV0095

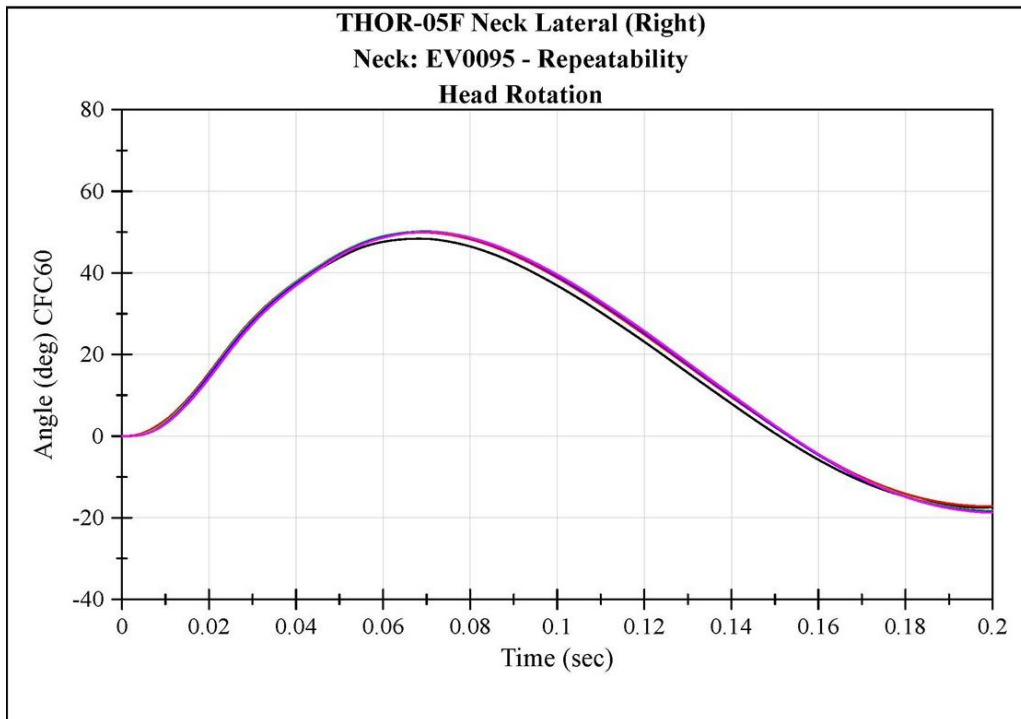


Figure 8-25. Humanetics neck right lateral flexion head rotation repeatability for THOR-05F Neck EV0095

8.2.9 THOR-05F Neck EV0095 Left Testing at Calspan

Repeatability results for neck left lateral flexion testing on Neck EV0095 (removed from ATD EV4675) at Calspan yielded CV values below 5 percent (Table 8-17 through Table 8-18, Figure 8-26 through Figure 8-28).

Table 8-17. Calspan THOR-05F Neck EV0095 Left Lateral Flexion Pulse Repeatability Results

Test Number	Pendulum Velocity at 5 ms after T0 (m/s)	Pendulum Velocity at 10 ms after T0 (m/s)	Pendulum Velocity at 15 ms after T0 (m/s)
2025_03_26 18_52	0.96	2.13	3.21
2025_03_26 19_45	0.94	2.15	3.21
2025_03_26 20_18	1.01	2.22	3.29
2025_03_26 20_56	0.97	2.19	3.29
2025_03_26 21_29	1.00	2.24	3.29
Mean	0.98	2.19	3.26
Standard Deviation	0.03	0.05	0.04
CV	3.0%	2.1%	1.3%

Table 8-18. Calspan THOR-05F Neck EV0095 Left Lateral Flexion Repeatability Results

Test Number	Maximum Upper Neck M_x after 40 ms (Nm)	Minimum Head ω_x (deg/s)	Minimum Head θ_x (deg)
2025_03_26 18_52	33.4	-1,449	-38.5
2025_03_26 19_45	33.2	-1,459	-39.6
2025_03_26 20_18	33.4	-1,469	-39.3
2025_03_26 20_56	33.4	-1,471	-39.6
2025_03_26 21_29	33.1	-1,462	-39.6
Mean	33.3	-1,462	-39.3
Standard Deviation	0.16	9.1	0.48
CV	0.5%	0.6%	1.2%

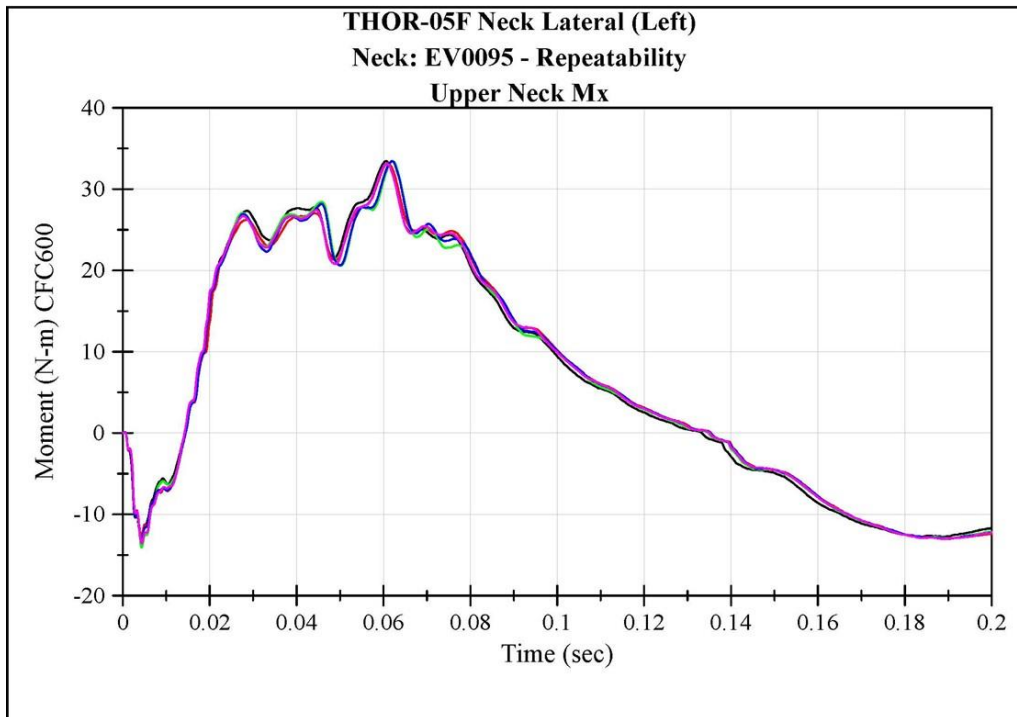


Figure 8-26. Calspan neck left lateral flexion upper neck moment Mx repeatability for THOR-05F Neck EV0095

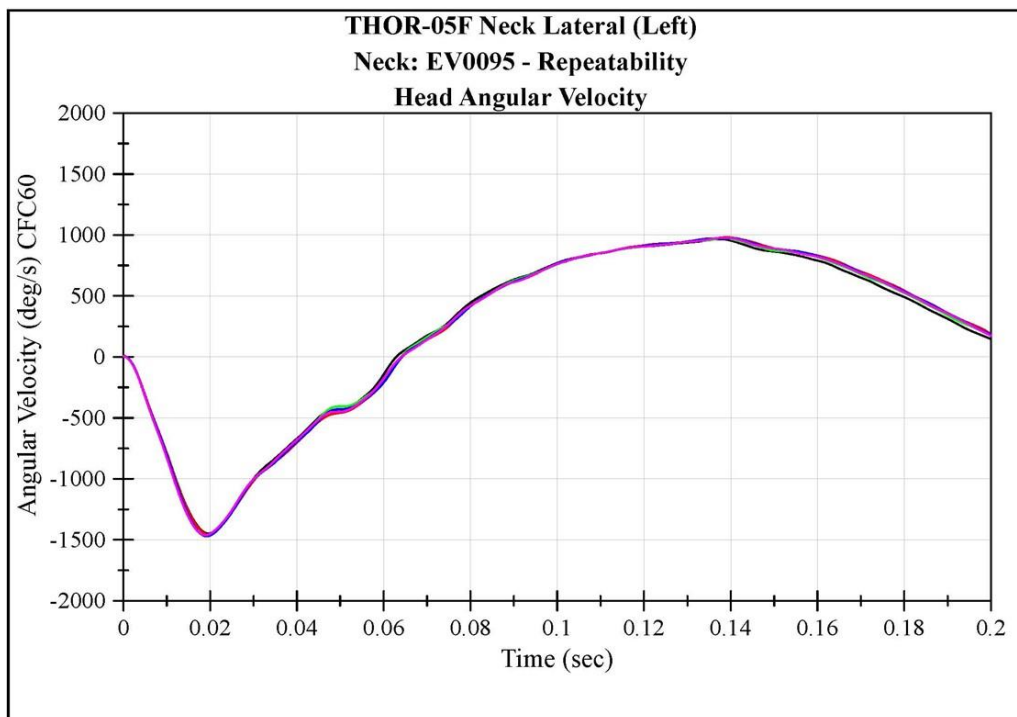


Figure 8-27. Calspan neck left lateral flexion head angular velocity about X repeatability for THOR-05F Neck EV0095

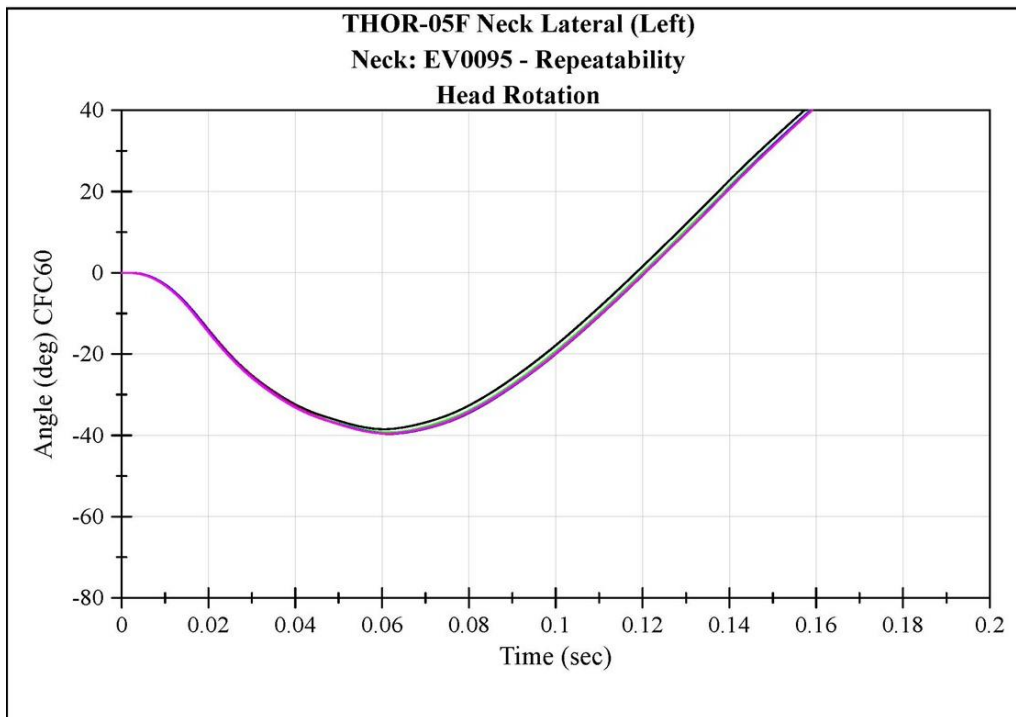


Figure 8-28. Calspan neck left lateral head rotation repeatability for THOR-05F Neck EV0095

8.2.10 THOR-05F Neck EV0095 Right Testing at Calspan

Repeatability results for neck right lateral flexion testing on Neck EV0095 (removed from ATD EV4675) at Calspan yielded CV values below 5 percent (Table 8-19 through Table 8-20, Figure 8-29 through Figure 8-31).

Table 8-19. Calspan THOR-05F Neck EV0095 Right Lateral Flexion Pulse Repeatability Results

Test Number	Pendulum Velocity at 5 ms after T0 (m/s)	Pendulum Velocity at 10 ms after T0 (m/s)	Pendulum Velocity at 15 ms after T0 (m/s)
2025_03_27 07_58	0.98	2.19	3.27
2025_03_27 08_33	1.00	2.20	3.25
2025_03_27 09_07	0.98	2.13	3.18
2025_03_27 09_40	0.96	2.12	3.16
2025_03_27 10_16	0.98	2.18	3.27
Mean	0.98	2.16	3.23
Standard Deviation	0.01	0.04	0.05
CV	1.4%	1.7%	1.6%

Table 8-20. Calspan THOR-05F Neck EV0095 Right Lateral Flexion Repeatability Results

Test Number	Minimum Upper Neck M _x after 40 ms (Nm)	Maximum Head ω _x (deg/s)	Maximum Head θ _x (deg)
2025_03_27 07_58	-32.9	1,472	38.9
2025_03_27 08_33	-32.8	1,453	38.9
2025_03_27 09_07	-32.9	1,447	39.8
2025_03_27 09_40	-32.6	1,438	39.3
2025_03_27 10_16	-32.9	1,462	39.3
Mean	-32.8	1,454	39.2
Standard Deviation	0.13	13.3	0.37
CV	0.4%	0.9%	0.9%

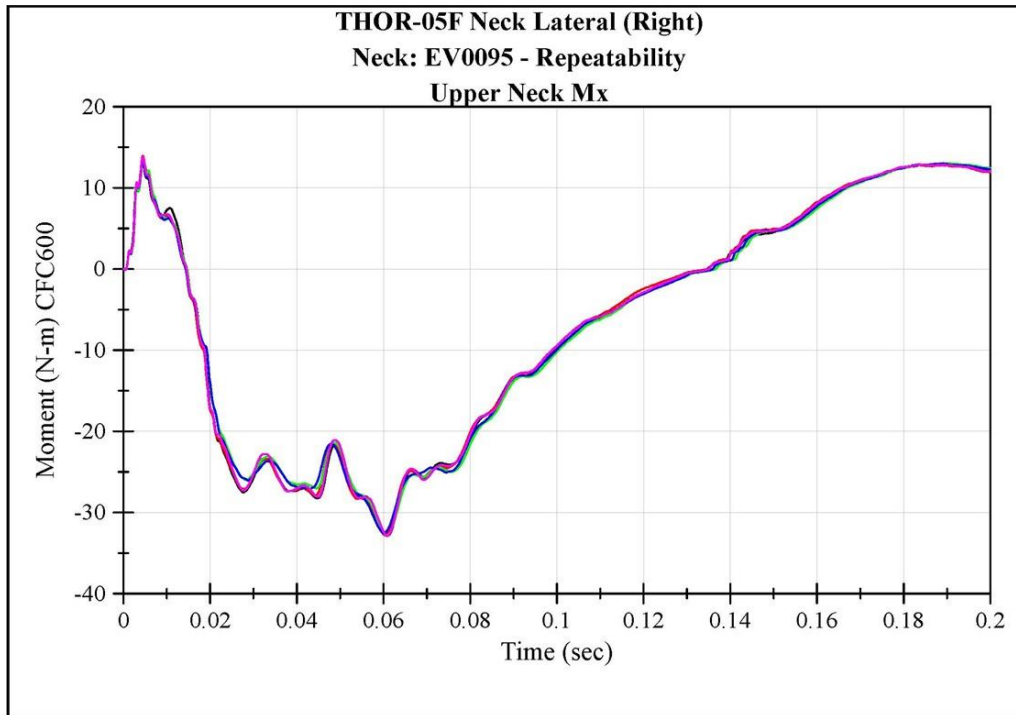


Figure 8-29. Calspan neck right lateral flexion upper neck moment Mx repeatability for THOR-05F Neck EV0095

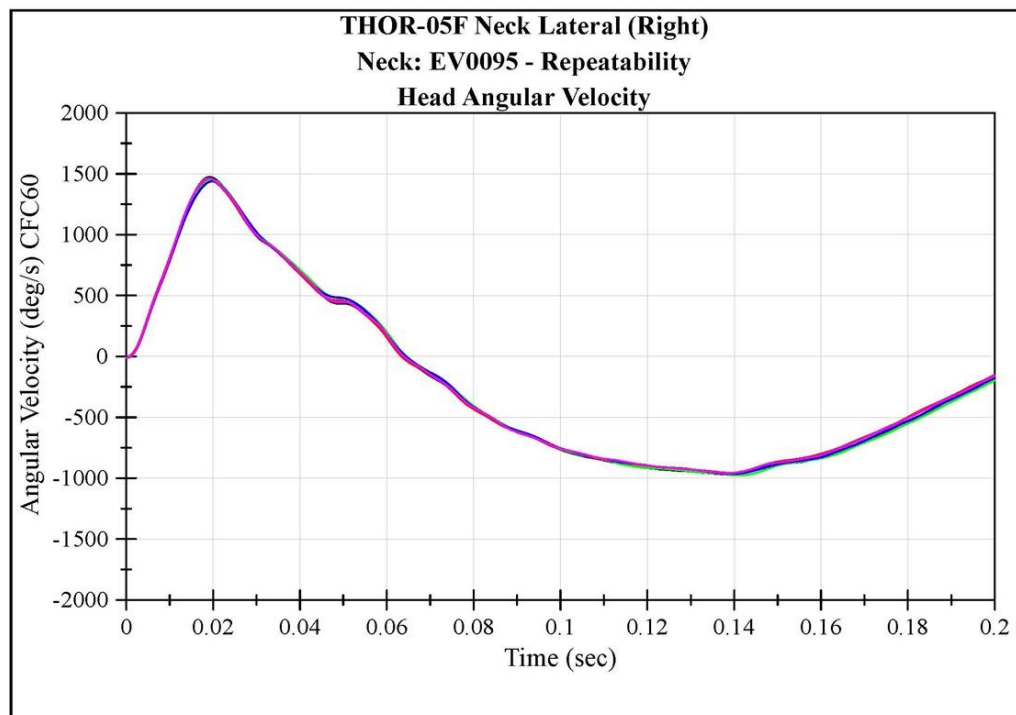


Figure 8-30. Calspan neck right lateral flexion head angular velocity about X repeatability for THOR-05F Neck EV0095

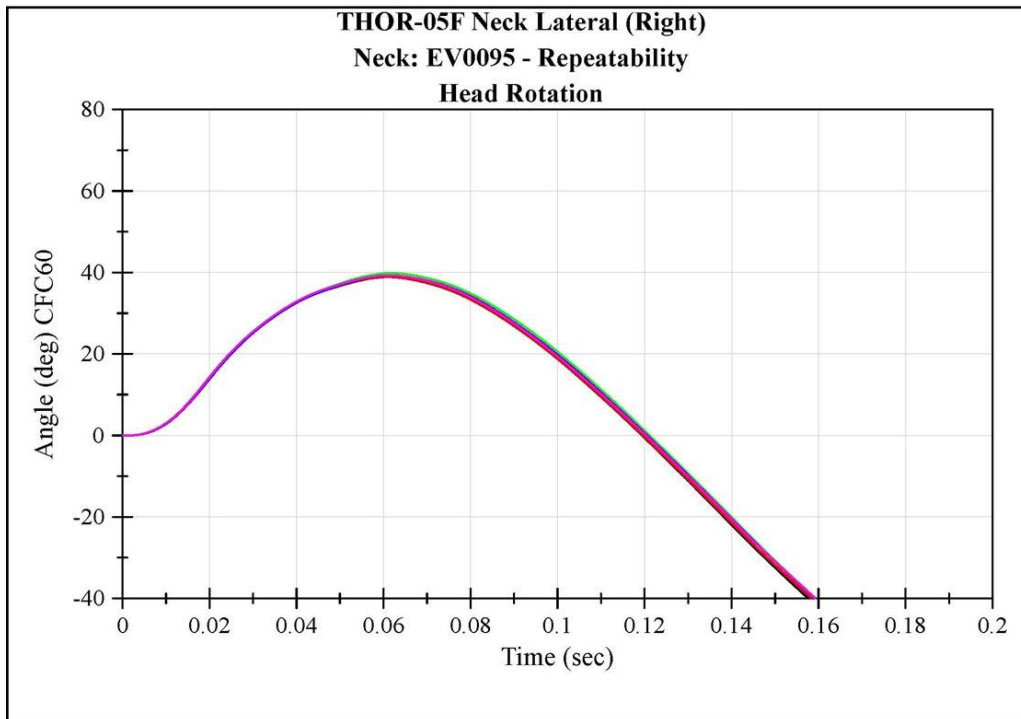


Figure 8-31. Calspan neck right lateral flexion head rotation repeatability for THOR-05F Neck EV0095

8.2.11 THOR-05F Neck EV0095 Left Testing at TRC

Repeatability results for neck left lateral flexion testing on Neck EV0095 (removed from ATD EV4675) at TRC yielded CV values below 5 percent (Table 8-21 through Table 8-22, Figure 8-32 through Figure 8-34).

Table 8-21. TRC THOR-05F Neck EV0095 Left Lateral Flexion Pulse Repeatability Results

Test Number	Pendulum Velocity at 5 ms after T0 (m/s)	Pendulum Velocity at 10 ms after T0 (m/s)	Pendulum Velocity at 15 ms after T0 (m/s)
2025_05_01 11_25	1.05	2.15	3.01
2025_05_01 11_46	1.09	2.22	3.18
2025_05_01 12_44	1.07	2.20	3.05
2025_05_01 13_16	1.08	2.19	3.15
2025_05_01 14_33	1.03	2.18	3.18
Mean	1.06	2.19	3.11
Standard Deviation	0.02	0.03	0.08
CV	2.3%	1.2%	2.5%

Table 8-22. TRC THOR-05F Neck EV0095 Left Lateral Flexion Repeatability Results

Test Number	Maximum Upper Neck M_x after 40 ms (Nm)	Minimum Head ω_x (deg/s)	Minimum Head θ_x (deg)
2025_05_01 11_25	29.8	-1,341	-51.2
2025_05_01 11_46	31.2	-1,377	-51.5
2025_05_01 12_44	29.4	-1,355	-51.8
2025_05_01 13_16	31.1	-1,381	-51.2
2025_05_01 14_33	30.5	-1,382	-51.4
Mean	30.4	-1,367	-51.4
Standard Deviation	0.80	18.4	0.23
CV	2.6%	1.3%	0.5%

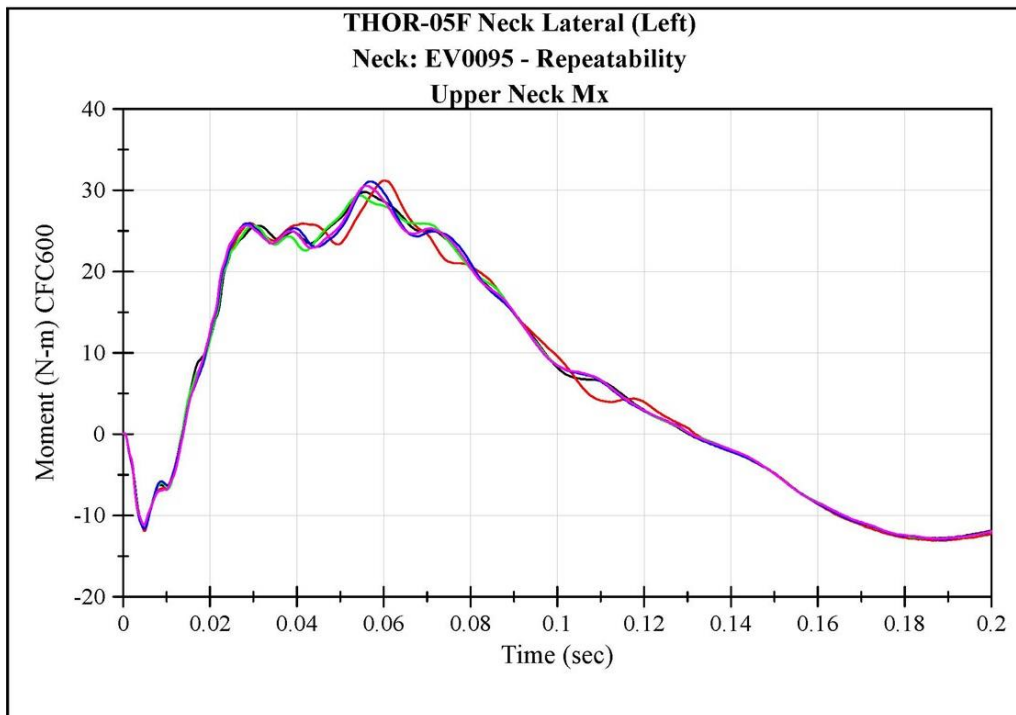


Figure 8-32. TRC neck left lateral flexion upper neck moment Mx repeatability for THOR-05F Neck EV0095

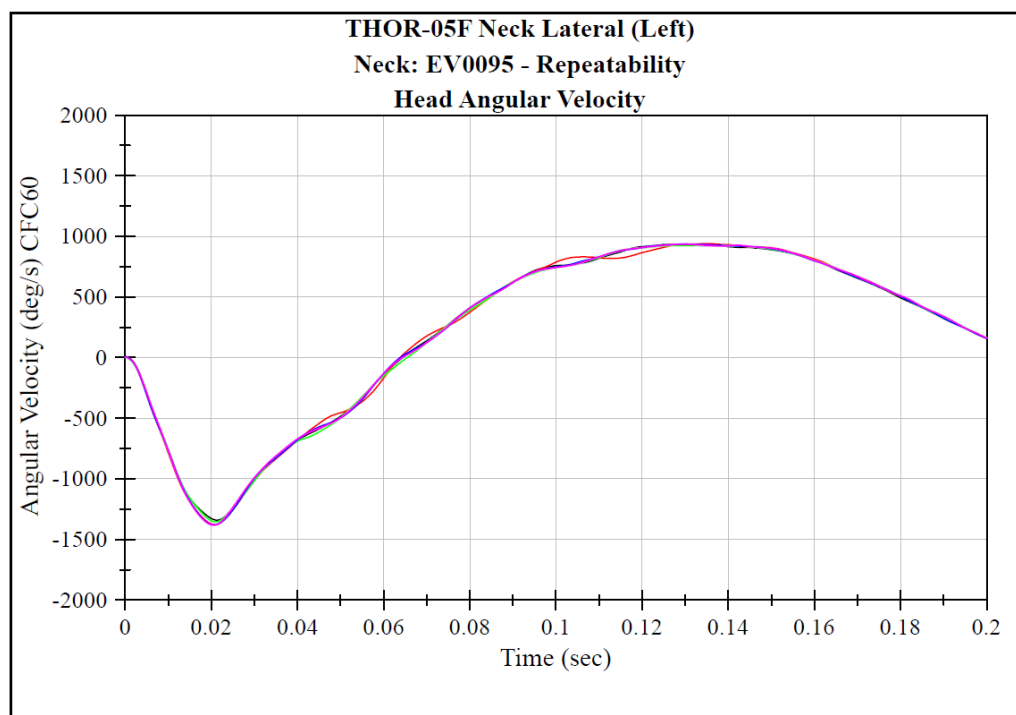


Figure 8-33. TRC neck left lateral flexion head angular velocity about X repeatability for THOR-05F Neck EV0095

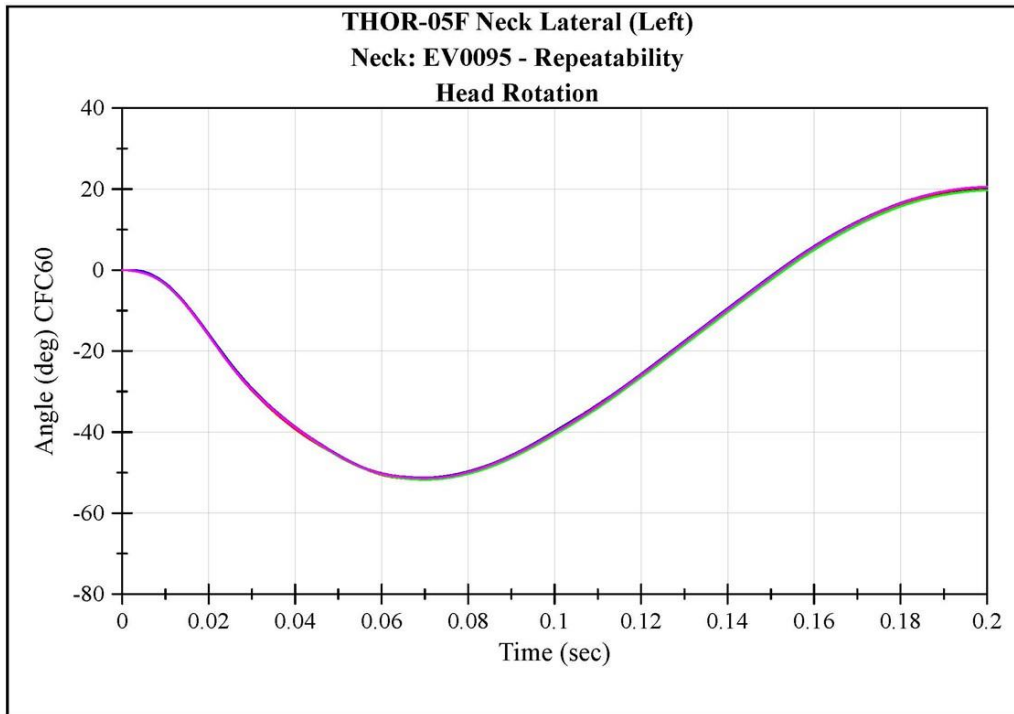


Figure 8-34. TRC neck left lateral head rotation repeatability for THOR-05F Neck EV0095

8.2.12 THOR-05F Neck EV0095 Right Testing at TRC

Repeatability results for neck right lateral flexion testing on Neck EV0095 (removed from ATD EV4675) at TRC yielded CV values below 5 percent (Table 8-23 through Table 8-24, Figure 8-35 through Figure 8-37).

Table 8-23. TRC THOR-05F Neck EV0095 Right Lateral Flexion Pulse Repeatability Results

Test Number	Pendulum Velocity at 5 ms after T0 (m/s)	Pendulum Velocity at 10 ms after T0 (m/s)	Pendulum Velocity at 15 ms after T0 (m/s)
2025_05_02 07_51	1.07	2.27	3.18
2025_05_02 08_11	1.08	2.24	3.24
2025_05_02 08_53	1.03	2.18	3.20
2025_05_02 09_17	1.03	2.22	3.27
2025_05_02 10_01	1.09	2.21	3.27
Mean	1.06	2.22	3.23
Standard Deviation	0.03	0.03	0.04
CV	2.7%	1.5%	1.3%

Table 8-24. TRC THOR-05F Neck EV0095 Right Lateral Flexion Repeatability Results

Test Number	Minimum Upper Neck M _x after 40 ms (Nm)	Maximum Head ω _x (deg/s)	Maximum Head θ _x (deg)
2025_05_02 07_51	-30.2	1,371	50.3
2025_05_02 08_11	-31.5	1,389	51.7
2025_05_02 08_53	-31.2	1,389	51.6
2025_05_02 09_17	-31.9	1,403	51.8
2025_05_02 10_01	-31.9	1,401	51.9
Mean	-31.3	1,391	51.5
Standard Deviation	0.69	13.0	0.66
CV	2.2%	0.9%	1.3%

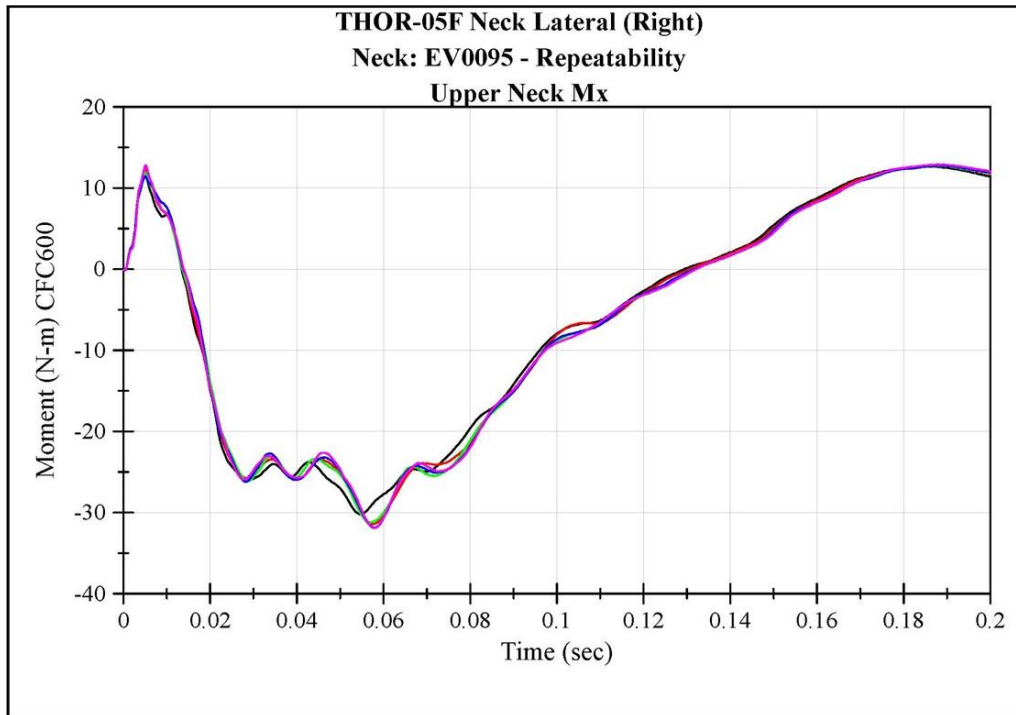


Figure 8-35. TRC neck right lateral flexion upper neck moment Mx repeatability for THOR-05F Neck EV0095

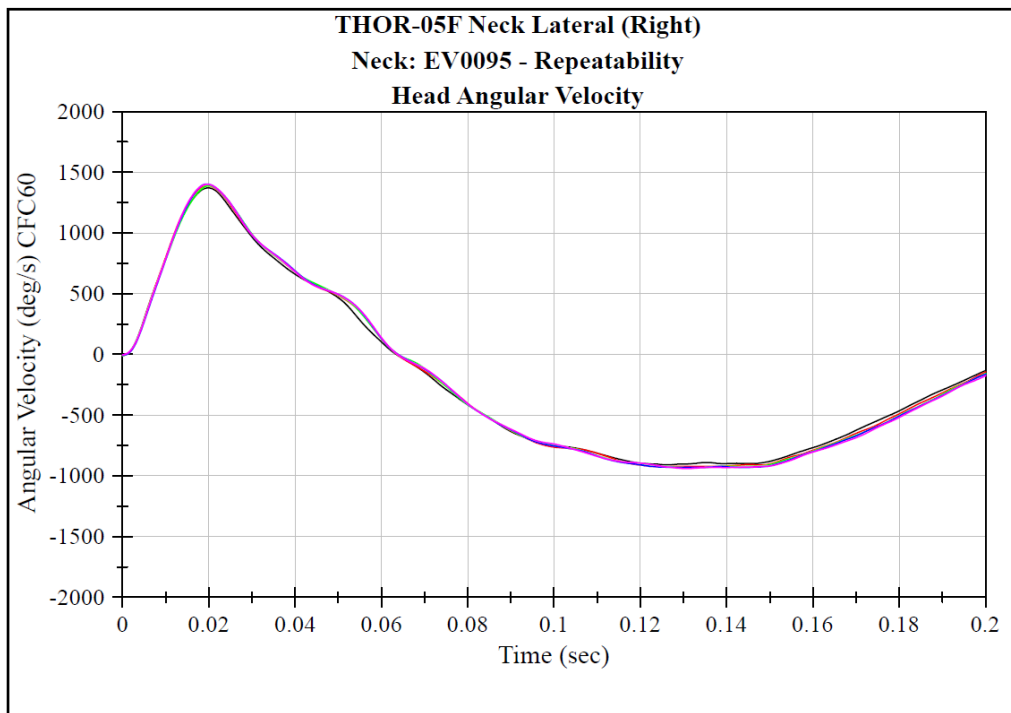


Figure 8-36. TRC neck right lateral flexion head angular velocity about X repeatability for THOR-05F Neck EV0095

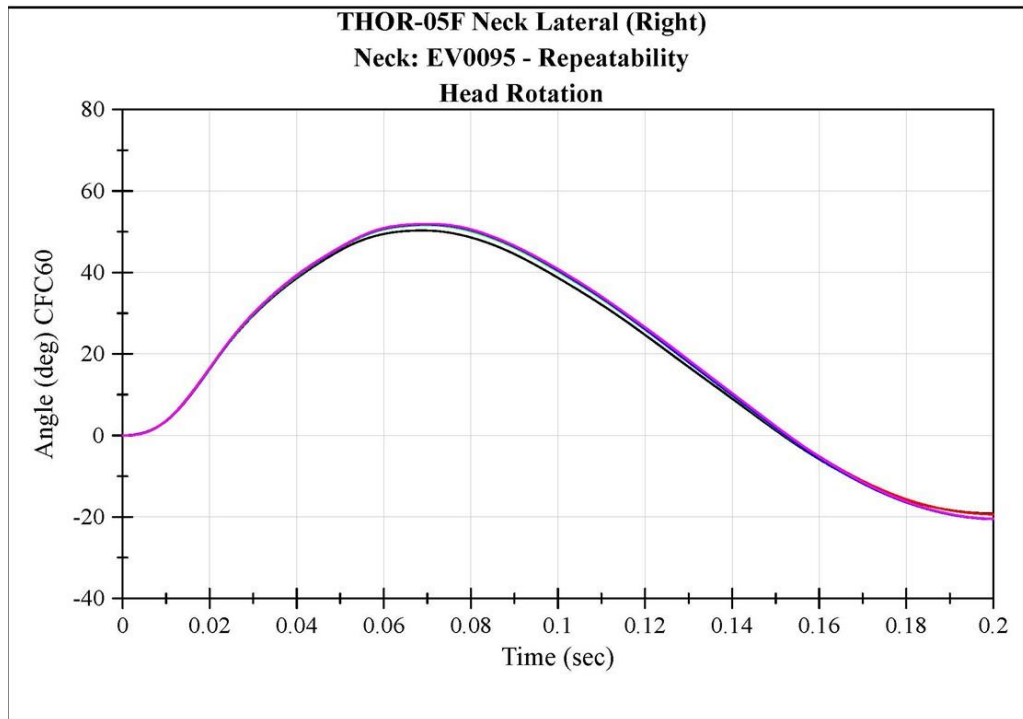


Figure 8-37. TRC neck right lateral flexion head rotation repeatability for THOR-05F Neck EV0095

8.3 Neck Lateral Flexion Dummy Reproducibility Results

Dummy Reproducibility results at VRTC for neck lateral flexion yielded CV values below the 5 percent (Table 8-25 and Table 8-26).

Table 8-25. THOR-05F Neck Lateral Flexion Pulse Reproducibility Results

Neck Number	Test Number	Pendulum Velocity at 5 ms after T0 (m/s)	Pendulum Velocity at 10 ms after T0 (m/s)	Pendulum Velocity at 15 ms after T0 (m/s)
VRTC THOR-05F EV9863 Left Neck EU9734	240327-5	0.94	2.00	2.93
	240327-6	0.98	2.07	3.00
	240327-7	1.01	2.10	2.95
	240327-8	1.02	2.08	3.01
	240327-9	0.99	2.03	2.98
VRTC THOR-05F EV0674 Left Neck EV1357	240531-2	0.99	2.05	2.97
	240531-3	0.98	2.03	2.98
	240531-4	1.04	2.11	3.03
	240531-5	0.97	2.00	2.87
	240531-6	0.95	1.99	2.85
VRTC THOR-05F EV4675 Left Neck EV0095	241126-11	0.95	2.05	2.96
	241126-12	0.99	2.02	2.94
	241126-13	0.96	1.96	2.81
	241126-14	0.93	1.95	2.78
	241126-15	0.97	2.02	2.91
VRTC THOR-05F EV9863 Right Neck EU9734	240327-10	1.03	2.09	3.05
	240327-11	1.02	2.14	3.10
	240327-12	0.99	2.03	2.92
	240327-13	1.00	2.12	3.07
	240327-14	0.98	2.03	2.92
VRTC THOR-05F EV0674 Right Neck EV1357	240531-7	0.98	2.05	3.01
	240605-13	0.99	2.02	2.93
	240605-14	0.97	2.02	2.95
	240605-15	1.04	2.15	3.10
	240605-16	0.95	1.98	2.90
VRTC THOR-05F EV4675 Right Neck EV0095	241127-1	0.99	2.07	3.02
	241127-2	0.98	2.02	2.90
	241127-3	0.98	2.11	3.04
	241127-4	1.01	2.11	3.00
	241127-5	1.01	2.15	3.03
Mean		0.99	2.05	2.96
Standard Deviation		0.03	0.06	0.08
CV		2.8%	2.7%	2.6%

Table 8-26. THOR-05F Left Neck Lateral Flexion Reproducibility Results

Test Number	Test Number	Max/Min Upper Neck M _x after 40 ms * (Nm)	Max/Min Head ω _x * (deg/s)	Max/Min Head θ _x * (deg)
VRTC THOR-05F EV9863 Left Neck EU9734	240327-5	29.4	1,355	51.7
	240327-6	28.6	1,373	53.1
	240327-7	28.1	1,349	53.9
	240327-8	28.3	1,385	54.8
	240327-9	28.2	1,380	54.4
VRTC THOR-05F EV0674 Left Neck EV1357	240531-2	31.2	1,309	50.4
	240531-3	31.2	1,317	50.3
	240531-4	31.0	1,318	50.8
	240531-5	30.7	1,303	50.6
	240531-6	30.2	1,282	50.7
VRTC THOR-05F EV4675 Left Neck EV0095	241126-11	29.6	1,333	49.6
	241126-12	29.3	1,334	50.8
	241126-13	29.0	1,305	51.0
	241126-14	28.7	1,287	51.0
	241126-15	29.0	1,338	51.4
VRTC THOR-05F EV9863 Right Neck EU9734	240327-10	29.2	1,390	53.6
	240327-11	28.8	1,396	54.5
	240327-12	28.3	1,350	54.5
	240327-13	28.4	1,389	54.9
	240327-14	28.1	1,355	54.6
VRTC THOR-05F EV0674 Right Neck EV1357	240531-7	31.2	1,315	49.3
	240605-13	31.2	1,292	49.5
	240605-14	31.1	1,305	50.7
	240605-15	31.5	1,319	50.7
	240605-16	30.7	1,298	50.6
VRTC THOR-05F EV4675 Right Neck EV0095	241127-1	30.1	1,325	50.3
	241127-2	29.1	1,303	51.3
	241127-3	29.5	1,329	51.7
	241127-4	29.4	1,313	51.2
	241127-5	29.4	1,325	51.5
Mean		29.6	1,332	51.8
Standard Deviation		1.12	33.0	1.77
CV		3.8%	2.5%	3.4%

*Absolute value is shown, as used in corridor determination

8.4 Lab-to-Lab Variability Analysis

The results of the neck lateral flexion qualification tests from each lab are presented in Table 8-27 and Table 8-28. The last three rows of the tables show the Test Reproducibility results when data from all four labs are combined. Test Reproducibility results at VRTC, Humanetics, Calspan, and TRC for the neck lateral flexion tests displayed CV values for all pendulum velocities are 5 percent or below (Table 8-27). The results yielded CV values for upper neck moment and head angular velocity below 5 percent (Table 8-28). Peak head rotation was above 10 percent for all labs combined.

Table 8-27. THOR-05F Neck Lateral Flexion Pulse Reproducibility Results

Neck Number	Test Number	Pendulum Velocity at 5 ms after T0 (m/s)	Pendulum Velocity at 10 ms after T0 (m/s)	Pendulum Velocity at 15 ms after T0 (m/s)
VRTC THOR-05F EV4675 Left Neck EV0095	241126-11	0.95	2.05	2.96
	241126-12	0.99	2.02	2.94
	241126-13	0.96	1.96	2.81
	241126-14	0.93	1.95	2.78
	241126-15	0.97	2.02	2.91
Humanetics THOR-05F EV4675 Left Neck EV0095	686129	1.01	2.09	3.08
	686057	0.94	1.95	2.90
	686096	0.91	1.94	2.84
	686111	1.04	2.18	3.23
	686105	1.08	2.24	3.26
Calspan THOR-05F EV4675 Left Neck EV0095	2025_03_26 18_52	0.96	2.13	3.21
	2025_03_26 19_45	0.94	2.15	3.21
	2025_03_26 20_18	1.01	2.22	3.29
	2025_03_26 20_56	0.97	2.19	3.29
	2025_03_26 21_29	1.00	2.24	3.29
TRC THOR-05F EV4675 Left Neck EV0095	2025_05_01 11_25	1.05	2.15	3.01
	2025_05_01 11_46	1.09	2.22	3.18
	2025_05_01 12_44	1.07	2.20	3.05
	2025_05_01 13_16	1.08	2.19	3.15
	2025_05_01 14_33	1.03	2.18	3.18
VRTC THOR-05F EV4675 Right Neck EV0095	241127-1	0.99	2.07	3.02
	241127-2	0.98	2.02	2.90
	241127-3	0.98	2.11	3.04
	241127-4	1.01	2.11	3.00
	241127-5	1.01	2.15	3.03
Humanetics THOR-05F EV4675 Right Neck EV0095	686407	0.95	1.97	2.88
	686403	0.99	2.04	2.97
	686398	0.98	2.04	2.97
	686395	0.99	2.01	2.97
	686314	1.01	2.07	3.06
Calspan THOR-05F EV4675 Right Neck EV0095	2025_03_27 07_58	0.98	2.19	3.27
	2025_03_27 08_33	1.00	2.20	3.25
	2025_03_27 09_07	0.98	2.13	3.18
	2025_03_27 09_40	0.96	2.12	3.16
	2025_03_27 10_16	0.98	2.18	3.27
TRC THOR-05F EV4675 Right Neck EV0095	2025_05_02 07_51	1.07	2.27	3.18
	2025_05_02 08_11	1.08	2.24	3.24
	2025_05_02 08_53	1.03	2.18	3.20
	2025_05_02 09_17	1.03	2.22	3.27
	2025_05_02 10_01	1.09	2.21	3.27
Test Reproducibility Neck EV0095				
Mean		1.00	2.12	3.09
Standard Deviation		0.05	0.10	0.15
CV		4.7%	4.5%	5.0%

Table 8-28. THOR-05F Neck Lateral Flexion Reproducibility Results

Neck Number	Test Number	Max/Min Upper Neck M _x after 40 ms * (Nm)	Max/Min Head ω _x * (deg/s)	Max/Min Head θ _x * (deg)
VRTC THOR-05F EV4675 Left Neck EV0095	241126-11	29.6	1,333	49.6
	241126-12	29.3	1,334	50.8
	241126-13	29.0	1,305	51.0
	241126-14	28.7	1,287	51.0
	241126-15	29.0	1,338	51.4
Humanetics THOR-05F EV4675 Left Neck EV0095	686129	31.9	1,330	50.1
	686057	30.8	1,307	49.7
	686096	30.1	1,289	48.8
	686111	33.1	1,360	50.1
	686105	32.5	1,358	49.7
Calspan THOR-05F EV4675 Left Neck EV0095	2025_03_26 18_52	33.4	1,449	38.5
	2025_03_26 19_45	33.2	1,459	39.6
	2025_03_26 20_18	33.4	1,469	39.3
	2025_03_26 20_56	33.4	1,471	39.6
	2025_03_26 21_29	33.1	1,462	39.6
TRC THOR-05F EV4675 Left Neck EV0095	2025_05_01 11_25	29.8	1,341	51.2
	2025_05_01 11_46	31.2	1,377	51.5
	2025_05_01 12_44	29.4	1,355	51.8
	2025_05_01 13_16	31.1	1,381	51.2
	2025_05_01 14_33	30.5	1,382	51.4
VRTC THOR-05F EV4675 Right Neck EV0095	241127-1	30.1	1,325	50.3
	241127-2	29.1	1,303	51.3
	241127-3	29.5	1,329	51.7
	241127-4	29.4	1,313	51.2
	241127-5	29.4	1,325	51.5
Humanetics THOR-05F EV4675 Right Neck EV0095	686407	30.0	1,290	50.0
	686403	30.7	1,298	50.1
	686398	31.2	1,315	50.2
	686395	30.6	1,297	49.9
	686314	31.5	1,331	48.4
Calspan THOR-05F EV4675 Right Neck EV0095	2025_03_27 07_58	32.9	1,472	38.9
	2025_03_27 08_33	32.8	1,453	38.9
	2025_03_27 09_07	32.9	1,447	39.8
	2025_03_27 09_40	32.6	1,438	39.3
	2025_03_27 10_16	32.9	1,462	39.3
TRC THOR-05F EV4675 Right Neck EV0095	2025_05_02 07_51	30.2	1,371	50.3
	2025_05_02 08_11	31.5	1,389	51.7
	2025_05_02 08_53	31.2	1,389	51.6
	2025_05_02 09_17	31.9	1,403	51.8
	2025_05_02 10_01	31.9	1,401	51.9
Test Reproducibility Neck EV0095				
Mean		31.1	1,368	47.8
Standard Deviation		1.51	61.0	5.08
CV		4.9%	4.5%	10.6%

8.5 Corridor Development

All the data used to determine the neck lateral flexion qualification corridors is shown in Table 8-29 and Table 8-30. The qualification corridors were calculated using the mean plus or minus 10 percent of the peak for the specified measured or calculated channels (Table 8-31).

Table 8-29. THOR-05F Neck Lateral Flexion Pulse Qualification Corridor Results

Neck Number		Test Number	Pendulum Velocity at 5 ms after T0 (m/s)	Pendulum Velocity at 10 ms after T0 (m/s)	Pendulum Velocity at 15 ms after T0 (m/s)
VRTC Neck EU9734	Left	240327-5	0.94	2.00	2.93
		240327-6	0.98	2.07	3.00
		240327-7	1.01	2.10	2.95
		240327-8	1.02	2.08	3.01
		240327-9	0.99	2.03	2.98
	Right	240327-10	1.03	2.09	3.05
		240327-11	1.02	2.14	3.10
		240327-12	0.99	2.03	2.92
		240327-13	1.00	2.12	3.07
		240327-14	0.98	2.03	2.92
VRTC Neck EV1357	Left	240531-2	0.99	2.05	2.97
		240531-3	0.98	2.03	2.98
		240531-4	1.04	2.11	3.03
		240531-5	0.97	2.00	2.87
		240531-6	0.95	1.99	2.85
	Right	240531-7	0.98	2.05	3.01
		240605-13	0.99	2.02	2.93
		240605-14	0.97	2.02	2.95
		240605-15	1.04	2.15	3.10
		240605-16	0.95	1.98	2.90
VRTC Neck EV0095	Left	241126-11	0.95	2.05	2.96
		241126-12	0.99	2.02	2.94
		241126-13	0.96	1.96	2.81
		241126-14	0.93	1.95	2.78
		241126-15	0.97	2.02	2.91
	Right	241127-1	0.99	2.07	3.02
		241127-2	0.98	2.02	2.90
		241127-3	0.98	2.11	3.04
		241127-4	1.01	2.11	3.00
		241127-5	1.01	2.15	3.03
Humanetics Neck EV0095	Left	686129	1.01	2.09	3.08
		686057	0.94	1.95	2.90
		686096	0.91	1.94	2.84
		686111	1.04	2.18	3.23
		686105	1.08	2.24	3.26
	Right	686407	0.95	1.97	2.88
		686403	0.99	2.04	2.97
		686398	0.98	2.04	2.97
		686395	0.99	2.01	2.97
		686314	1.01	2.07	3.06

Calspan Neck EV0095	Left	2025_03_26 18_52	0.96	2.13	3.21
		2025_03_26 19_45	0.94	2.15	3.21
		2025_03_26 20_18	1.01	2.22	3.29
		2025_03_26 20_56	0.97	2.19	3.29
		2025_03_26 21_29	1.00	2.24	3.29
	Right	2025_03_27 07_58	0.98	2.19	3.27
		2025_03_27 08_33	1.00	2.20	3.25
		2025_03_27 09_07	0.98	2.13	3.18
		2025_03_27 09_40	0.96	2.12	3.16
		2025_03_27 10_16	0.98	2.18	3.27
TRC Neck EV0095	Left	2025_05_01 11_25	1.05	2.15	3.01
		2025_05_01 11_46	1.09	2.22	3.18
		2025_05_01 12_44	1.07	2.20	3.05
		2025_05_01 13_16	1.08	2.19	3.15
		2025_05_01 14_33	1.03	2.18	3.18
	Right	2025_05_02 07_51	1.07	2.27	3.18
		2025_05_02 08_11	1.08	2.24	3.24
		2025_05_02 08_53	1.03	2.18	3.20
		2025_05_02 09_17	1.03	2.22	3.27
		2025_05_02 10_01	1.09	2.21	3.27
Mean			1.00	2.10	3.05
Standard Deviation			0.04	0.09	0.14
CV			4.2%	4.2%	4.7%

*Absolute value is shown, as used in corridor determination

**Table 8-30. THOR-05F Neck Lateral Flexion Qualification Corridor Results
(Highlighted values fell outside average $\pm 10\%$.)**

Neck Number		Test Number	Max/Min Upper Neck M _x after 40 ms * (Nm)	Max/Min Head ω_x * (deg/s)	Max/Min Head θ_x * (deg)
VRTC Neck EU9734	Left	240327-5	29.4	1,355	51.7
		240327-6	28.6	1,373	53.1
		240327-7	28.1	1,349	53.9
		240327-8	28.3	1,385	54.8
		240327-9	28.2	1,380	54.4
	Right	240327-10	29.2	1,390	53.6
		240327-11	28.8	1,396	54.5
		240327-12	28.3	1,350	54.5
		240327-13	28.4	1,389	54.9
		240327-14	28.1	1,355	54.6
VRTC Neck EV1357	Left	240531-2	31.2	1,309	50.4
		240531-3	31.2	1,317	50.3
		240531-4	31.0	1,318	50.8
		240531-5	30.7	1,303	50.6
		240531-6	30.2	1,282	50.7
	Right	240531-7	31.2	1,315	49.3
		240605-13	31.2	1,292	49.5
		240605-14	31.1	1,305	50.7
		240605-15	31.5	1,319	50.7
		240605-16	30.7	1,298	50.6

VRTC Neck EV0095	Left	241126-11	29.6	1,333	49.6
		241126-12	29.3	1,334	50.8
		241126-13	29.0	1,305	51
		241126-14	28.7	1,287	51
		241126-15	29.0	1,338	51.4
	Right	241127-1	30.1	1,325	50.3
		241127-2	29.1	1,303	51.3
		241127-3	29.5	1,329	51.7
		241127-4	29.4	1,313	51.2
		241127-5	29.4	1,325	51.5
Humanetics Neck EV0095	Left	686129	31.9	1,330	50.1
		686057	30.8	1,307	49.7
		686096	30.1	1,289	48.8
		686111	33.1	1,360	50.1
		686105	32.5	1,358	49.7
	Right	686407	30.0	1,290	50
		686403	30.7	1,298	50.1
		686398	31.2	1,315	50.2
		686395	30.6	1,297	49.9
		686314	31.5	1,331	48.4
Calspan Neck EV0095	Left	2025_03_26 18_52	33.4	1,449	38.5
		2025_03_26 19_45	33.2	1,459	39.6
		2025_03_26 20_18	33.4	1,469	39.3
		2025_03_26 20_56	33.4	1,471	39.6
		2025_03_26 21_29	33.1	1,462	39.6
	Right	2025_03_27 07_58	32.9	1,472	38.9
		2025_03_27 08_33	32.8	1,453	38.9
		2025_03_27 09_07	32.9	1,447	39.8
		2025_03_27 09_40	32.6	1,438	39.3
		2025_03_27 10_16	32.9	1,462	39.3
TRC Neck EV0095	Left	2025_05_01 11_25	29.8	1,341	51.2
		2025_05_01 11_46	31.2	1,377	51.5
		2025_05_01 12_44	29.4	1,355	51.8
		2025_05_01 13_16	31.1	1,381	51.2
		2025_05_01 14_33	30.5	1,382	51.4
	Right	2025_05_02 07_51	30.2	1,371	50.3
		2025_05_02 08_11	31.5	1,389	51.7
		2025_05_02 08_53	31.2	1,389	51.6
		2025_05_02 09_17	31.9	1,403	51.8
		2025_05_02 10_01	31.9	1,401	51.9
Mean			30.7	1,359	49.3
Standard Deviation			1.57	55.7	4.75
CV			5.1%	4.1%	9.6%

*Absolute value is shown, as used in corridor determination

Table 8-31. Neck Lateral Flexion Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width $\pm\%$
Pendulum Velocity at 5 ms after T0	m/s	0.90	1.10	1.00	10.0%
Pendulum Velocity at 10 ms after T0	m/s	1.89	2.31	2.10	10.0%
Pendulum Velocity at 15 ms after T0	m/s	2.75	3.36	3.05	10.0%
Impact Velocity	m/s	3.35	3.45	3.40	
Left Lateral Flexion					
Maximum Upper Neck Moment M_x after 40 ms	N-m	27.6	33.7	30.7	10.0%
Minimum Head Angular Velocity ω_x (relative to earth)	deg/s	-1,495	-1,223	-1,359	10.0%
Minimum Head Rotation Angle θ_x (relative to pendulum)	deg	-54.2	-44.4	-49.3	10.0%
Right Lateral Flexion					
Minimum Upper Neck Moment M_x after 40 ms	N-m	-33.7	-27.6	-30.7	10.0%
Maximum Head Angular Velocity ω_x (relative to earth)	deg/s	1,223	1,495	1,359	10.0%
Maximum Head Rotation Angle θ_x (relative to pendulum)	deg	44.4	54.2	49.3	10.0%

Discussion. For corridor development, all pendulum velocities were below 5 percent (

Table 8-29). The other test specifications compiled in Table 8-30 indicate CV values below 5 percent for head angular velocity and between 5 and 10 percent for upper neck moment and head rotation.

Highlighted cells in Table 8-30 indicate test values that were not within the respective target response $\pm 10\%$ defined in Table 8-31. All of these occurred in the head rotation specification. Nearly all head rotation values at VRTC for neck EU9734 were above the corridor. For neck EV0095 tested at Calspan, the head rotations were all below the corridor.

Repeatability displayed CV values below 5 percent for all test responses for all dummies, with the exception of the test for left lateral neck EV0095 at Humanetics, where all pendulum velocities were above 5 percent. Since the pendulum velocities for right side tests at Humanetics were all below 5 percent, there may have been a setup issue, rather than a problem with the neck itself. Furthermore, despite the pulse difference between left and right, the outputs were similar, with ATD CV values all below 5 percent for left and right sides (Table 8-14 and Table 8-16).

Dummy Reproducibility pendulum results were all below 5 percent for all dummies (Table 8-25 and Table 8-26).

Test Reproducibility results showed all pendulum velocity, upper neck moment, and head angular velocity CV values below 5 percent. (Table 8-27 and Table 8-28). The CV value for lab-to-lab peak head rotation was just above 10 percent. The low head rotation values for the tests at Calspan all fell below the $\pm 10\%$ corridor, so this is the cause for the high CV, and likely due to differences in test equipment. Those Calspan tests also resulted in higher head angular velocities compared to the other test labs, but the head angular velocities were within the corridor.

9 NECK TORSION

9.1 Methodology

Repeatability and reproducibility tests were performed using the neck torsion qualification procedures described in the *THOR-05F Qualification Procedures and Requirements*. 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 DL474-1000) is used (Figure 9-1). The neck qualification in the torsion mode utilizes 76.2 mm Hexcel aluminum honeycomb (or equivalent) for pendulum deceleration from an impact velocity of 3.40 ± 0.05 m/s. During these tests, the upper neck moment (M_z), head angular velocity, and head rotation were measured.

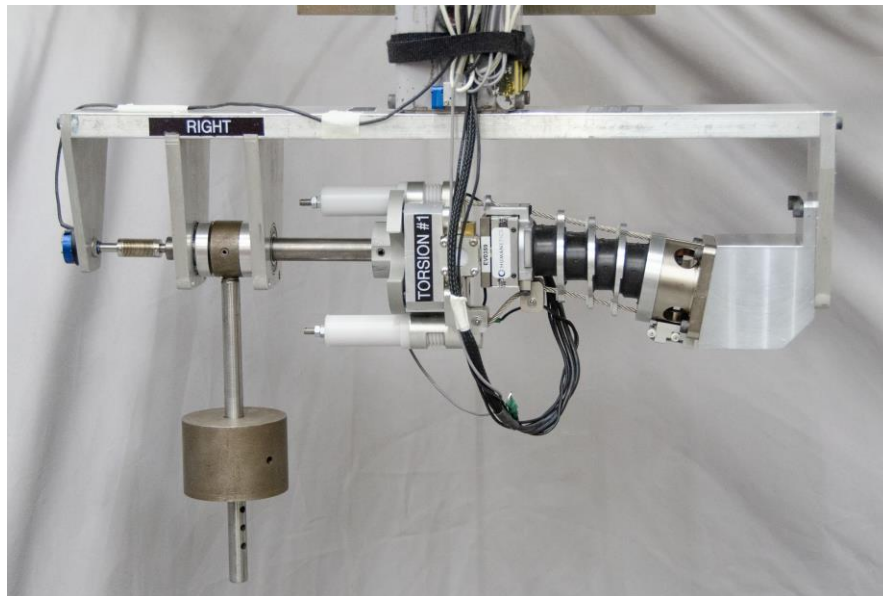


Figure 9-1: Neck torsion test setup

9.2 Neck Torsion Repeatability Results

Sections 9.2.1 through 9.2.6 illustrate the results of the neck torsion repeatability tests. For this study, the left and right sides were tested (i.e., simulates head turning about the z-axis towards the left and right shoulder) to confirm the neck is symmetrical. The results were combined for corridor determination. Each section contains a table providing the quantified test data, followed by plot overlays of the five repeat tests of the THOR-05F conducted at all four 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-05F Neck EU9734 Left Torsion Testing at VRTC

Repeatability results for neck left torsion testing on Neck EU9734 (removed from ATD EU9863) at VRTC yielded CV values below 5 percent, except for velocity at 7 ms which was slightly above 5 percent (5.1%) (Table 9-1 through Table 9-2, Figure 9-2 through Figure 9-4).

Table 9-1. VRTC THOR-05F Neck EU9734 Left Torsion Pulse Repeatability Results

Test Number	Pendulum Velocity at 7 ms after T0 (m/s)	Pendulum Velocity at 14 ms after T0 (m/s)	Pendulum Velocity at 21 ms after T0 (m/s)
240327-18	1.11	2.02	2.96
240327-19	1.00	2.02	2.99
240327-20	0.97	1.99	2.99
240328-1	1.04	2.08	3.08
240328-2	1.03	2.08	3.07
Mean	1.03	2.04	3.02
Standard Deviation	0.05	0.04	0.05
CV	5.1%	2.1%	1.7%

Table 9-2. VRTC THOR-05F Neck EU9734 Left Torsion Repeatability Results

Test Number	Maximum Upper Neck M _z (Nm)	Minimum Upper Neck ω _z (deg/s)	Minimum Neck Fixture θ _z (deg)
240327-18	19.9	-1,266	-54.0
240327-19	19.7	-1,285	-54.2
240327-20	19.6	-1,282	-54.4
240328-1	19.8	-1,266	-53.0
240328-2	19.7	-1,288	-53.8
Mean	19.8	-1,277	-53.9
Standard Deviation	0.10	10.7	0.57
CV	0.5%	0.8%	1.1%

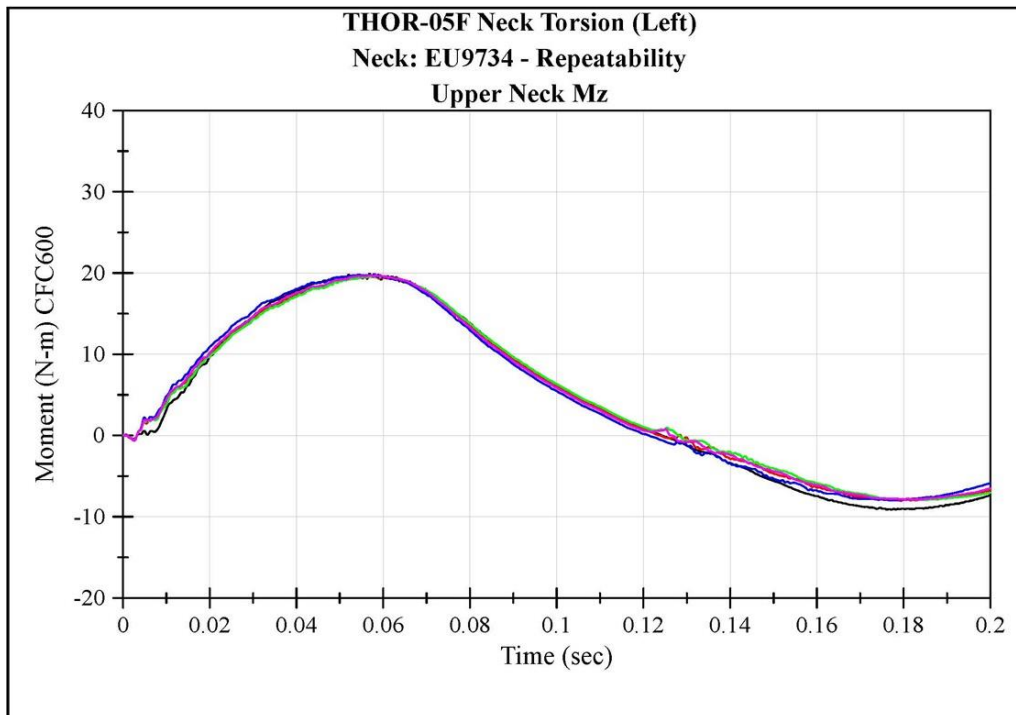


Figure 9-2. VRTC neck left torsion upper neck Mz for THOR-05F Neck EU9734

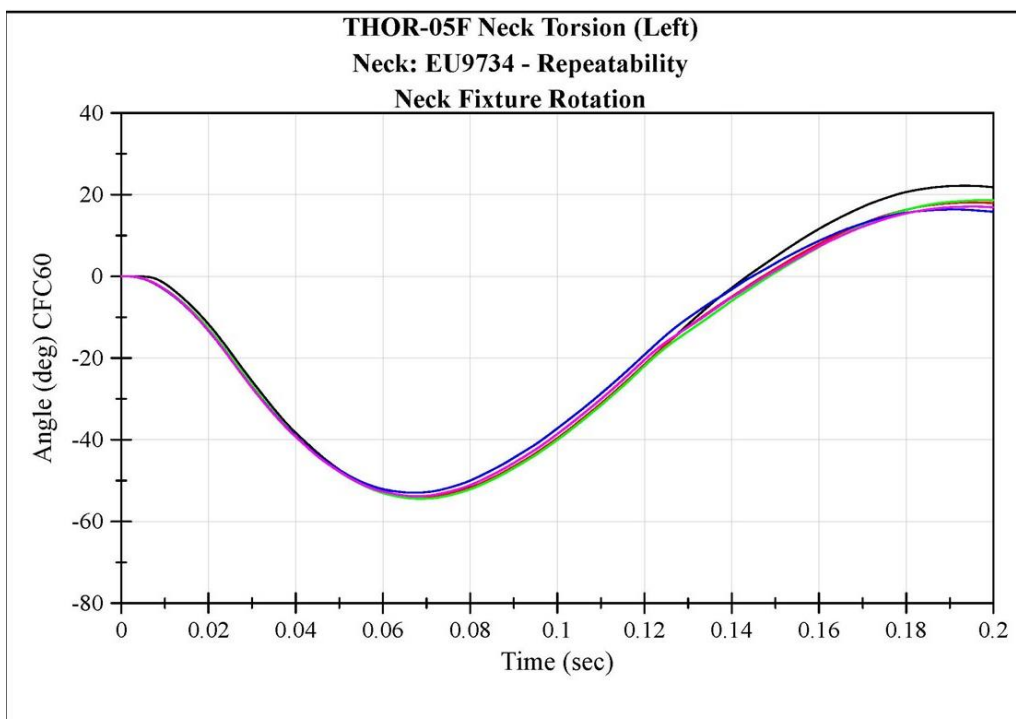


Figure 9-3. VRTC neck left torsion neck fixture rotation for THOR-05F Neck EU9734

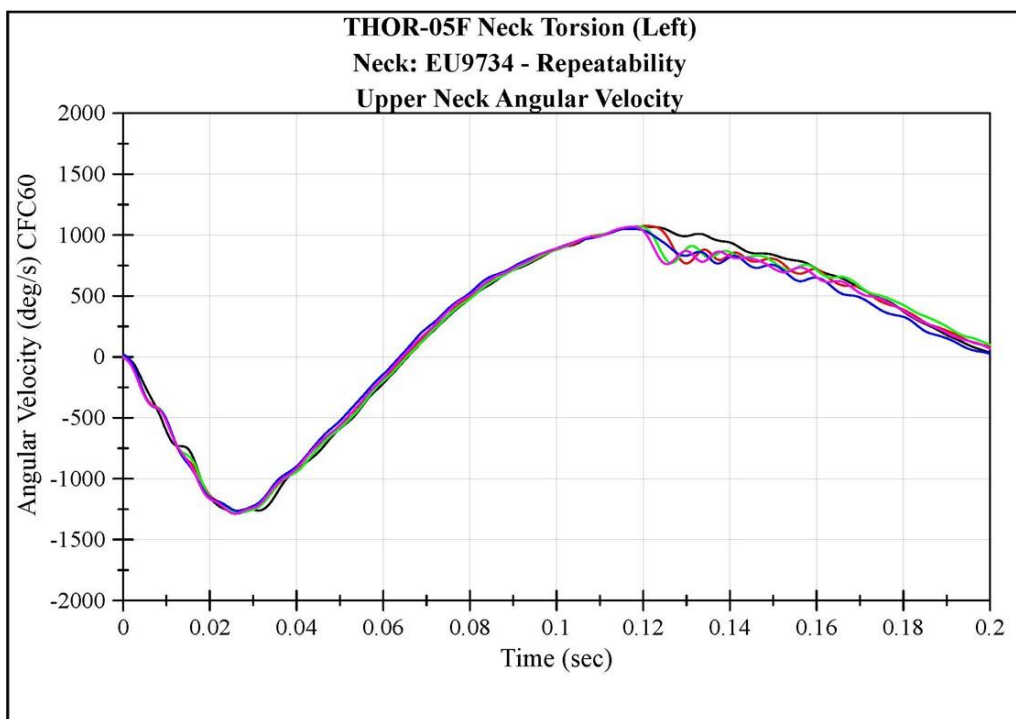


Figure 9-4. VRTC neck left torsion head angular velocity about Z for THOR-05F Neck EU9734

9.2.2 THOR-05F Neck EU9734 Right Torsion Testing at VRTC

Repeatability results for neck right torsion testing on Neck EU9734 (removed from ATD EU9863) at VRTC yielded CV values all below 5 percent (Table 9-3 through Table 9-4, Figure 9-5 through Figure 9-7).

Table 9-3. VRTC THOR-05F Neck EU9734 Right Torsion Pulse Repeatability Results

Test Number	Pendulum Velocity at 7 ms after T0 (m/s)	Pendulum Velocity at 14 ms after T0 (m/s)	Pendulum Velocity at 21 ms after T0 (m/s)
240328-3	1.08	2.02	3.02
240328-4	0.98	1.97	2.93
240328-5	1.01	2.03	3.07
240328-6	0.96	1.99	2.98
240328-7	1.03	2.10	3.11
Mean	1.01	2.02	3.02
Standard Deviation	0.05	0.05	0.07
CV	4.7%	2.5%	2.5%

Table 9-4. VRTC EU9863 THOR-05F Neck EU9734 Right Torsion Repeatability Results

Test Number	Minimum Upper Neck M_z (Nm)	Maximum Upper Neck ω_z (deg/s)	Maximum Neck Fixture θ_z (deg)
240328-3	-20.4	1,283	52.9
240328-4	-20.0	1,289	54.3
240328-5	-20.0	1,289	54.0
240328-6	-19.9	1,276	54.6
240328-7	-19.9	1,294	54.6
Mean	-20.0	1,286	54.1
Standard Deviation	0.18	7.1	0.70
CV	0.9%	0.6%	1.3%

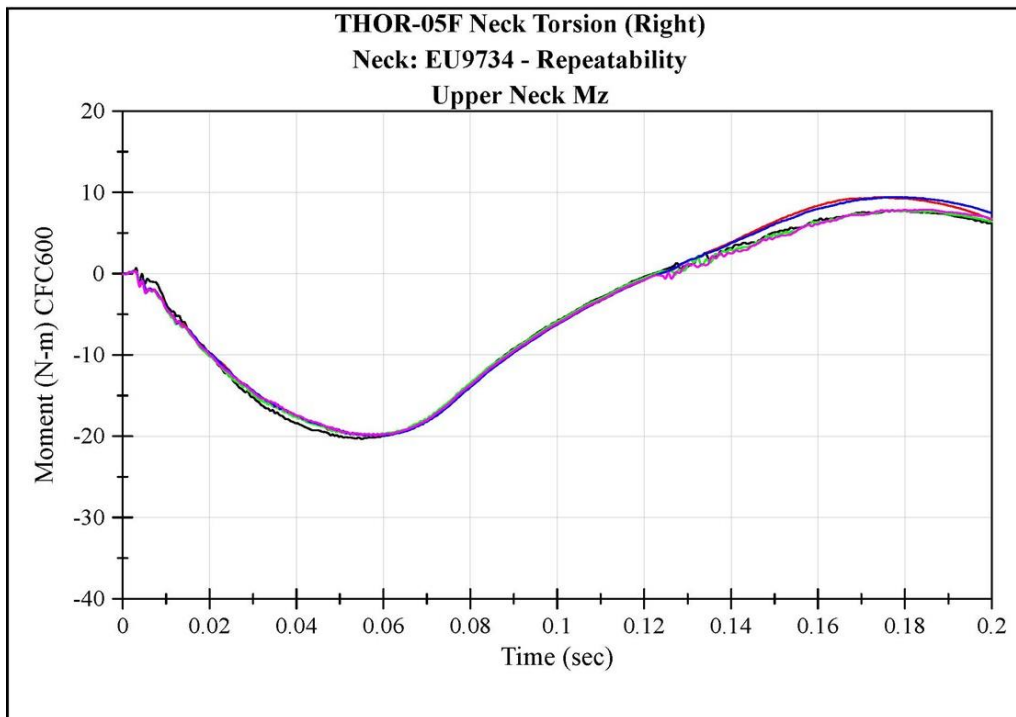


Figure 9-5. VRTC neck right torsion upper neck Mz for THOR-05F Neck EU9734

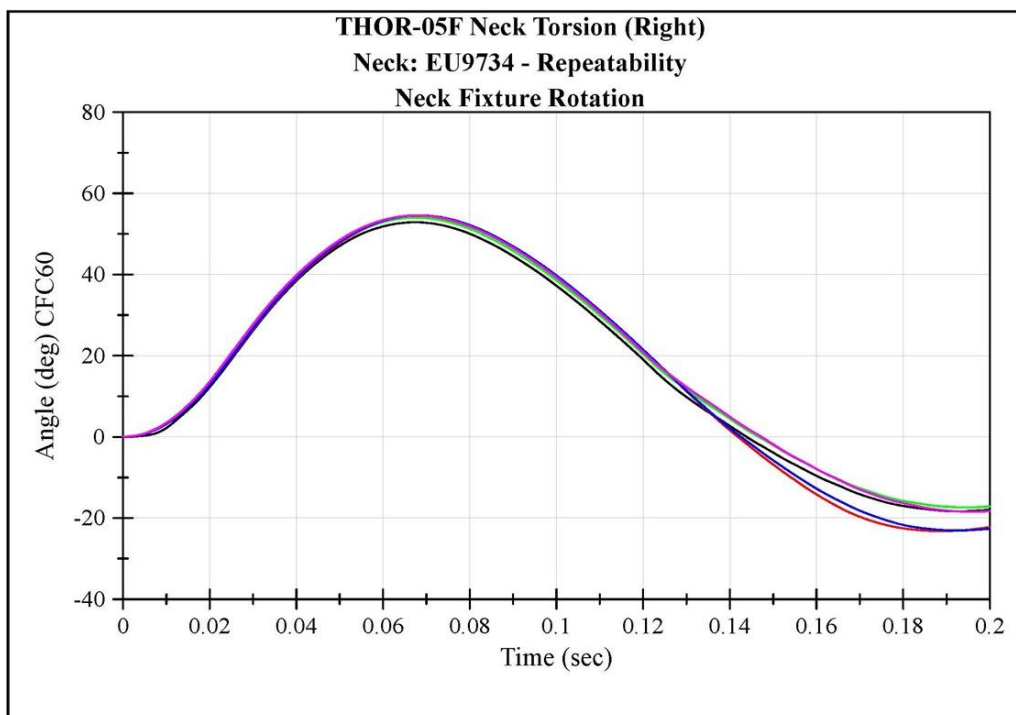


Figure 9-6. VRTC neck right torsion neck fixture rotation for THOR-05F Neck EU9734

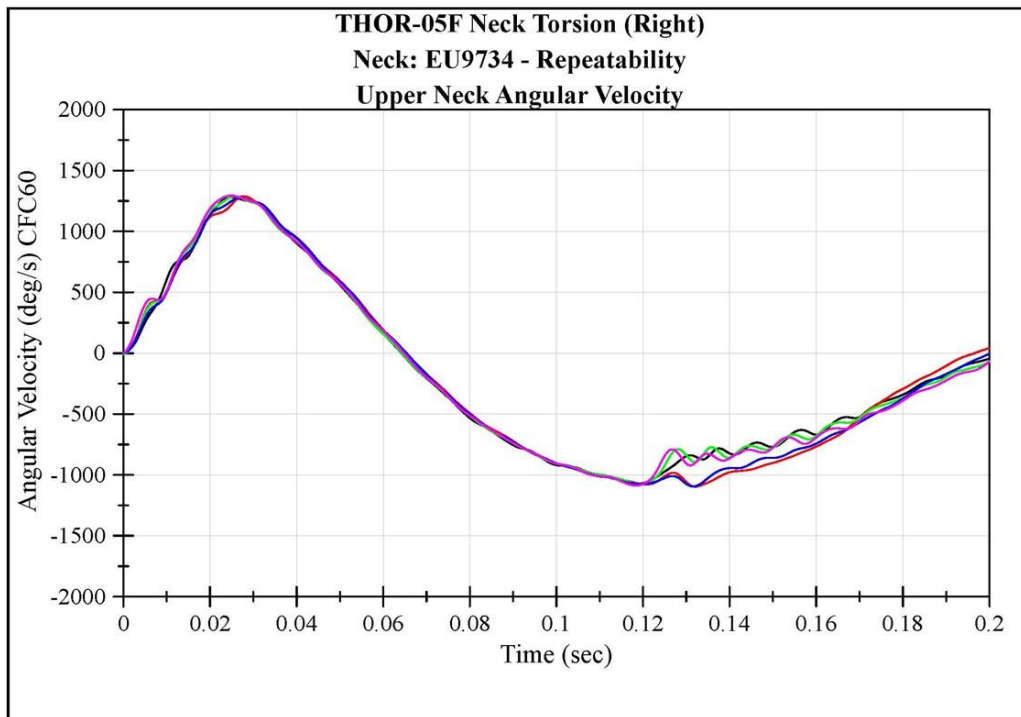


Figure 9-7. VRTC neck right torsion head angular velocity about Z-axis for THOR-05F Neck EU9734

9.2.3 THOR-05F Neck EV1357 Left Torsion Testing at VRTC

Repeatability results for left torsion testing on Neck EV1357 (removed from ATD EV0674) at VRTC yielded CV values all below 5 percent, with the exception of the pendulum velocity at 7 ms which had a CV value between 5 and 10 percent (Table 9-5 through Table 9-6, Figure 9-8 through Figure 9-10). Although five left torsion tests were performed on this neck, only four tests were included in the R&R analysis. The response in the initial left torsion test was non-uniform and indicative of a setup issue, likely the mismanagement of instrumentation cables that pulled on the neck during rotation. It was discarded to avoid corridor development using compromised data.

Table 9-5. VRTC THOR-05F Neck EV1357 Left Torsion Pulse Repeatability Results

Test Number	Pendulum Velocity at 7 ms after T0 (m/s)	Pendulum Velocity at 14 ms after T0 (m/s)	Pendulum Velocity at 21 ms after T0 (m/s)
240524-2	0.99	2.07	3.09
240524-3	1.04	2.10	3.10
240528-2	0.93	1.92	2.92
240528-10	1.06	2.15	3.13
Mean	1.01	2.06	3.06
Standard Deviation	0.06	0.10	0.09
CV	5.8%	4.8%	3.1%

Table 9-6. VRTC THOR-05F Neck EV1357 Left Torsion Repeatability Results

Test Number	Maximum Upper Neck M _z (Nm)	Minimum Upper Neck ω _z (deg/s)	Minimum Neck Fixture θ _z (deg)
240524-2	20.9	-1,261	-51.1
240524-3	21.1	-1,261	-51.9
240528-2	20.8	-1,253	-51.1
240528-10	20.9	-1,248	-51.5
Mean	20.9	-1,256	-51.4
Standard Deviation	0.10	6.4	0.39
CV	0.5%	0.5%	0.8%

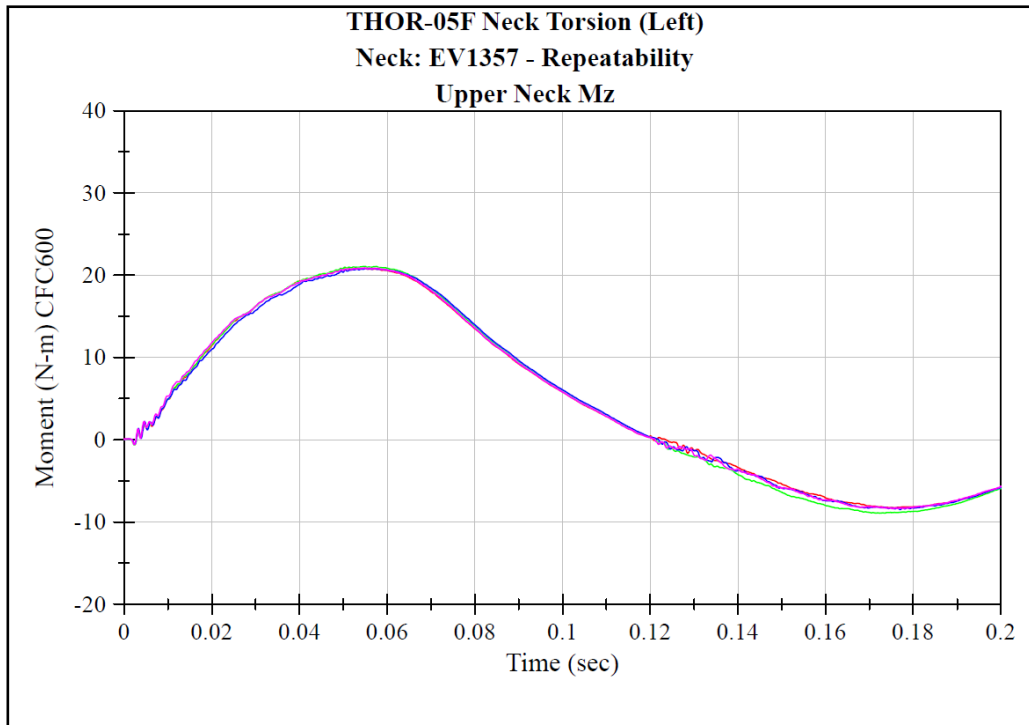


Figure 9-8. VRTC neck left torsion upper neck Mz for THOR-05F Neck EV1357

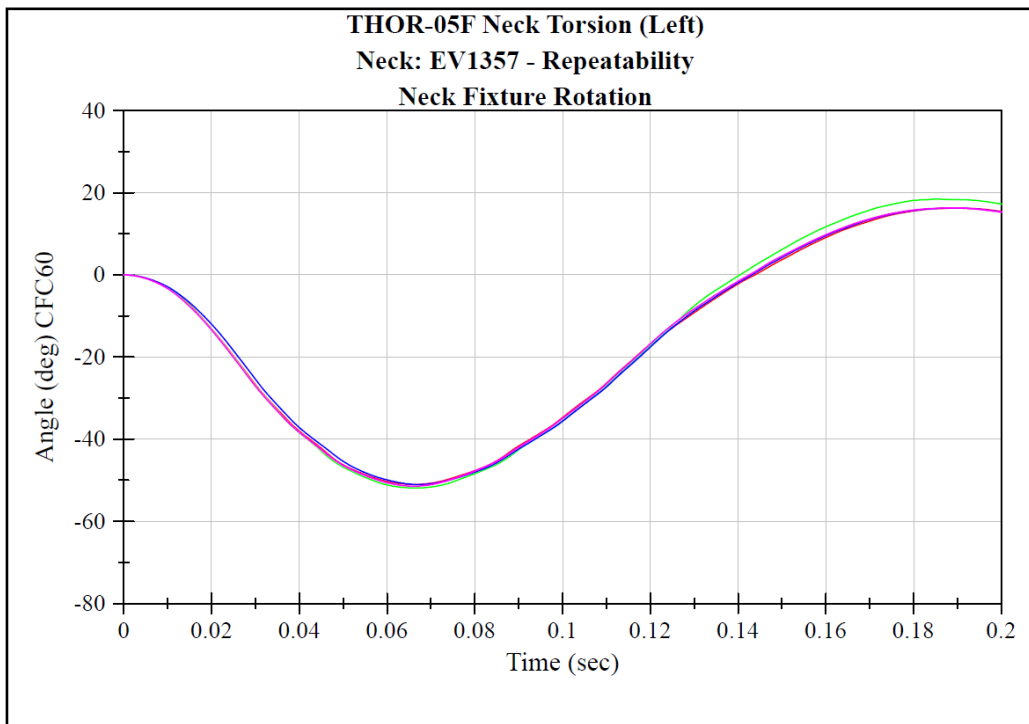


Figure 9-9. VRTC neck left torsion neck fixture rotation for THOR-05F Neck EV1357

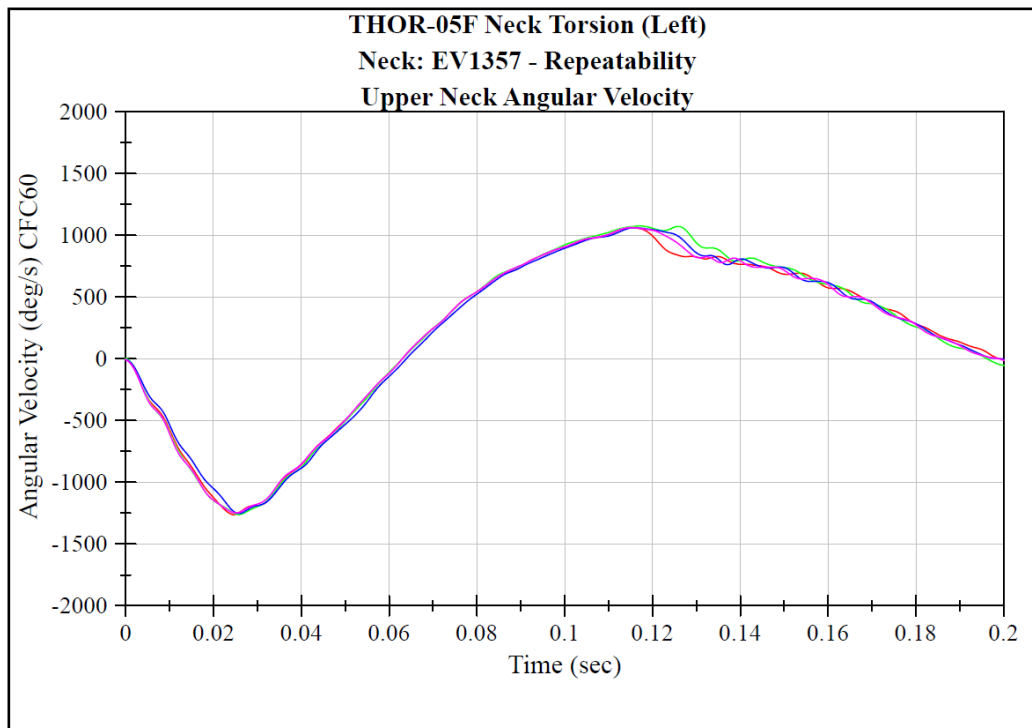


Figure 9-10. VRTC neck left torsion head angular velocity about Z for THOR-05F Neck EV1357

9.2.4 THOR-05F Neck EV1357 Right Torsion Testing at VRTC

Repeatability results for neck right torsion testing on Neck EV1357 (removed from ATD EV0674) at VRTC yielded all CV values below 5 percent (Table 9-7 through Table 9-8, Figure 9-11 through Figure 9-13).

Table 9-7. VRTC THOR-05F Neck EV1357 Right Torsion Pulse Repeatability Results

Test Number	Pendulum Velocity at 7 ms after T0 (m/s)	Pendulum Velocity at 14 ms after T0 (m/s)	Pendulum Velocity at 21 ms after T0 (m/s)
240528-11	1.10	2.15	3.15
240528-12	1.00	2.01	2.97
240528-15	0.99	2.05	3.08
240528-19	1.01	1.98	2.98
240528-20	1.01	2.01	2.97
Mean	1.02	2.04	3.03
Standard Deviation	0.05	0.06	0.08
CV	4.6%	3.1%	2.6%

Table 9-8. VRTC THOR-05F Neck EV1357 Right Torsion Repeatability Results

Test Number	Minimum Upper Neck M _z (Nm)	Maximum Upper Neck ω _z (deg/s)	Maximum Neck Fixture θ _z (deg)
240528-11	-21.1	1,266	51.6
240528-12	-21.2	1,259	51.5
240528-15	-21.0	1,259	51.6
240528-19	-21.2	1,256	52.0
240528-20	-21.0	1,264	52.0
Mean	-21.1	1,261	51.7
Standard Deviation	0.09	4.0	0.22
CV	0.4%	0.3%	0.4%

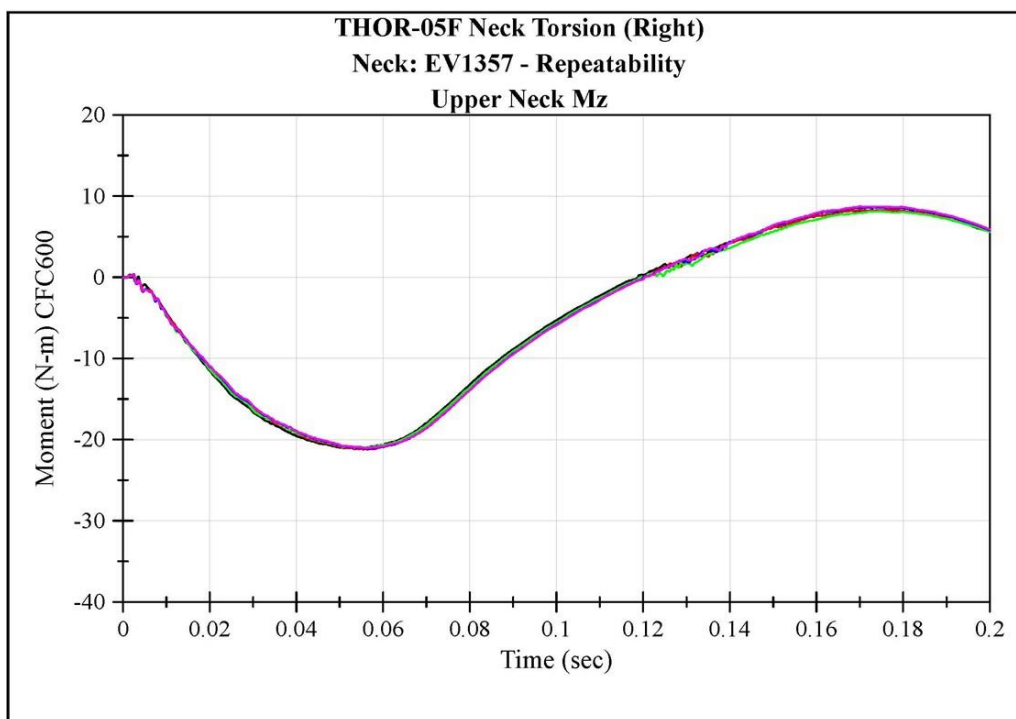


Figure 9-11. VRTC neck right torsion upper neck Mz for THOR-05F Neck EV1357

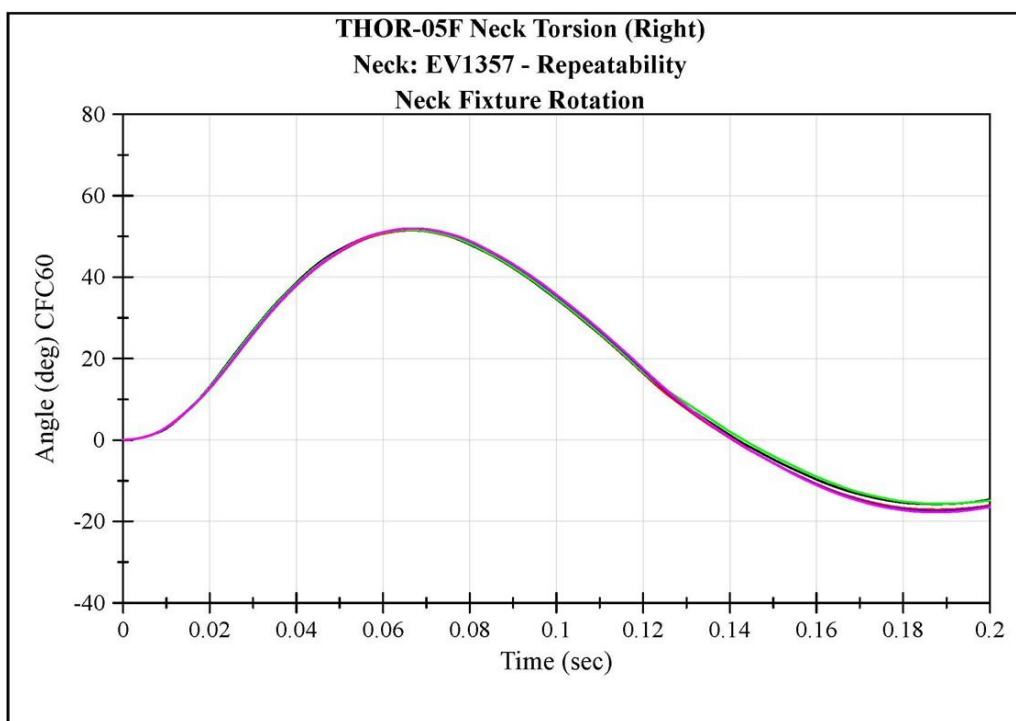


Figure 9-12. VRTC neck right torsion neck fixture rotation for THOR-05F Neck EV1357

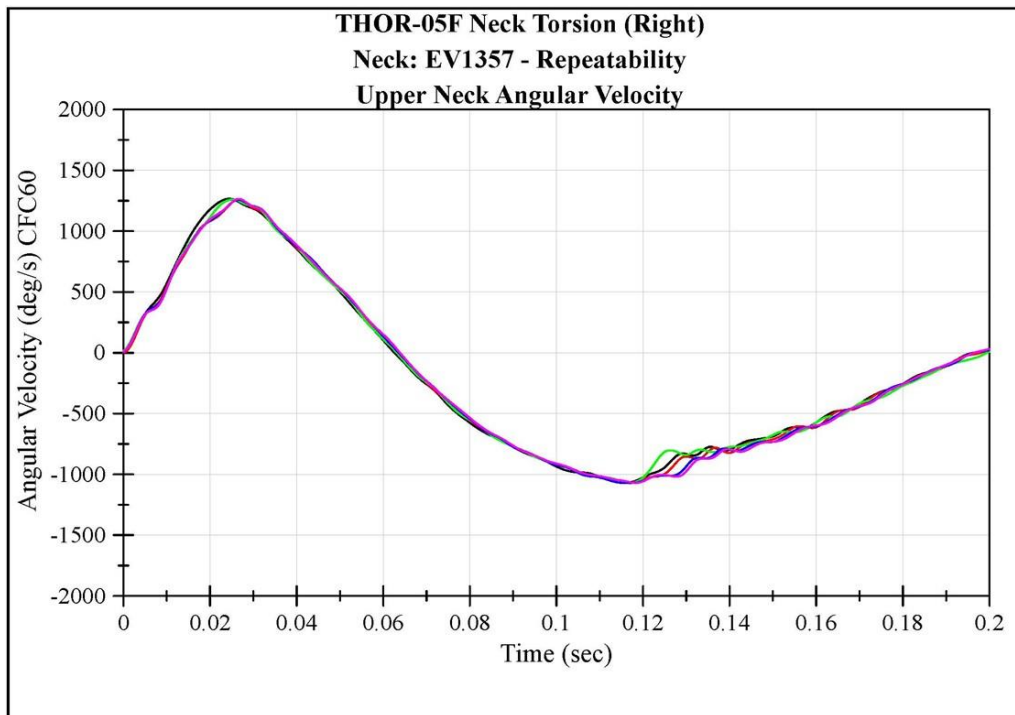


Figure 9-13. VRTC neck right torsion head angular velocity about Z for THOR-05F Neck EV1357

9.2.5 THOR-05F Neck EV0095 Left Torsion Testing at VRTC

Repeatability results for neck left torsion testing on Neck EV1357 (removed from ATD EV4675) at VRTC yielded CV values below 5 percent (Table 9-9 through Table 9-10, Figure 9-14 through Figure 9-16).

Table 9-9. VRTC THOR-05F Neck EV0095 Left Torsion Pulse Repeatability Results

Test Number	Pendulum Velocity at 7 ms after T0 (m/s)	Pendulum Velocity at 14 ms after T0 (m/s)	Pendulum Velocity at 21 ms after T0 (m/s)
241125-5	1.03	1.90	2.85
241125-7	1.01	2.08	3.14
241126-2	0.98	2.01	3.01
241126-3	0.96	1.92	2.86
241126-4	0.94	1.93	2.90
Mean	0.98	1.97	2.95
Standard Deviation	0.04	0.08	0.12
CV	3.7%	3.8%	4.2%

Table 9-10. VRTC THOR-05F Neck EV0095 Left Torsion Repeatability Results

Test Number	Maximum Upper Neck M_z (Nm)	Minimum Upper Neck ω_z (deg/s)	Minimum Neck Fixture θ_z (deg)
241125-5	20.5	-1,237	-51.8
241125-7	20.4	-1,272	-53.7
241126-2	20.3	-1,255	-52.9
241126-3	20.3	-1,252	-53.9
241126-4	20.1	-1,255	-54.2
Mean	20.3	-1,254	-53.3
Standard Deviation	0.15	12.5	0.97
CV	0.7%	1.0%	1.8%

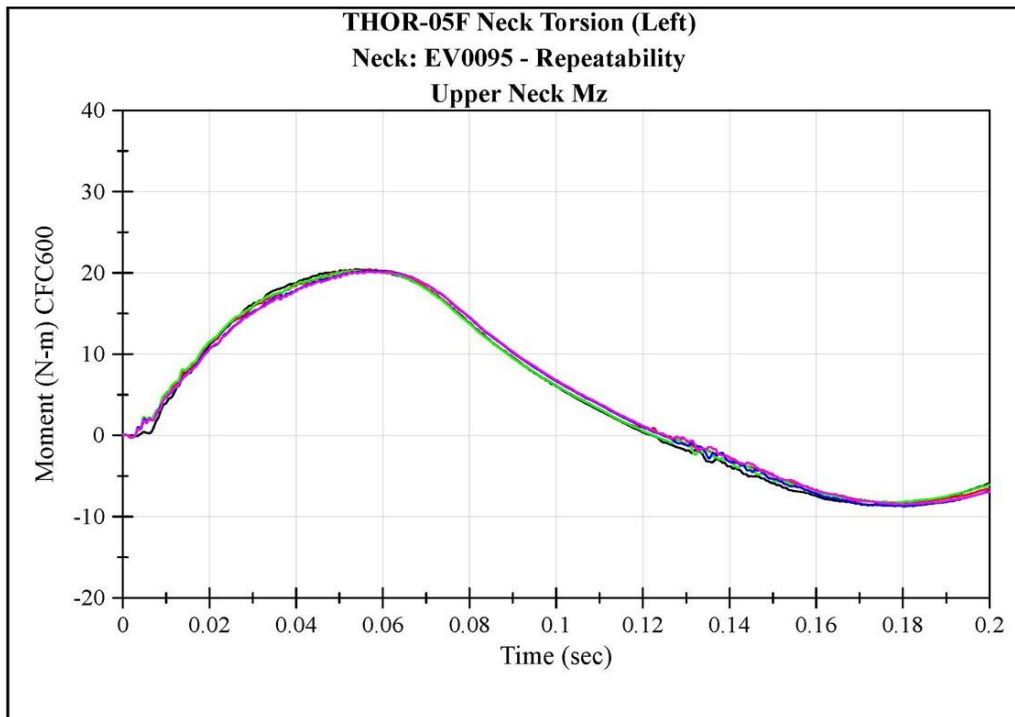


Figure 9-14. VRTC neck left torsion upper neck Mz for THOR-05F Neck EV0095

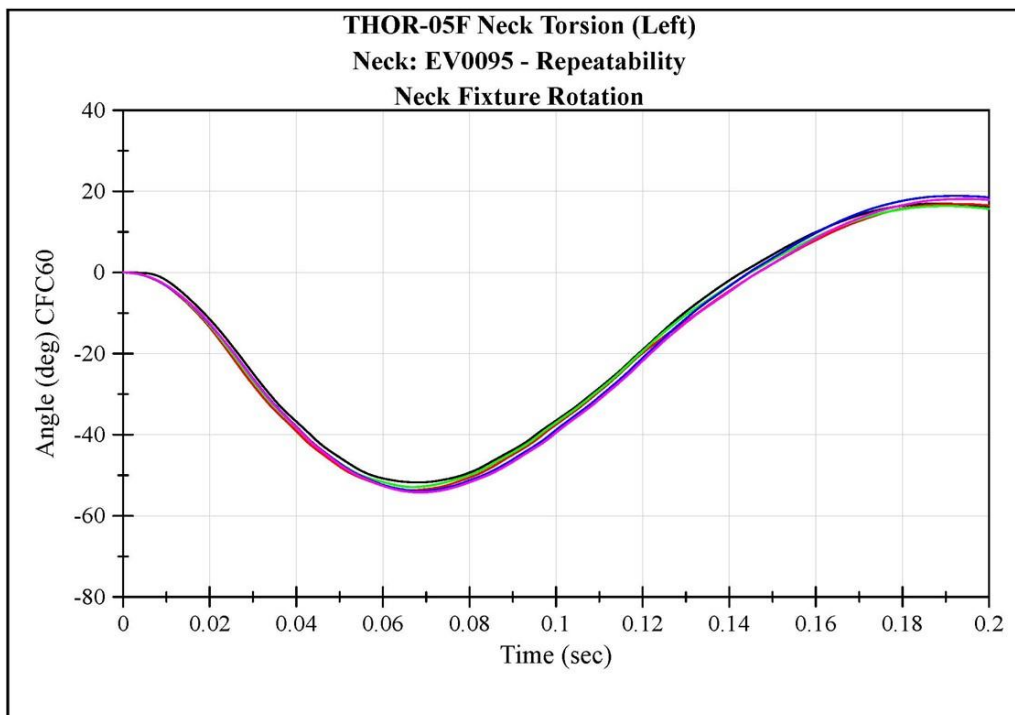


Figure 9-15. VRTC neck left torsion neck fixture rotation for THOR-05F Neck EV0095

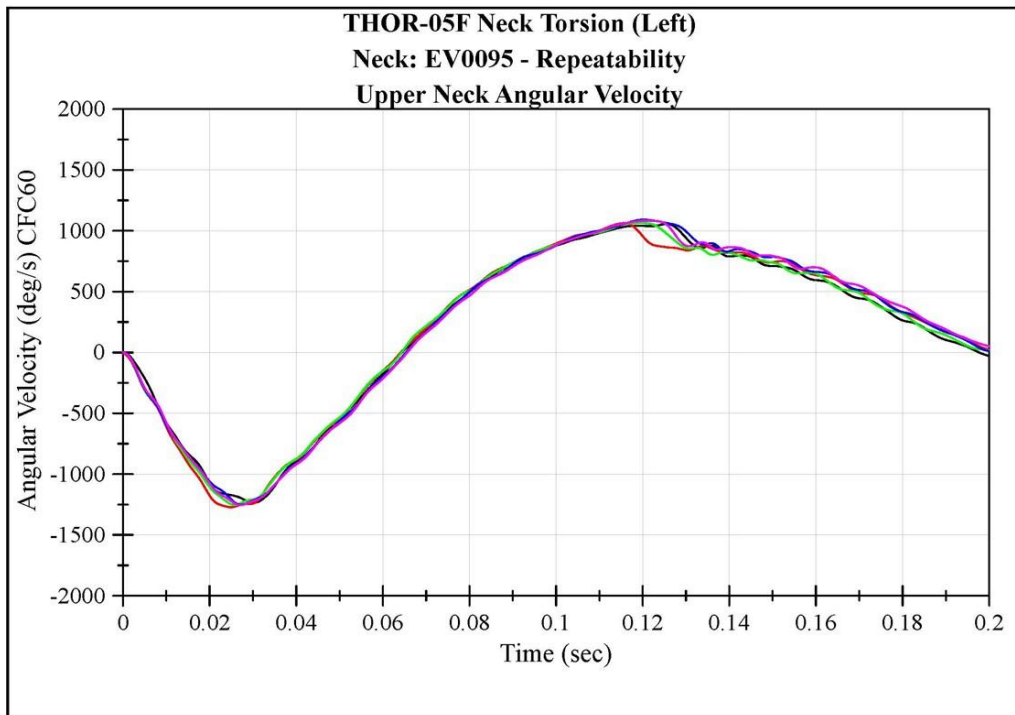


Figure 9-16. VRTC neck left torsion head angular velocity about Z for THOR-05F Neck EV0095

9.2.6 THOR-05F Neck EV0095 Right Torsion Testing at VRTC

Repeatability results for neck right torsion testing on Neck EV0095 (removed from ATD EV4675) at VRTC yielded CV values below 5%, except for velocity at 14 ms which was between 5 and 10 percent (Table 9-11 through Table 9-12, Figure 9-17 through Figure 9-19).

Table 9-11. VRTC THOR-05F Neck EV0095 Right Torsion Pulse Repeatability Results

Test Number	Pendulum Velocity at 7 ms after T0 (m/s)	Pendulum Velocity at 14 ms after T0 (m/s)	Pendulum Velocity at 21 ms after T0 (m/s)
241126-6	1.01	1.91	2.84
241126-7	0.93	1.88	2.82
241126-8	1.05	2.12	3.12
241126-9	1.02	2.06	3.06
241126-10	1.00	2.05	3.06
Mean	1.00	2.00	2.98
Standard Deviation	0.04	0.10	0.14
CV	4.4%	5.2%	4.7%

Table 9-12. VRTC THOR-05F Neck EV0095 Right Torsion Repeatability Results

Test Number	Minimum Upper Neck M_z (Nm)	Maximum Upper Neck ω_z (deg/s)	Maximum Neck Fixture θ_z (deg)
241126-6	-20.4	1,278	54.4
241126-7	-20.3	1,230	53.6
241126-8	-20.4	1,269	54.0
241126-9	-20.3	1,275	54.0
241126-10	-20.3	1,278	54.2
Mean	-20.3	1,266	54.0
Standard Deviation	0.05	20.5	0.30
CV	0.3%	1.6%	0.5%

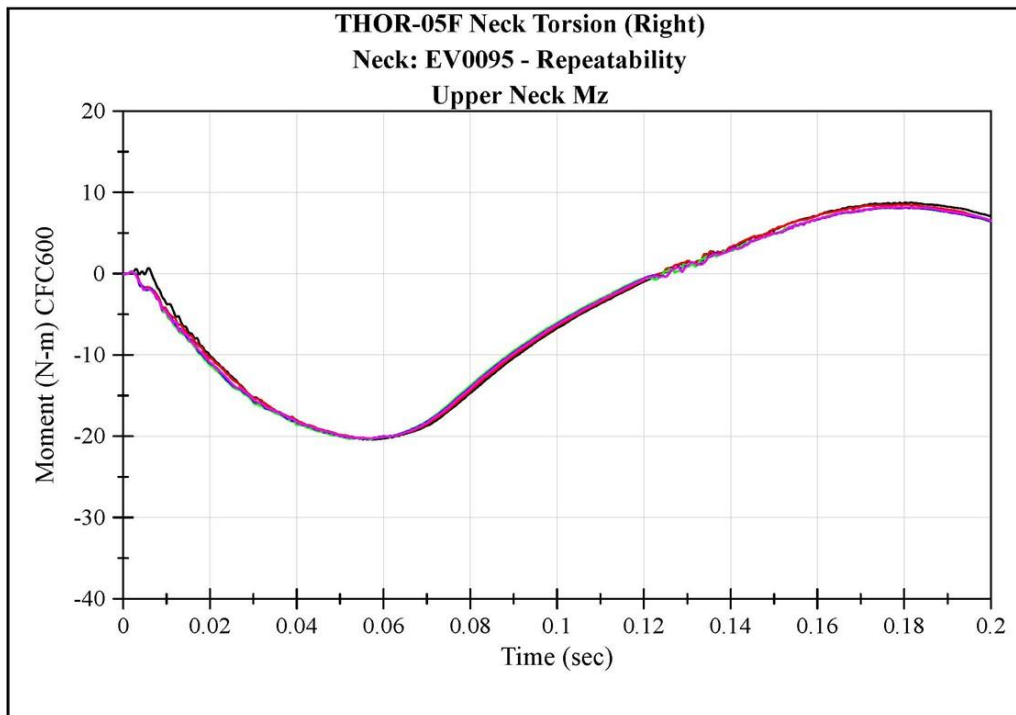


Figure 9-17. VRTC neck right torsion upper neck Mz for THOR-05F Neck EV0095

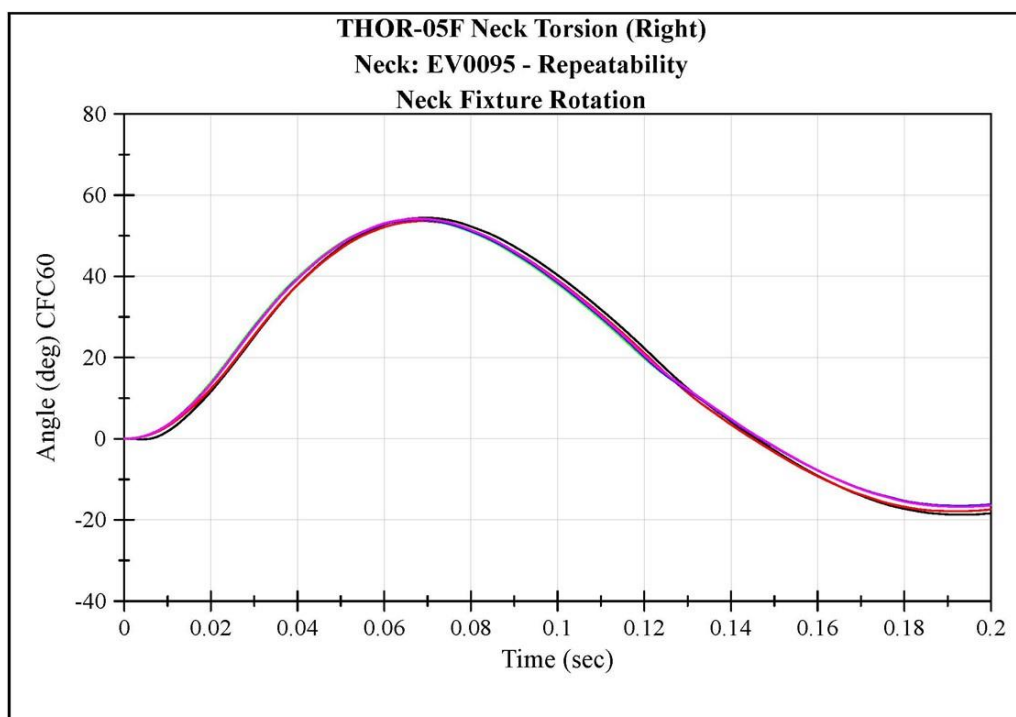


Figure 9-18. VRTC neck right torsion neck fixture rotation for THOR-05F Neck EV0095

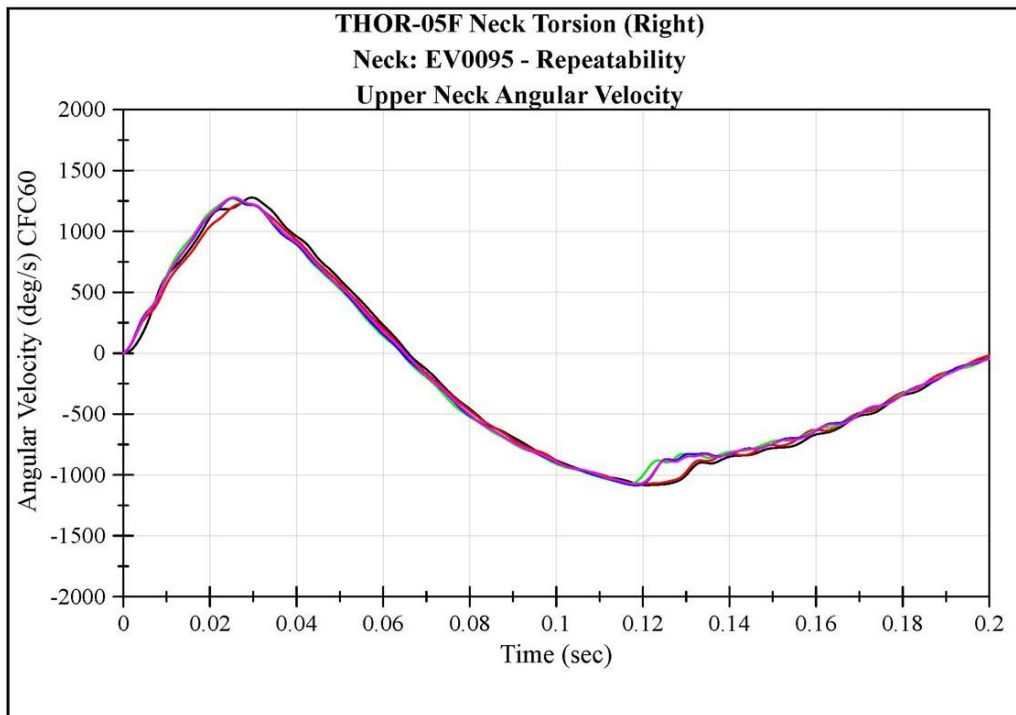


Figure 9-19. VRTC neck right torsion head angular velocity about Z for THOR-05F Neck EV0095

9.2.7 THOR-05F Neck EV0095 Left Torsion Testing at Humanetics

Repeatability results for neck left torsion testing on Neck EV0095 (removed from ATD EV4675) at Humanetics yielded CV values below 5 percent, except for velocity at 14 ms and 21 ms which were between 5 and 10 percent (Table 9-13 through Table 9-14, Figure 9-20 through Figure 9-22).

Table 9-13. Humanetics THOR-05F Neck EV0095 Left Torsion Pulse Repeatability Results

Test Number	Pendulum Velocity at 7 ms after T0 (m/s)	Pendulum Velocity at 14 ms after T0 (m/s)	Pendulum Velocity at 21 ms after T0 (m/s)
686554	1.00	2.10	3.20
686521	1.03	2.20	3.28
686536	0.94	1.96	2.95
686544	0.96	1.95	2.92
686554	1.00	2.10	3.20
Mean	0.98	2.04	3.07
Standard Deviation	0.04	0.11	0.16
CV	3.6%	5.3%	5.3%

Table 9-14. Humanetics THOR-05F Neck EV0095 Left Torsion Repeatability Results

Test Number	Maximum Upper Neck M_z (Nm)	Minimum Upper Neck ω_z (deg/s)	Minimum Neck Fixture θ_z (deg)
686486	19.9	-1,248	-48.8
686554	20.3	-1,289	-49.5
686521	20.5	-1,283	-49.1
686536	20.1	-1,262	-48.8
686544	19.9	-1,242	-48.5
Mean	20.1	-1,265	-48.9
Standard Deviation	0.25	20.9	0.39
CV	1.2%	1.7%	0.8%

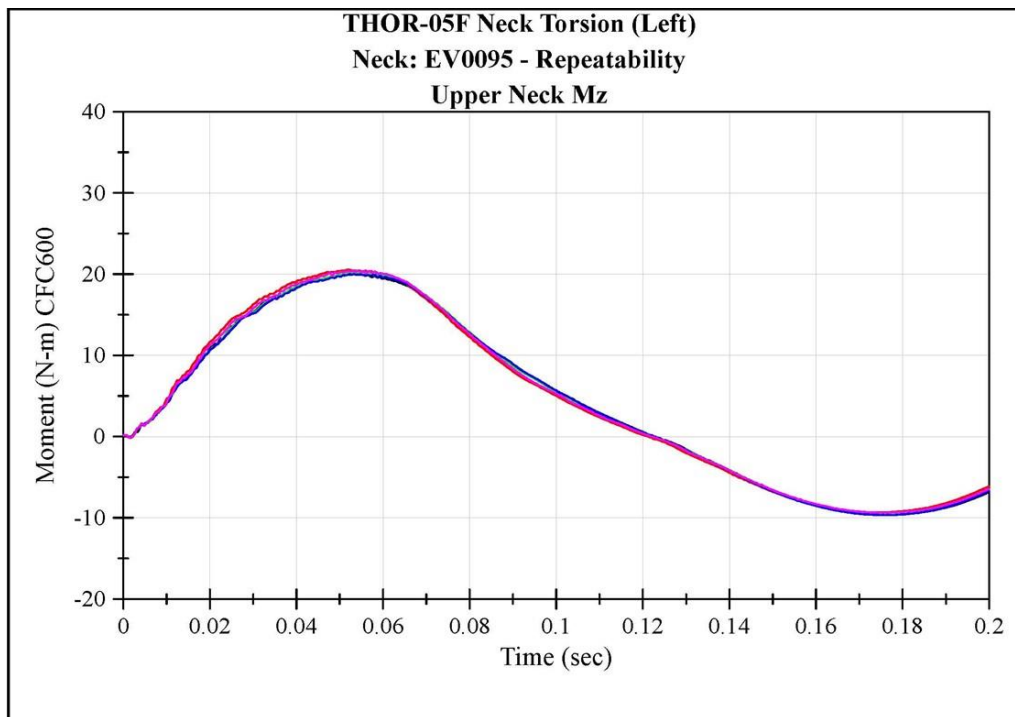


Figure 9-20. Humanetics neck left torsion upper neck Mz for THOR-05F Neck EV0095

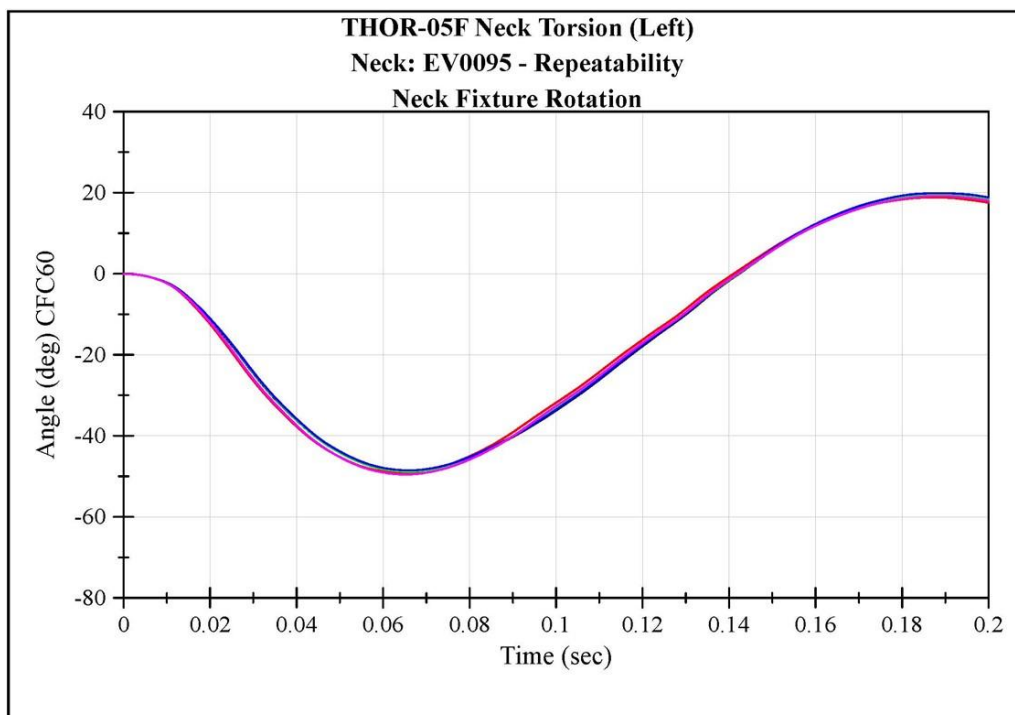


Figure 9-21. Humanetics neck left torsion neck fixture rotation for THOR-05F Neck EV0095

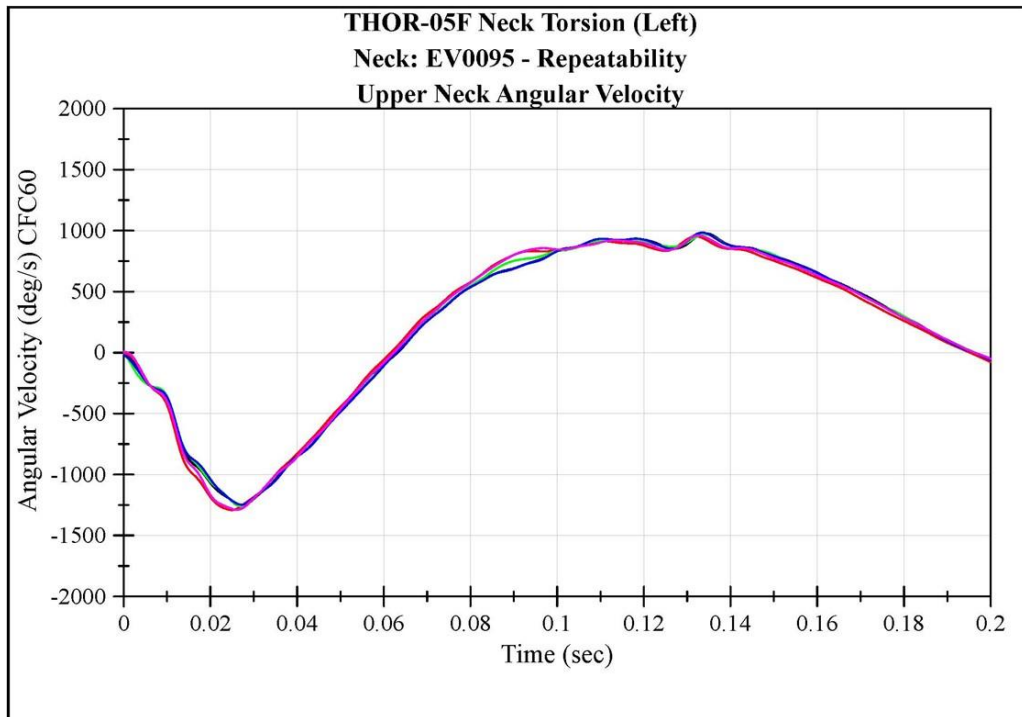


Figure 9-22. Humanetics neck left torsion head angular velocity about Z for THOR-05F Neck EV0095

9.2.8 THOR-05F Neck EV0095 Right Torsion Testing at Humanetics

Repeatability results for neck right torsion testing on Neck EV0095 (removed from ATD EV4675) at Humanetics yielded CV values below 5 percent (Table 9-15 through Table 9-16, Figure 9-23 through Figure 9-25).

Table 9-15. Humanetics THOR-05F Neck EV0095 Right Torsion Pulse Repeatability Results

Test Number	Pendulum Velocity at 7 ms after T0 (m/s)	Pendulum Velocity at 14 ms after T0 (m/s)	Pendulum Velocity at 21 ms after T0 (m/s)
686599	0.95	2.05	3.06
686595	0.95	1.95	2.91
686618	0.93	1.98	2.95
686690	0.96	2.05	3.08
686569	0.96	2.01	3.01
Mean	0.95	2.01	3.00
Standard Deviation	0.01	0.04	0.07
CV	1.3%	2.2%	2.4%

Table 9-16. Humanetics THOR-05F Neck EV0095 Right Torsion Repeatability Results

Test Number	Minimum Upper Neck M _z (Nm)	Maximum Upper Neck ω _z (deg/s)	Maximum Neck Fixture θ _z (deg)
686599	-20.4	1,286	48.8
686595	-20.1	1,242	47.6
686618	-20.0	1,239	47.9
686690	-20.2	1,271	48.1
686569	-20.1	1,254	48.4
Mean	-20.2	1,258	48.2
Standard Deviation	0.18	19.5	0.49
CV	0.9%	1.6%	1.0%

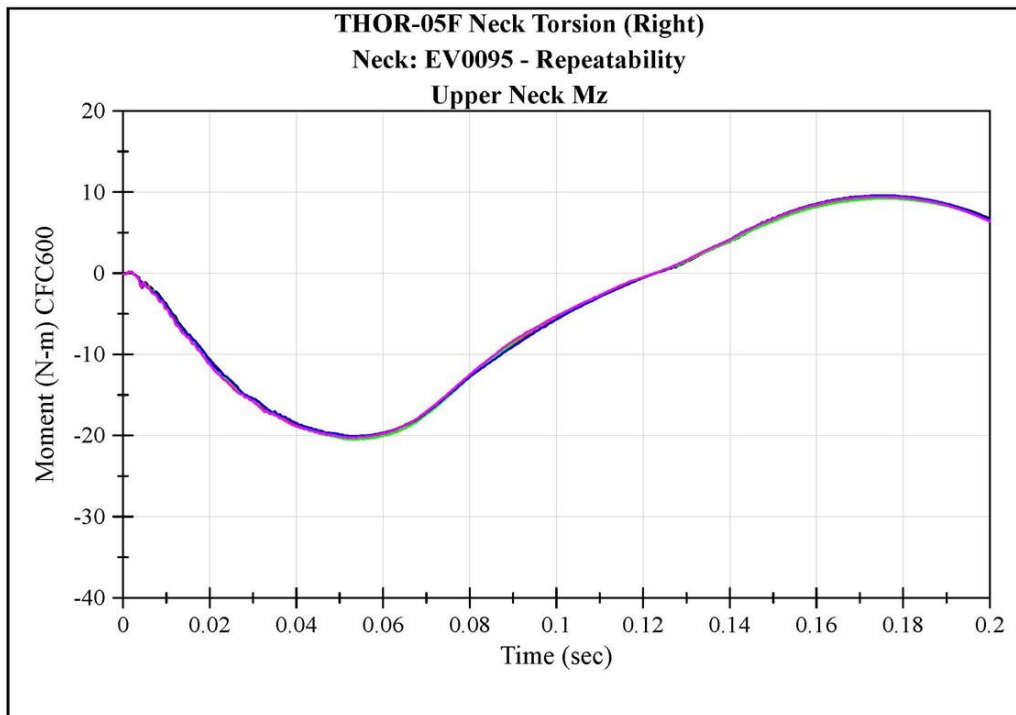


Figure 9-23. Humanetics neck right torsion upper neck Mz for THOR-05F Neck EV0095

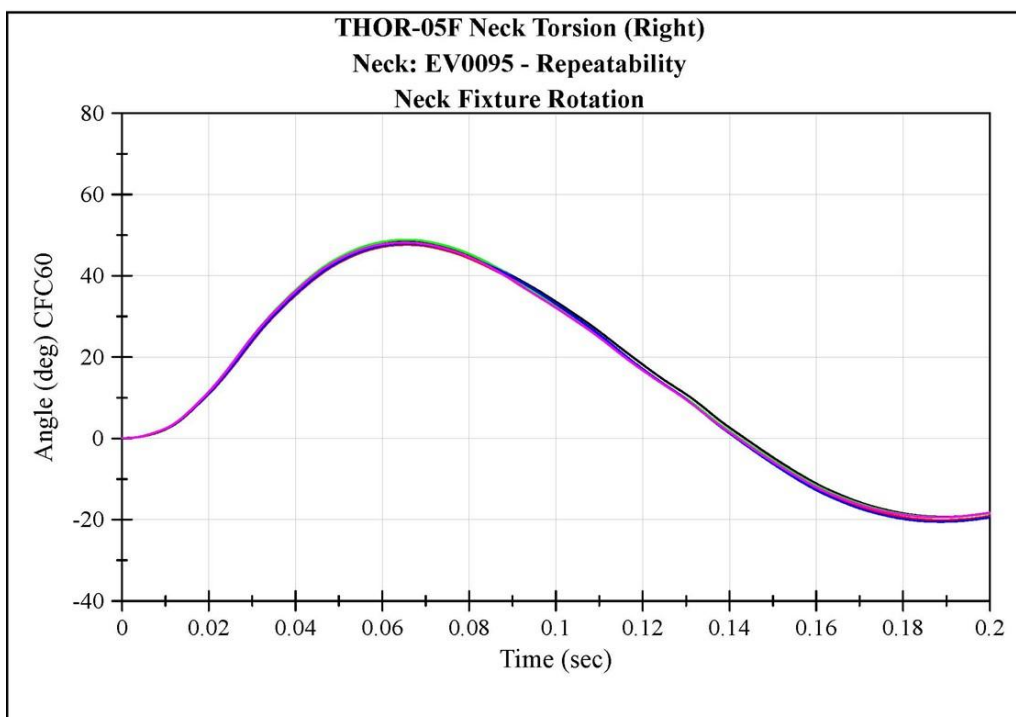


Figure 9-24. Humanetics neck right torsion neck fixture rotation for THOR-05F Neck EV0095

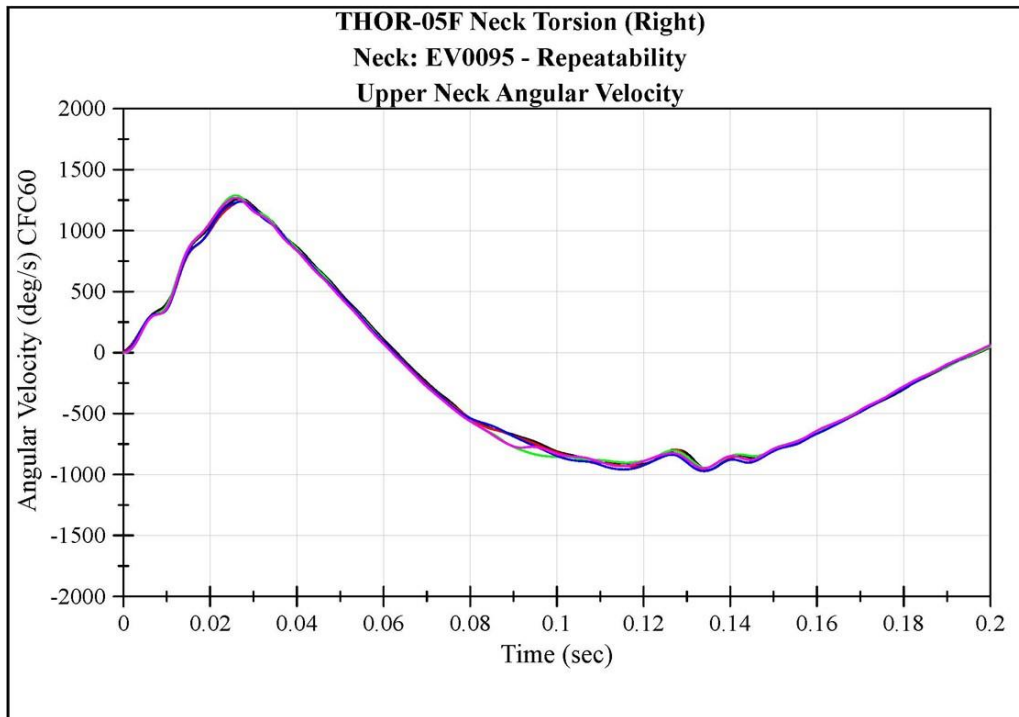


Figure 9-25. Humanetics neck right torsion head angular velocity about Z for THOR-05F Neck EV0095

9.2.9 THOR-05F Neck EV0095 Left Torsion Testing at Calspan

Repeatability results for neck left torsion testing on Neck EV0095 (removed from ATD EV4675) at Calspan yielded CV values below 5 percent (Table 9-17 and Table 9-18, Figure 9-26 through Figure 9-28).

Table 9-17. Calspan THOR-05F Neck EV0095 Left Torsion Pulse Repeatability Results

Test Number	Pendulum Velocity at 7 ms after T0 (m/s)	Pendulum Velocity at 14 ms after T0 (m/s)	Pendulum Velocity at 21 ms after T0 (m/s)
2025_03_12 17_32	0.97	2.18	3.35
2025_03_17 09_45	0.95	2.10	3.24
2025_03_17 16_10	0.95	2.13	3.26
2025_03_17 16_43	0.95	2.11	3.28
2025_03_18 08_13	0.94	2.15	3.32
Mean	0.95	2.13	3.29
Standard Deviation	0.01	0.03	0.04
CV	1.2%	1.5%	1.4%

Table 9-18. Calspan THOR-05F Neck EV0095 Left Torsion Repeatability Results

Test Number	Maximum Upper Neck M _z (Nm)	Minimum Upper Neck ω _z (deg/s)	Minimum Neck Fixture θ _z (deg)
2025_03_12 17_32	21.2	-1,386	-50.5
2025_03_17 09_45	20.8	-1,336	-49.8
2025_03_17 16_10	20.8	-1,335	-49.4
2025_03_17 16_43	21.1	-1,342	-49.1
2025_03_18 08_13	21.2	-1,347	-48.9
Mean	21.0	-1,349	-49.5
Standard Deviation	0.18	21.0	0.62
CV	0.9%	1.6%	1.3%

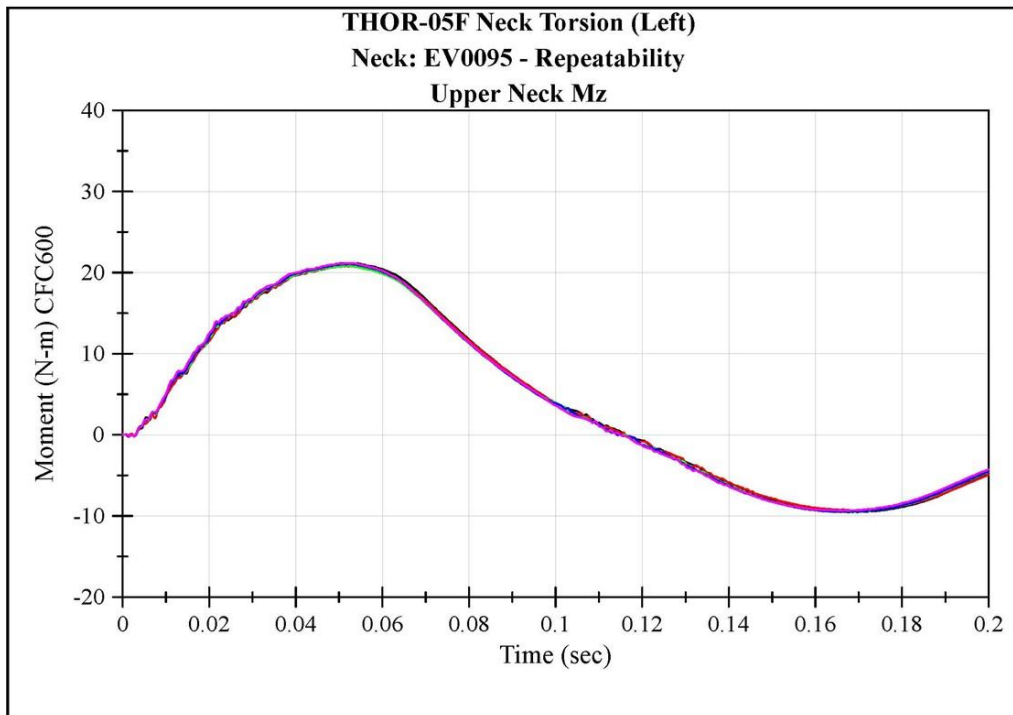


Figure 9-26. Calspan neck left torsion upper neck Mz for THOR-05F Neck EV0095

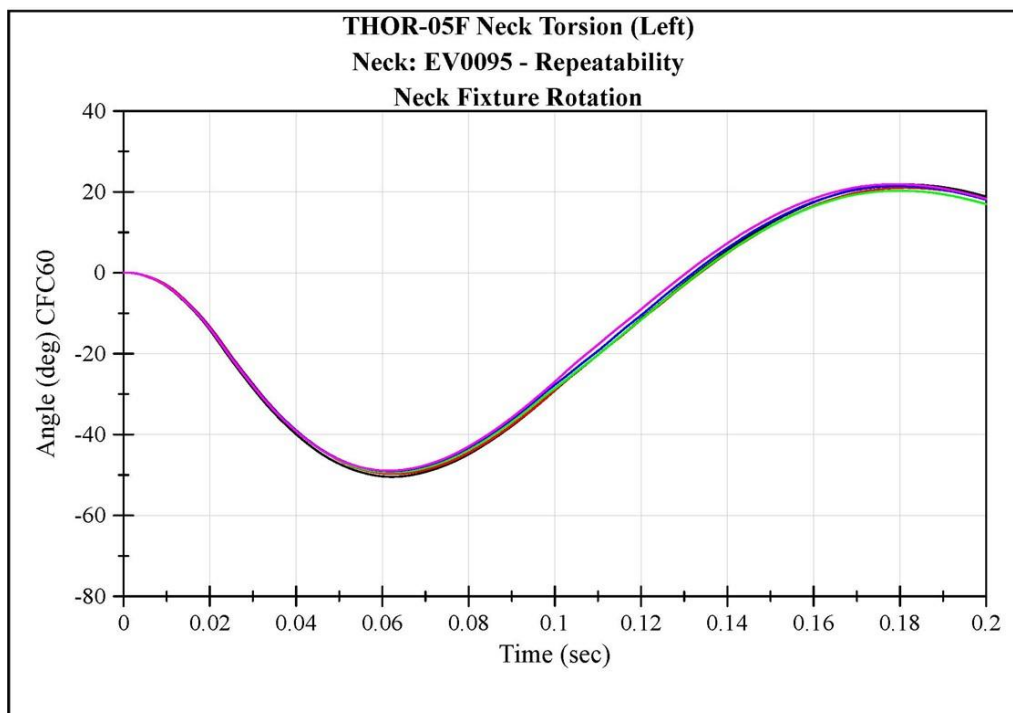


Figure 9-27. Calspan neck left torsion neck fixture rotation for THOR-05F Neck EV0095

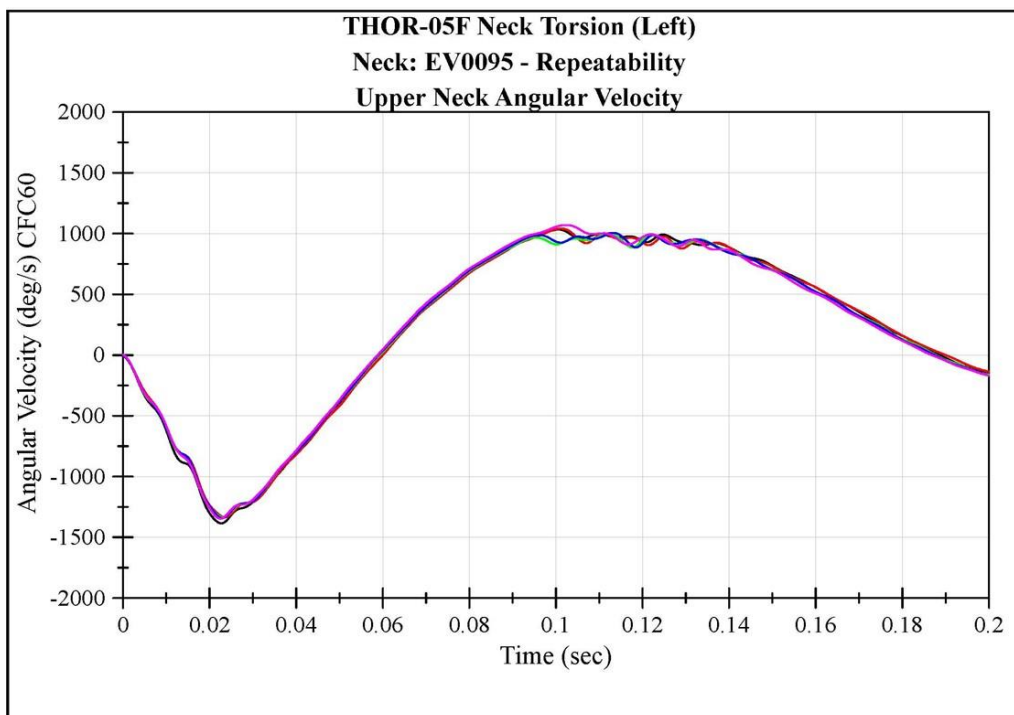


Figure 9-28. Calspan neck left torsion head angular velocity about Z for THOR-05F Neck EV0095

9.2.10 THOR-05F Neck EV0095 Right Torsion Testing at Calspan

Repeatability results for neck right torsion testing on Neck EV0095 (removed from ATD EV4675) at Calspan yielded CV values below 5 percent (Table 9-19 through Table 9-20, Figure 9-29 through Figure 9-31).

Table 9-19. Calspan THOR-05F Neck EV0095 Right Torsion Pulse Repeatability Results

Test Number	Pendulum Velocity at 7 ms after T0 (m/s)	Pendulum Velocity at 14 ms after T0 (m/s)	Pendulum Velocity at 21 ms after T0 (m/s)
2025_03_12 18_01	0.93	2.08	3.22
2025_03_13 11_02	0.93	2.08	3.26
2025_03_14 15_53	0.97	2.15	3.28
2025_03_17 08_36	1.01	2.19	3.29
2025_03_17 09_09	0.99	2.17	3.29
Mean	0.97	2.13	3.27
Standard Deviation	0.04	0.05	0.03
CV	3.7%	2.4%	0.9%

Table 9-20. Calspan THOR-05F Neck EV0095 Right Torsion Repeatability Results

Test Number	Minimum Upper Neck M _z (Nm)	Maximum Upper Neck ω_z (deg/s)	Maximum Neck Fixture θ_z (deg)
2025_03_12 18_01	-21.1	1,319	49.8
2025_03_13 11_02	-21.2	1,309	48.8
2025_03_14 15_53	-21.0	1,347	51.6
2025_03_17 08_36	-22.0	1,304	50.7
2025_03_17 09_09	-21.0	1,324	50.1
Mean	-21.3	1,321	50.2
Standard Deviation	0.39	16.6	1.05
CV	1.8%	1.3%	2.1%

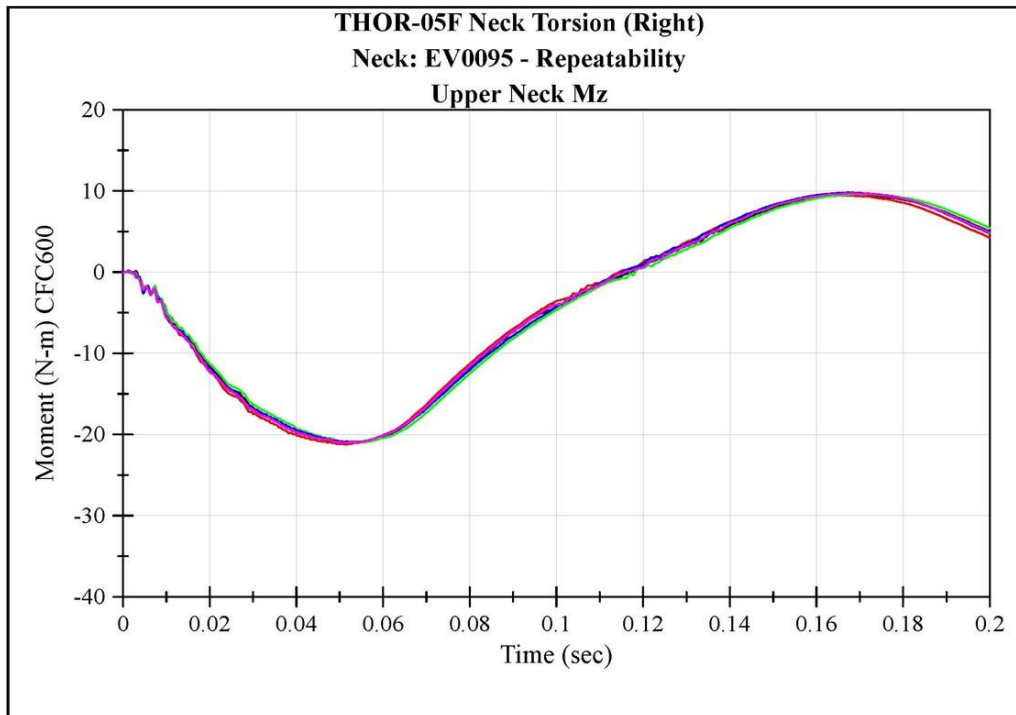


Figure 9-29. Calspan neck right torsion upper neck Mz for THOR-05F Neck EV0095

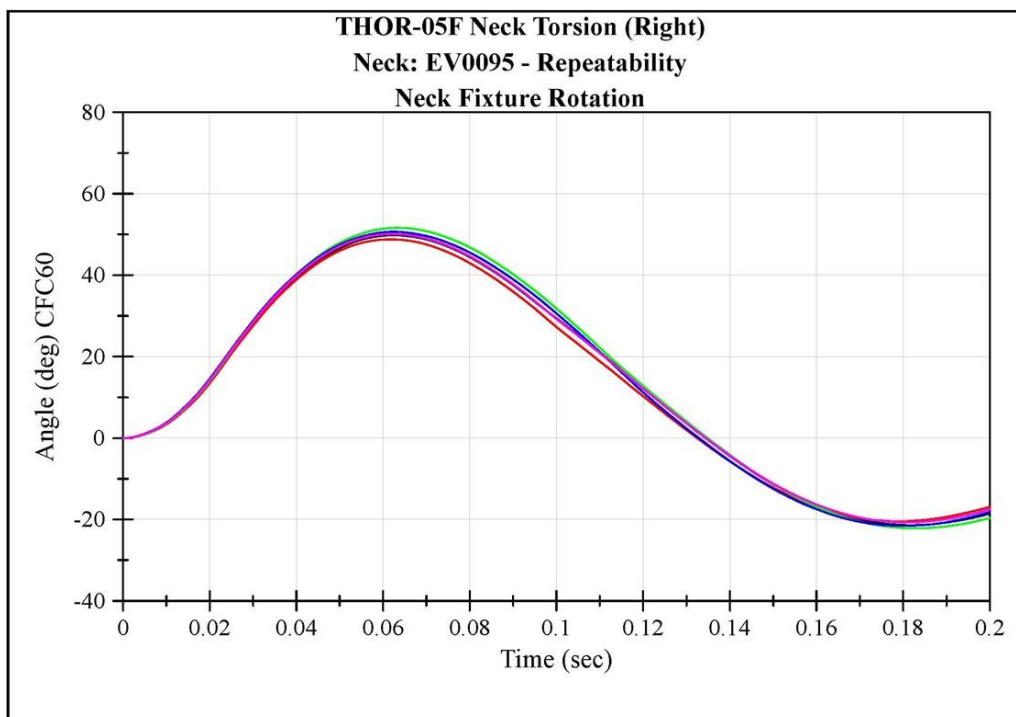


Figure 9-30. Calspan neck right torsion neck fixture rotation for THOR-05F Neck EV0095

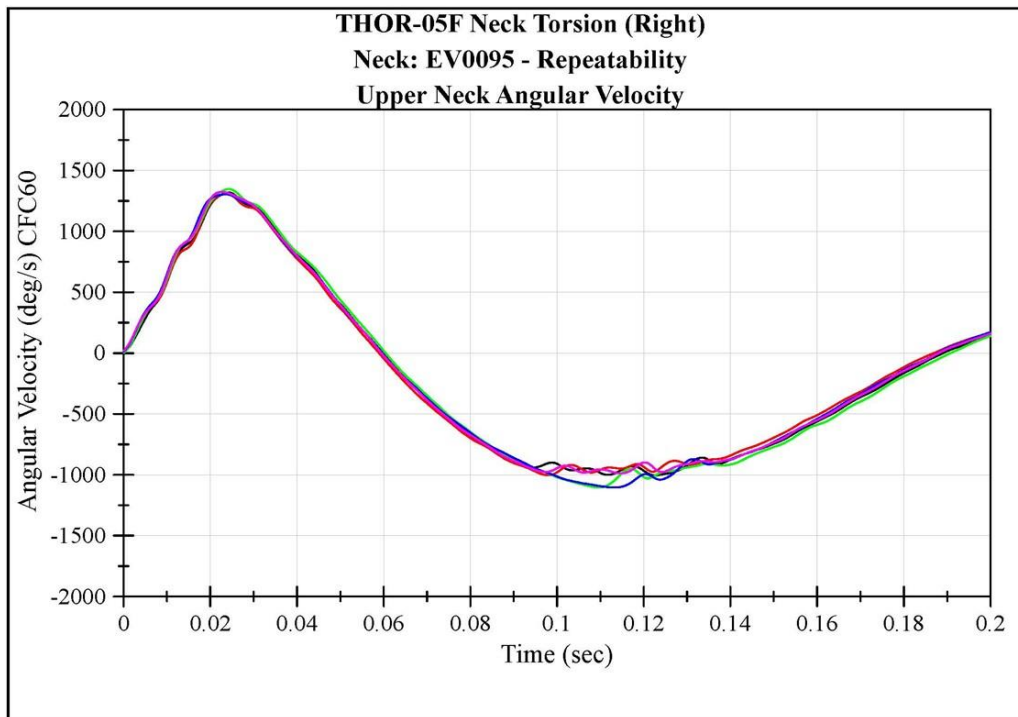


Figure 9-31. Calspan neck right torsion head angular velocity about Z for THOR-05F Neck EV0095

9.2.11 THOR-05F Neck EV0095 Left Torsion Testing at TRC

Repeatability results for neck left torsion testing on Neck EV0095 (removed from ATD EV4675) at TRC yielded CV values below 5 percent (Table 9-21 and Table 9-22, Figure 9-32 through Figure 9-34).

Table 9-21. TRC THOR-05F Neck EV0095 Left Torsion Pulse Repeatability Results

Test Number	Pendulum Velocity at 7 ms after T0 (m/s)	Pendulum Velocity at 14 ms after T0 (m/s)	Pendulum Velocity at 21 ms after T0 (m/s)
2025_04_25 10_59	1.06	2.24	3.32
2025_04_25 11_45	1.05	2.22	3.29
2025_04_25 12_36	1.06	2.22	3.34
2025_04_25 13_25	1.06	2.20	3.29
2025_04_25 13_39	1.03	2.15	3.22
Mean	1.05	2.21	3.29
Standard Deviation	0.01	0.03	0.05
CV	1.2%	1.6%	1.4%

Table 9-22. TRC THOR-05F Neck EV0095 Left Torsion Repeatability Results

Test Number	Maximum Upper Neck M _z (Nm)	Minimum Upper Neck ω _z (deg/s)	Minimum Neck Fixture θ _z (deg)
2025_04_25 10_59	19.9	-1,321	-51.3
2025_04_25 11_45	19.8	-1,318	-51.0
2025_04_25 12_36	19.8	-1,319	-51.4
2025_04_25 13_25	19.9	-1,315	-51.5
2025_04_25 13_39	19.7	-1,314	-51.2
Mean	19.8	-1,317	-51.3
Standard Deviation	0.08	3.2	0.19
CV	0.4%	0.2%	0.4%

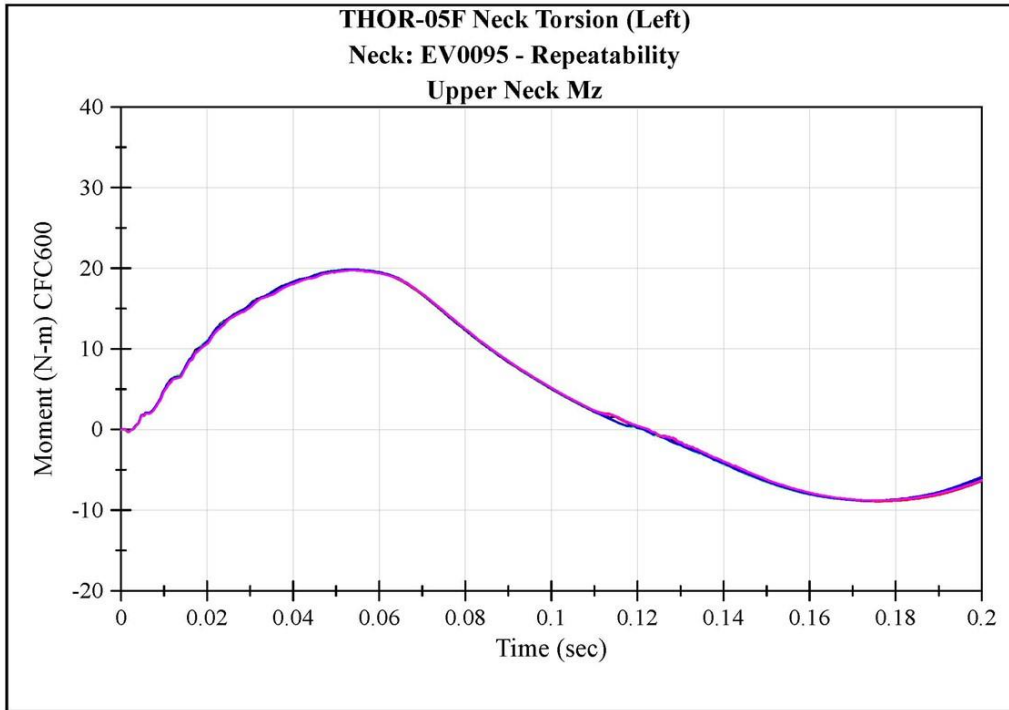


Figure 9-32. TRC neck left torsion upper neck Mz for THOR-05F Neck EV0095

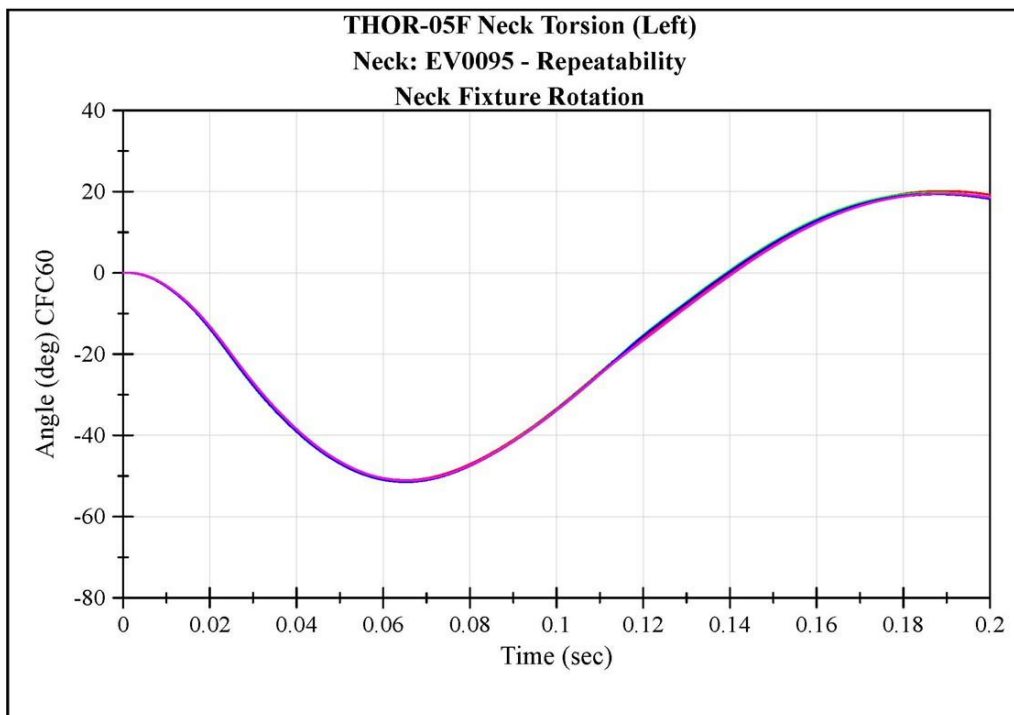


Figure 9-33. TRC neck left torsion neck fixture rotation for THOR-05F Neck EV0095

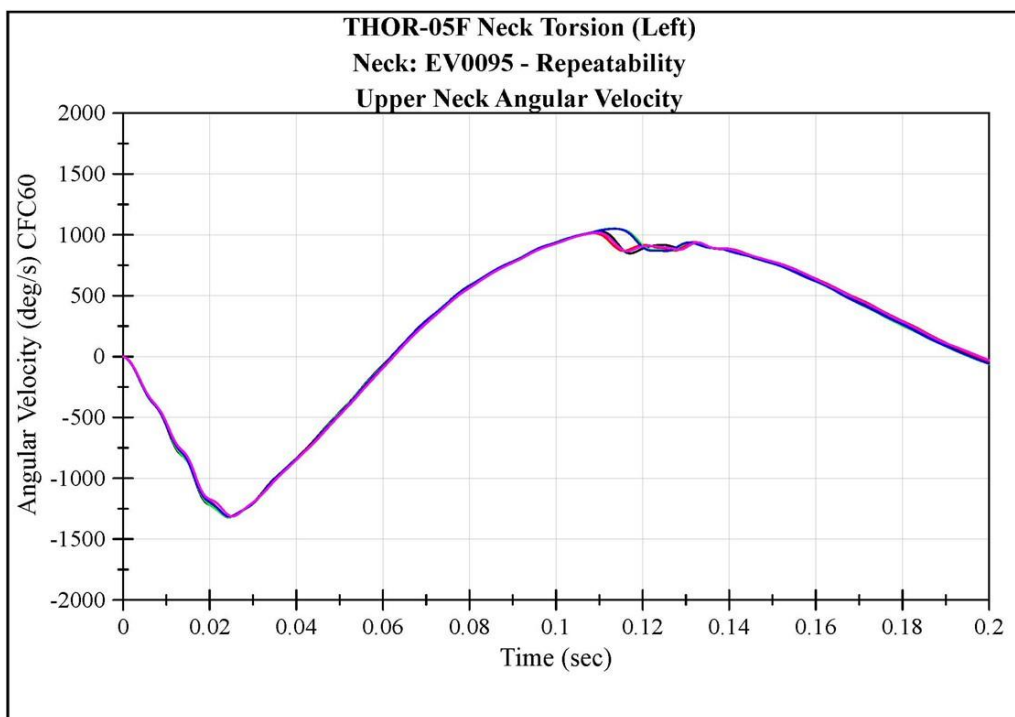


Figure 9-34. TRC neck left torsion head angular velocity about Z for THOR-05F Neck EV0095

9.2.12 THOR-05F Neck EV0095 Right Torsion Testing at TRC

Repeatability results for neck right torsion testing on Neck EV0095 (removed from ATD EV4675) at TRC yielded CV values below 5 percent (Table 9-23 through Table 9-24, Figure 9-35 through Figure 9-37).

Table 9-23. TRC THOR-05F Neck EV0095 Right Torsion Pulse Repeatability Results

Test Number	Pendulum Velocity at 7 ms after T0 (m/s)	Pendulum Velocity at 14 ms after T0 (m/s)	Pendulum Velocity at 21 ms after T0 (m/s)
2025_04_25 14_32	1.06	2.17	3.30
2025_04_28 08_10	1.02	2.08	3.10
2025_04_28 08_38	1.07	2.17	3.29
2025_04_28 09_19	1.02	2.10	3.22
2025_04_28 11_11	1.06	2.12	3.17
Mean	1.05	2.13	3.22
Standard Deviation	0.02	0.04	0.08
CV	2.3%	1.9%	2.6%

Table 9-24. TRC THOR-05F Neck EV0095 Right Torsion Repeatability Results

Test Number	Minimum Upper Neck M_z (Nm)	Maximum Upper Neck ω_z (deg/s)	Maximum Neck Fixture θ_z (deg)
2025_04_25 14_32	-20.0	1,318	51.1
2025_04_28 08_10	-19.7	1,264	50.2
2025_04_28 08_38	-19.9	1,300	51.2
2025_04_28 09_19	-19.8	1,302	51.2
2025_04_28 11_11	-19.8	1,286	51.1
Mean	-19.8	1,294	51.0
Standard Deviation	0.11	20.3	0.43
CV	0.6%	1.6%	0.8%

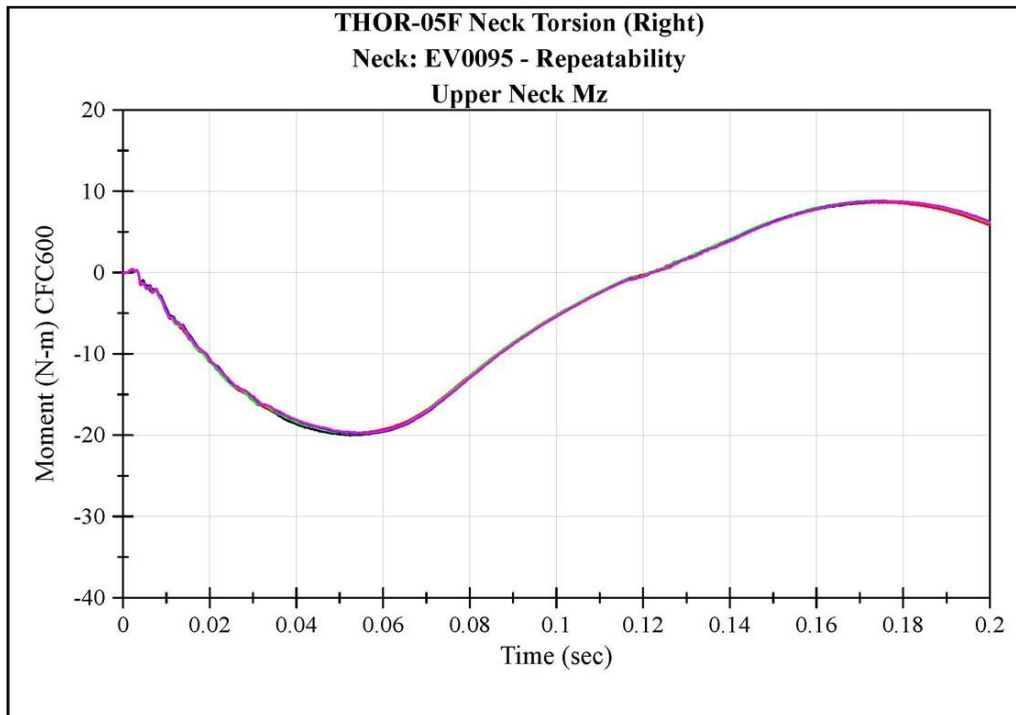


Figure 9-35. TRC neck right torsion upper neck Mz for THOR-05F Neck EV0095

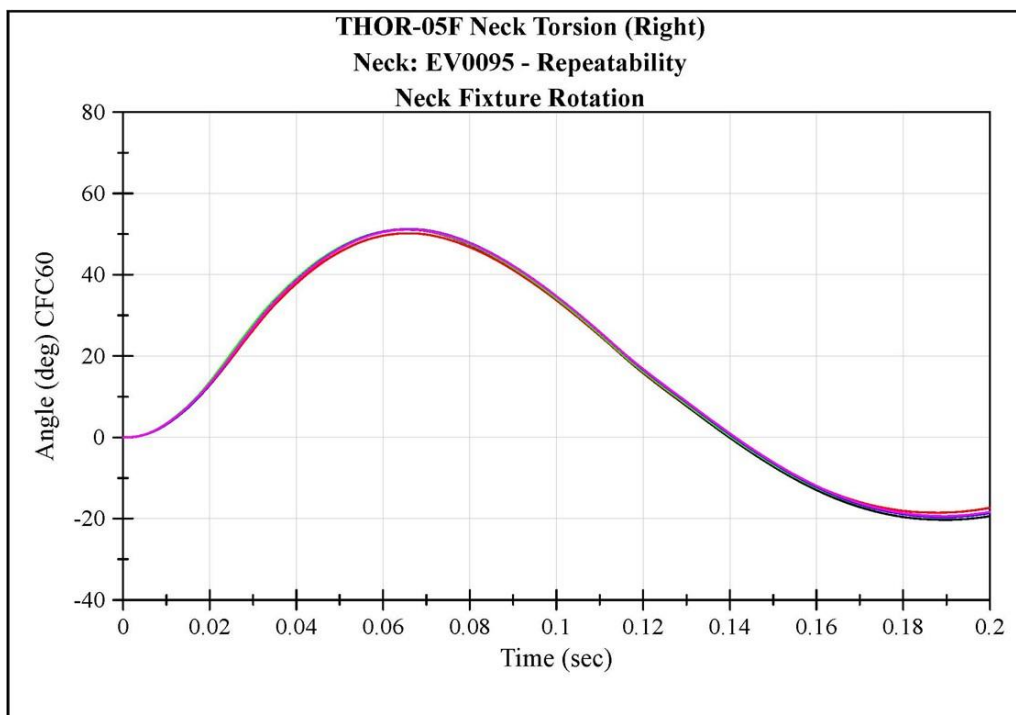


Figure 9-36. TRC neck right torsion neck fixture rotation for THOR-05F Neck EV0095

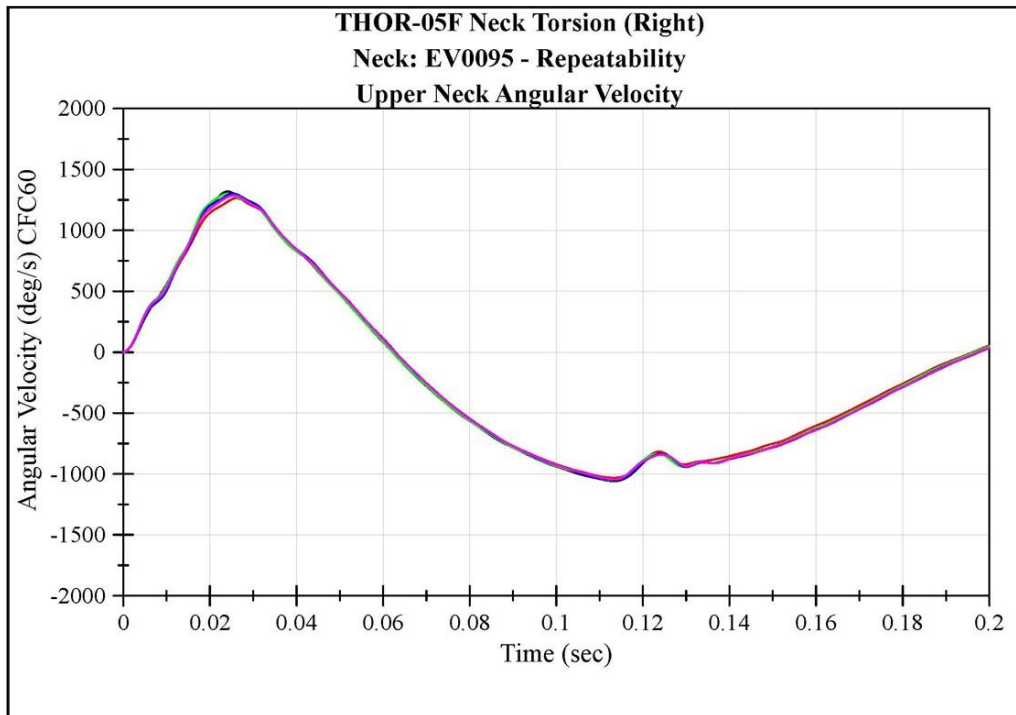


Figure 9-37. TRC neck right torsion head angular velocity about Z for THOR-05F Neck EV0095

9.3 Neck Torsion Dummy Reproducibility Results

Dummy Reproducibility results at VRTC for neck torsion yielded CV values below 5 percent (Table 9-25 through Table 9-26).

Table 9-25. THOR-05F Torsion Pulse Reproducibility Results

Neck Number	Test Number	Pendulum Velocity at 7 ms after T0 (m/s)	Pendulum Velocity at 14 ms after T0 (m/s)	Pendulum Velocity at 21 ms after T0 (m/s)
VRTC EU9863 Neck EU9734 Left	240327-18	1.11	2.02	2.96
	240327-19	1.00	2.02	2.99
	240327-20	0.97	1.99	2.99
	240328-1	1.04	2.08	3.08
	240328-2	1.03	2.08	3.07
VRTC EU9863 Neck EU9734 Right	240328-3	1.08	2.02	3.02
	240328-4	0.98	1.97	2.93
	240328-5	1.01	2.03	3.07
	240328-6	0.96	1.99	2.98
	240328-7	1.03	2.10	3.11
VRTC EV0674 Neck EV1357 Left	240524-2	0.99	2.07	3.09
	240524-3	1.04	2.10	3.10
	240528-2	0.93	1.92	2.92
	240528-10	1.06	2.15	3.13
VRTC EV0674 Neck EV1357 Right	240528-11	1.10	2.15	3.15
	240528-12	1.00	2.01	2.97
	240528-15	0.99	2.05	3.08
	240528-19	1.01	1.98	2.98
	240528-20	1.01	2.01	2.97
VRTC EV4675 Neck EV0095 Left	241125-5	1.03	1.90	2.85
	241125-7	1.01	2.08	3.14
	241126-2	0.98	2.01	3.01
	241126-3	0.96	1.92	2.86
	241126-4	0.94	1.93	2.90
VRTC EV4675 Neck EV0095 Right	241126-6	1.01	1.91	2.84
	241126-7	0.93	1.88	2.82
	241126-8	1.05	2.12	3.12
	241126-9	1.02	2.06	3.06
	241126-10	1.00	2.05	3.06
Mean		1.01	2.02	3.01
Standard Deviation		0.05	0.07	0.10
CV		4.6%	3.6%	3.2%

Table 9-26. THOR-05F Neck Torsion Reproducibility Results

Neck Number	Test Number	Min/Max* Upper Neck M_z (N-m)	Min/Max* Upper Neck ω_z (deg/s)	Min/Max Neck* Fixture Rotation ω_z (deg)
VRTC EU9863 Neck EU9734 Left	240327-18	19.9	1,266	54.0
	240327-19	19.7	1,285	54.2
	240327-20	19.6	1,282	54.4
	240328-1	19.8	1,266	53.0
	240328-2	19.7	1,288	53.8
VRTC EU9863 Neck EU9734 Right	240328-3	20.4	1,283	52.9
	240328-4	20.0	1,289	54.3
	240328-5	20.0	1,289	54.0
	240328-6	19.9	1,276	54.6
	240328-7	19.9	1,294	54.6
VRTC EV0674 Neck EV1357 Left	240524-2	20.9	1,261	51.1
	240524-3	21.1	1,261	51.9
	240528-2	20.8	1,253	51.1
	240528-10	20.9	1,248	51.5
VRTC EV0674 Neck EV1357 Right	240528-11	21.1	1,266	51.6
	240528-12	21.2	1,259	51.5
	240528-15	21.0	1,259	51.6
	240528-19	21.2	1,256	52.0
	240528-20	21.0	1,264	52.0
VRTC EU4675 Neck EV0095 Left	241125-5	20.5	1,237	51.8
	241125-7	20.4	1,272	53.7
	241126-2	20.3	1,255	52.9
	241126-3	20.3	1,252	53.9
	241126-4	20.1	1,255	54.2
VRTC EU4675 Neck EV0095 Right	241126-6	20.4	1,278	54.4
	241126-7	20.3	1,230	53.6
	241126-8	20.4	1,269	54.0
	241126-9	20.3	1,275	54.0
	241126-10	20.3	1,278	54.2
Mean		20.4	1,267	53.1
Standard Deviation		0.49	15.8	1.22
CV		2.4%	1.3%	2.3%

*Absolute value is shown, as used in corridor determination; these values are the minimum or maximum depending on if it is a left or right torsion test

9.4 Lab-to-Lab Variability Analysis

The results of the neck torsion qualification tests from each lab are presented in Figure 9-27 and Table 9-28. The last three rows of the tables show the *Test Reproducibility* results when data from all four labs are combined. *Test Reproducibility* results at VRTC, Humanetics, Calspan, and TRC for the neck torsion tests displayed CV values below 5 percent, except for velocity at 21 ms which was above 5 percent, but under 10 percent (Table 9-25 through Table 9-26).

Table 9-27. THOR-05F Torsion Pulse Reproducibility Results

Neck Number	Test Number	Pendulum Velocity at 7 ms after T0 (m/s)	Pendulum Velocity at 14 ms after T0 (m/s)	Pendulum Velocity at 21 ms after T0 (m/s)
VRTC EV4675 Neck EV0095 Left	241125-5	1.03	1.90	2.85
	241125-7	1.01	2.08	3.14
	241126-2	0.98	2.01	3.01
	241126-3	0.96	1.92	2.86
	241126-4	0.94	1.93	2.90
VRTC EV4675 Neck EV0095 Right	241126-6	1.01	1.91	2.84
	241126-7	0.93	1.88	2.82
	241126-8	1.05	2.12	3.12
	241126-9	1.02	2.06	3.06
	241126-10	1.00	2.05	3.06
Humanetics EV4675 Neck EV0095 Left	686486	0.97	1.98	2.99
	686554	1.00	2.10	3.20
	686521	1.03	2.20	3.28
	686536	0.94	1.96	2.95
	686544	0.96	1.95	2.92
Humanetics EV4675 Neck EV0095 Right	686599	0.95	2.05	3.06
	686595	0.95	1.95	2.91
	686618	0.93	1.98	2.95
	686690	0.96	2.05	3.08
	686569	0.96	2.01	3.01
Calspan EV4675 Neck EV0095 Left	2025_03_12_17_32	0.97	2.18	3.35
	2025_03_17_09_45	0.95	2.10	3.24
	2025_03_17_16_10	0.95	2.13	3.26
	2025_03_17_16_43	0.95	2.11	3.28
	2025_03_18_08_13	0.94	2.15	3.32
Calspan EV4675 Neck EV0095 Right	2025_03_12_18_01	0.93	2.08	3.22
	2025_03_13_11_02	0.93	2.08	3.26
	2025_03_14_15_53	0.97	2.15	3.28
	2025_03_17_08_36	1.01	2.19	3.29
	2025_03_17_09_09	0.99	2.17	3.29
TRC EV4675 Neck EV0095 Left	2025_04_25_10_59	1.06	2.24	3.32
	2025_04_25_11_45	1.05	2.22	3.29
	2025_04_25_12_36	1.06	2.22	3.34
	2025_04_25_13_25	1.06	2.20	3.29
	2025_04_25_13_39	1.03	2.15	3.22
TRC EV4675 Neck EV0095 Right	2025_04_25_14_32	1.06	2.17	3.30
	2025_04_28_08_10	1.02	2.08	3.10
	2025_04_28_08_38	1.07	2.17	3.29
	2025_04_28_09_19	1.02	2.10	3.22
	2025_04_28_11_11	1.06	2.12	3.17
Test Reproducibility Neck EV0095				
Mean		0.99	2.08	3.13
Standard Deviation		0.05	0.100	0.166
CV		4.6%	4.8%	5.3%

Table 9-28. THOR-05F Neck Torsion Reproducibility Results

Neck Number	Test Number	Min/Max* Upper Neck M_z (N-m)	Min/Max* Upper Neck ω_z (deg/s)	Min/Max Neck* Fixture Rotation ω_z (deg)
VRTC EV4675 Neck EV0095 Left	241125-5	20.5	1,237	51.8
	241125-7	20.4	1,272	53.7
	241126-2	20.3	1,255	52.9
	241126-3	20.3	1,252	53.9
	241126-4	20.1	1,255	54.2
VRTC EV4675 Neck EV0095 Right	241126-6	20.4	1,278	54.4
	241126-7	20.3	1,230	53.6
	241126-8	20.4	1,269	54.0
	241126-9	20.3	1,275	54.0
	241126-10	20.3	1,278	54.2
Humanetics EV4675 Neck EV0095 Left	686486	19.9	1,248	48.8
	686554	20.3	1,289	49.5
	686521	20.5	1,283	49.1
	686536	20.1	1,262	48.8
	686544	19.9	1,242	48.5
Humanetics EV4675 Neck EV0095 Right	686599	20.4	1,286	48.8
	686595	20.1	1,242	47.6
	686618	20.0	1,239	47.9
	686690	20.2	1,271	48.1
	686569	20.1	1,254	48.4
Calspan EV4675 Neck EV0095 Left	2025_03_12_17_32	21.2	1,386	50.5
	2025_03_17_09_45	20.8	1,336	49.8
	2025_03_17_16_10	20.8	1,335	49.4
	2025_03_17_16_43	21.1	1,342	49.1
	2025_03_18_08_13	21.2	1,347	48.9
Calspan EV4675 Neck EV0095 Right	2025_03_12_18_01	21.1	1,319	49.8
	2025_03_13_11_02	21.2	1,309	48.8
	2025_03_14_15_53	21.0	1,347	51.6
	2025_03_17_08_36	22.0	1,304	50.7
	2025_03_17_09_09	21.0	1,324	50.1
TRC EV4675 Neck EV0095 Left	2025_04_25_10_59	19.9	1,321	51.3
	2025_04_25_11_45	19.8	1,318	51.0
	2025_04_25_12_36	19.8	1,319	51.4
	2025_04_25_13_25	19.9	1,315	51.5
	2025_04_25_13_39	19.7	1,314	51.2
TRC EV4675 Neck EV0095 Right	2025_04_25_14_32	20.0	1,318	51.1
	2025_04_28_08_10	19.7	1,264	50.2
	2025_04_28_08_38	19.9	1,300	51.2
	2025_04_28_09_19	19.8	1,302	51.2
	2025_04_28_11_11	19.8	1,286	51.1
Test Reproducibility Neck EV0095				
Mean		20.4	1,291	50.8
Standard Deviation		0.53	37.0	2.03
CV		2.6%	2.9%	4.0%

* Absolute value is shown, as used in corridor determination; these values are the minimum or maximum depending on if it is a left or right torsion test

9.5 Corridor Development

All the data used to determine the neck torsion qualification corridors is shown in Table 9-29 and Table 9-30. The qualification corridors were calculated using the mean plus or minus 10 percent of the peak for the specified measured or calculated channels (Table 9-31). All data used for the corridor development resulted in CV values below 5 percent.

Table 9-29. THOR-05F Neck Torsion Pulse Qualification Corridor Results
(Highlighted values fell outside average $\pm 10\%$.)

Neck Number		Test Number	Pendulum Velocity at 7 ms after T0 (m/s)	Pendulum Velocity at 14 ms after T0 (m/s)	Pendulum Velocity at 21 ms after T0 (m/s)
VRTC Neck EU9734	Left	240327-18	1.11	2.02	2.96
		240327-19	1.00	2.02	2.99
		240327-20	0.97	1.99	2.99
		240328-1	1.04	2.08	3.08
		240328-2	1.03	2.08	3.07
	Right	240328-3	1.08	2.02	3.02
		240328-4	0.98	1.97	2.93
		240328-5	1.01	2.03	3.07
		240328-6	0.96	1.99	2.98
		240328-7	1.03	2.10	3.11
VRTC Neck EV1357	Left	240524-2	0.99	2.07	3.09
		240524-3	1.04	2.10	3.10
		240528-2	0.93	1.92	2.92
		240528-10	1.06	2.15	3.13
	Right	240528-11	1.10	2.15	3.15
		240528-12	1.00	2.01	2.97
		240528-15	0.99	2.05	3.08
		240528-19	1.01	1.98	2.98
		240528-20	1.01	2.01	2.97

VRTC Neck EV0095	Left	241125-5	1.03	1.90	2.85
		241125-7	1.01	2.08	3.14
		241126-2	0.98	2.01	3.01
		241126-3	0.96	1.92	2.86
		241126-4	0.94	1.93	2.90
	Right	241126-6	1.01	1.91	2.84
		241126-7	0.93	1.88	2.82
		241126-8	1.05	2.12	3.12
		241126-9	1.02	2.06	3.06
		241126-10	1.00	2.05	3.06
Humanetics Neck EV0095	Left	686486	0.97	1.98	2.99
		686554	1.00	2.10	3.20
		686521	1.03	2.20	3.28
		686536	0.94	1.96	2.95
		686544	0.96	1.95	2.92
	Right	686599	0.95	2.05	3.06
		686595	0.95	1.95	2.91
		686618	0.93	1.98	2.95
		686690	0.96	2.05	3.08
		686569	0.96	2.01	3.01
Calspan Neck EV0095	Left	2025_03_12_17_32	0.97	2.18	3.35
		2025_03_17_09_45	0.95	2.10	3.24
		2025_03_17_16_10	0.95	2.13	3.26
		2025_03_17_16_43	0.95	2.11	3.28
		2025_03_18_08_13	0.94	2.15	3.32
	Right	2025_03_12_18_01	0.93	2.08	3.22
		2025_03_13_11_02	0.93	2.08	3.26
		2025_03_14_15_53	0.97	2.15	3.28
		2025_03_17_08_36	1.01	2.19	3.29
		2025_03_17_09_09	0.99	2.17	3.29
TRC Neck EV0095	Left	2025_04_25_10_59	1.06	2.24	3.32
		2025_04_25_11_45	1.05	2.22	3.29
		2025_04_25_12_36	1.06	2.22	3.34
		2025_04_25_13_25	1.06	2.20	3.29
		2025_04_25_13_39	1.03	2.15	3.22
	Right	2025_04_25_14_32	1.06	2.17	3.30
		2025_04_28_08_10	1.02	2.08	3.10
		2025_04_28_08_38	1.07	2.17	3.29
		2025_04_28_09_19	1.02	2.10	3.22
		2025_04_28_11_11	1.06	2.12	3.17
Mean			1.00	2.06	3.10
Standard Deviation			0.05	0.09	0.15
CV			4.8%	4.4%	4.8%

Table 9-30. THOR-05F Neck Torsion Qualification Corridor Results

Neck Number		Test Number	Min/Max* Upper Neck M_z (N-m)	Min/Max* Head Angular Velocity ω_z (relative to earth) (deg/s)	Min/Max Head* Rotation (relative to pendulum) (deg)
VRTC Neck EU9734	Left	240327-18	19.9	1,266	54.0
		240327-19	19.7	1,285	54.2
		240327-20	19.6	1,282	54.4
		240328-1	19.8	1,266	53.0
		240328-2	19.7	1,288	53.8
	Right	240328-3	20.4	1,283	52.9
		240328-4	20.0	1,289	54.3
		240328-5	20.0	1,289	54.0
		240328-6	19.9	1,276	54.6
		240328-7	19.9	1,294	54.6
VRTC Neck EV1357	Left	240524-2	20.9	1,261	51.1
		240524-3	21.1	1,261	51.9
		240528-2	20.8	1,253	51.1
		240528-10	20.9	1,248	51.5
	Right	240528-11	21.1	1,266	51.6
		240528-12	21.2	1,259	51.5
		240528-15	21.0	1,259	51.6
		240528-19	21.2	1,256	52.0
		240528-20	21.0	1,264	52.0
VRTC Neck EV0095	Left	241125-5	20.5	1,237	51.8
		241125-7	20.4	1,272	53.7
		241126-2	20.3	1,255	52.9
		241126-3	20.3	1,252	53.9
		241126-4	20.1	1,255	54.2
	Right	241126-6	20.4	1,278	54.4
		241126-7	20.3	1,230	53.6
		241126-8	20.4	1,269	54.0
		241126-9	20.3	1,275	54.0
		241126-10	20.3	1,278	54.2
Humanetics Neck EV0095	Left	686486	19.9	1,248	48.8
		686554	20.3	1,289	49.5
		686521	20.5	1,283	49.1
		686536	20.1	1,262	48.8
		686544	19.9	1,242	48.5
	Right	686599	20.4	1,286	48.8
		686595	20.1	1,242	47.6
		686618	20.0	1,239	47.9
		686690	20.2	1,271	48.1
		686569	20.1	1,254	48.4

Calspan Neck EV0095	Left	2025_03_12 17_32	21.2	1,386	50.5
		2025_03_17 09_45	20.8	1,336	49.8
		2025_03_17 16_10	20.8	1,335	49.4
		2025_03_17 16_43	21.1	1,342	49.1
		2025_03_18 08_13	21.2	1,347	48.9
	Right	2025_03_12 18_01	21.1	1,319	49.8
		2025_03_13 11_02	21.2	1,309	48.8
		2025_03_14 15_53	21.0	1,347	51.6
		2025_03_17 08_36	22.0	1,304	50.7
		2025_03_17 09_09	21.0	1,324	50.1
TRC Neck EV0095	Left	2025_04_25 10_59	19.9	1,321	51.3
		2025_04_25 11_45	19.8	1,318	51.0
		2025_04_25 12_36	19.8	1,319	51.4
		2025_04_25 13_25	19.9	1,315	51.5
		2025_04_25 13_39	19.7	1,314	51.2
	Right	2025_04_25 14_32	20.0	1,318	51.1
		2025_04_28 08_10	19.7	1,264	50.2
		2025_04_28 08_38	19.9	1,300	51.2
		2025_04_28 09_19	19.8	1,302	51.2
		2025_04_28 11_11	19.8	1,286	51.1
Mean			20.4	1,284	51.5
Standard Deviation			0.55	32.7	2.06
CV			2.9%	2.5%	4.0%

*Absolute value is shown, as used in corridor determination; these values are the minimum or maximum depending on if it is a left or right torsion test

Table 9-31. Neck Torsion Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Pendulum Velocity at 7 ms after T0	m/s	0.90	1.10	1.00	10.0%
Pendulum Velocity at 14 ms after T0	m/s	1.86	2.27	2.06	10.0%
Pendulum Velocity at 21 ms after T0	m/s	2.79	3.41	3.10	10.0%
Impact Velocity	m/s	3.35	3.45	3.40	
Left Torsion					
Maximum Upper Neck Moment M_z	N-m	18.3	22.4	20.4	10.0%
Minimum Neck Fixture Rotation Angle θ_z	deg	-56.6	-46.3	-51.5	10.0%
Minimum Upper Neck Angular Velocity ω_z (relative to earth)	deg/s	-1,413	-1,156	-1,284	10.0%
Right Torsion					
Minimum Upper Neck Moment M_z	N-m	-22.4	-18.3	-20.4	10.0%
Maximum Neck Fixture Rotation Angle θ_z	deg	46.3	56.6	51.5	10.0%
Maximum Upper Neck Angular Velocity ω_z (relative to earth)	deg/s	1,156	1,413	1,284	10.0%

Discussion. The single highlighted cell in Table 9-29 indicates the only instance that the test failed to meet the response $\pm 10\%$ in Table 9-31. All CV values for corridor development are below 5 percent.

Repeatability CV values were all below 5 percent for moment, angular velocity, and rotation, both on left and right side tests. The only instances where CV values were slightly above 5 percent were in some cases with the pendulum velocity; considering the small magnitude of the target velocity and the limitations using Hexcel to control the pulse, the slightly elevated CV is not indicative of repeatability issues.

Dummy Reproducibility CV values were all below 5 percent.

The lab-to-lab *Test Reproducibility* CV values were all below 5 percent.

10 UPPER THORAX

10.1 Methodology

Repeatability and reproducibility tests were performed using the upper thorax qualification procedures described in the *THOR-05F Qualification Procedures and Requirements*. This test requires a blunt thoracic impact to the sternum, similar to the Hybrid III 5th percentile female certification test, but at a lower speed of $4.30 \text{ m/s} \pm 0.05 \text{ m/s}$ (Figure 10-1). The upper ribcage central impact test uses the same impactor as the Hybrid III 5th percentile female ATD. In this test, an impactor with a mass of $13.97 \pm 0.02 \text{ kg}$ and a $152.40 \pm 0.25 \text{ mm}$ diameter rigid cylinder 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.

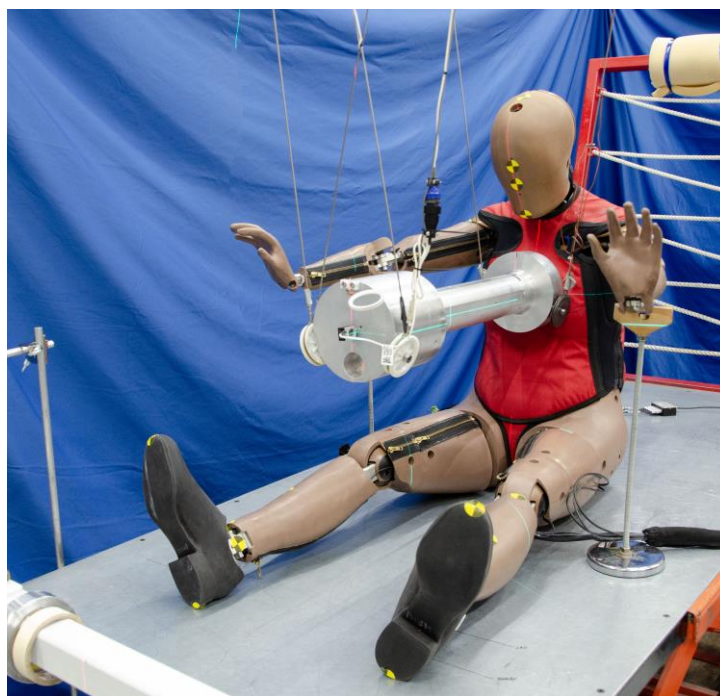


Figure 10-1. Upper thorax impact test setup

10.2 Upper Thorax Repeatability Results

Sections 10.2.1 through 10.2.6 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 four 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.

The difference between the left and right resultant deflections was also calculated to assure an even impact to the upper thorax. Ideally, the difference should be zero in a symmetrical impact scenario. The mean, standard deviation, and CV were not calculated for this metric since it is primarily intended be a threshold to ensure that the dummy is sitting normal to the probe and not twisted about the

z-axis. Additionally, left-to-right differences exceeding the 5 mm threshold could flag other setup variations which allowed a nonsymmetrical impact or a problem with the instrumentation.

10.2.1 THOR-05F EU9863 Testing at VRTC

Repeatability results for upper thorax testing on EU9863 at VRTC yielded CV values below 5 percent (Table 10-1, Figure 10-2 through Figure 10-6).

Table 10-1. VRTC THOR-05F Upper Thorax Repeatability Results for EU9863

Test Number	Maximum Probe Force (N)	Maximum Upper Left Resultant Deflection (mm)	Maximum Upper Right Resultant Deflection (mm)	Difference Between Max Left & Right Resultant Deflections (mm)	Force at Left Max Resultant Deflection (N)	Force at Right Max Resultant Deflection (N)
240212-1	1,905	32.6	36.8	4.2	1,881	1,868
240212-6	1,986	34.2	35.5	1.3	1,803	1,795
240212-7	2,010	33.4	34.9	1.5	1,819	1,830
240213-1	1,925	34.1	34.2	0.1	1,823	1,807
240213-2	1,936	34.5	34.8	0.4	1,830	1,854
Mean	1,952	34.5		N/A	1,831	
Standard Deviation	43.8	1.1		N/A	28.6	
CV	2.2%	3.3%		N/A	1.6%	

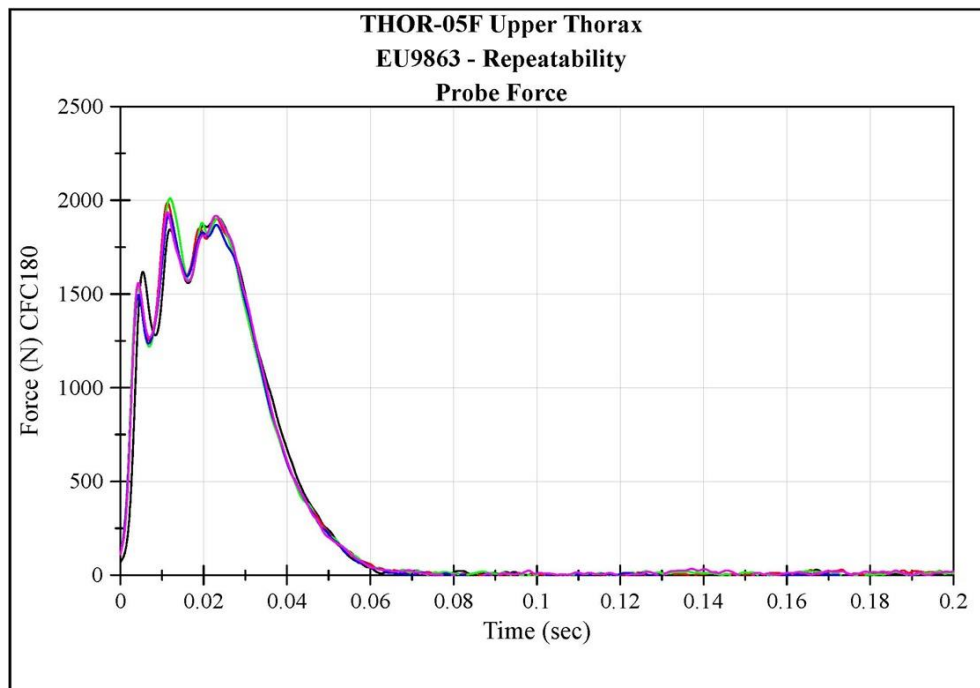


Figure 10-2. VRTC probe force for upper thorax impact repeatability tests for EU9863

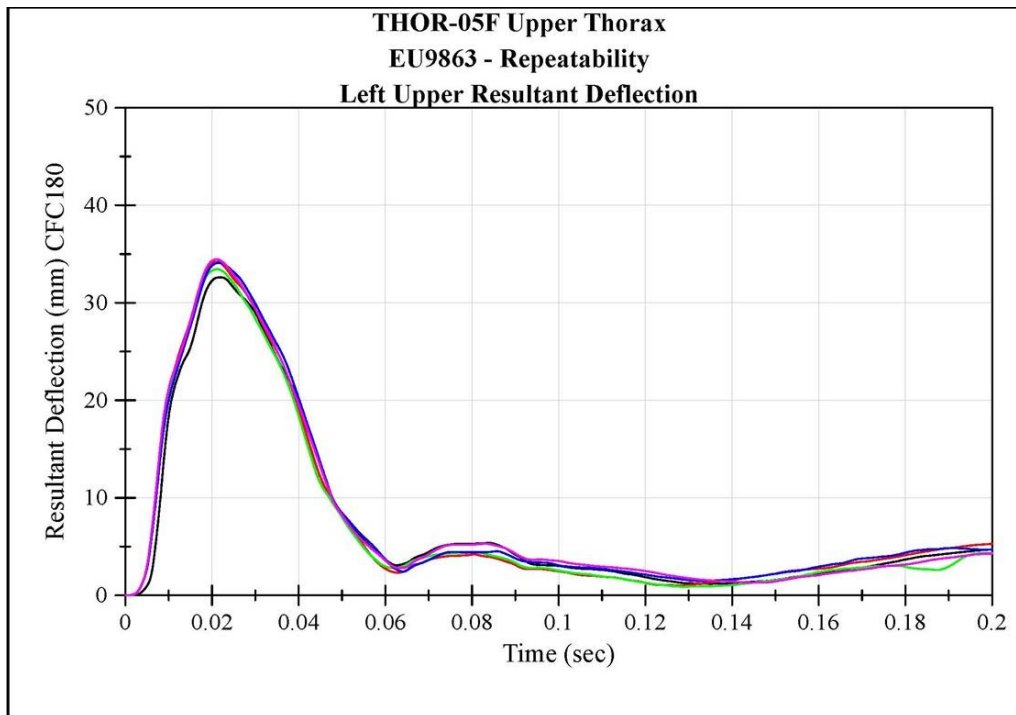


Figure 10-3. VRTC upper left resultant deflection for upper thorax impact repeatability tests for EU9863

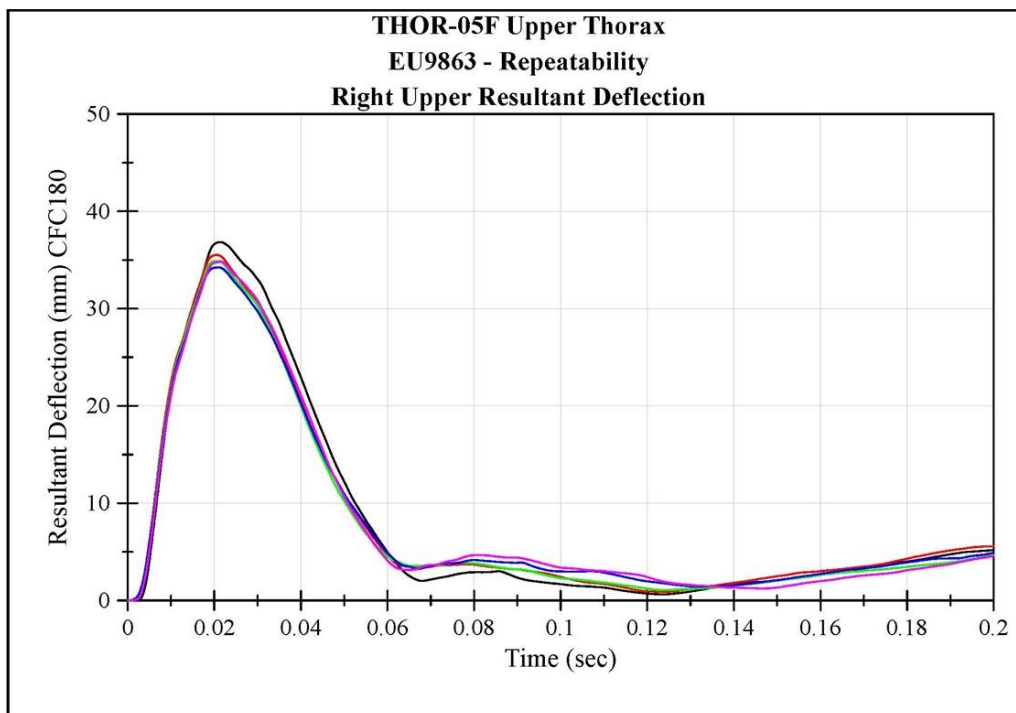


Figure 10-4. VRTC upper right resultant deflection for upper thorax impact repeatability tests for EU9863

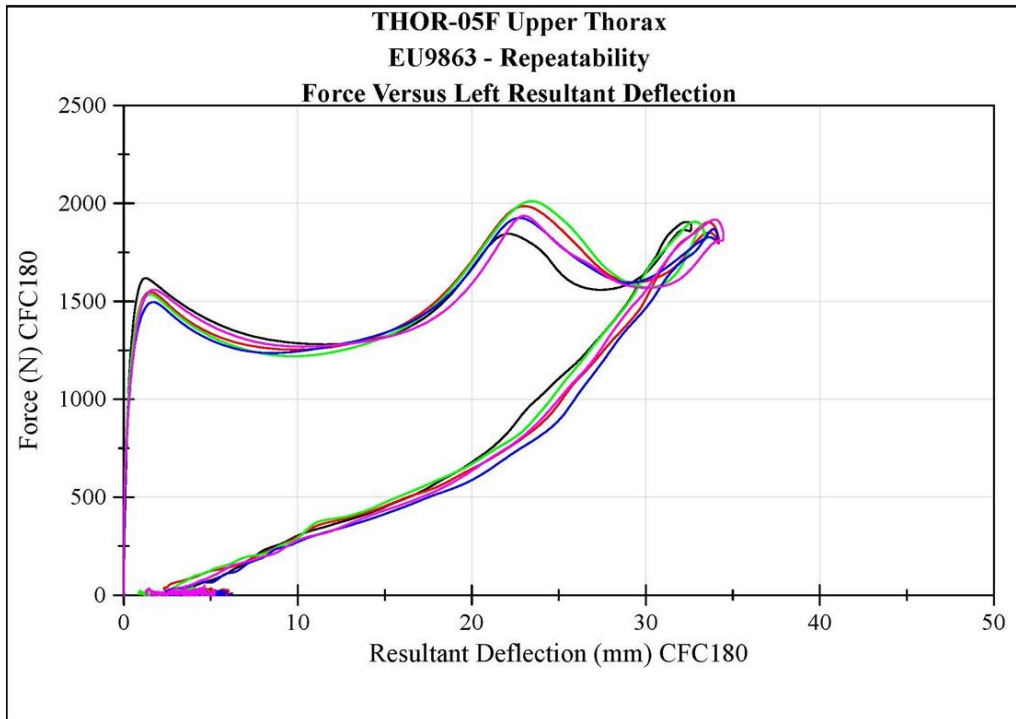


Figure 10-5. VRTC force vs. left resultant deflection for upper thorax repeatability tests for EU9863

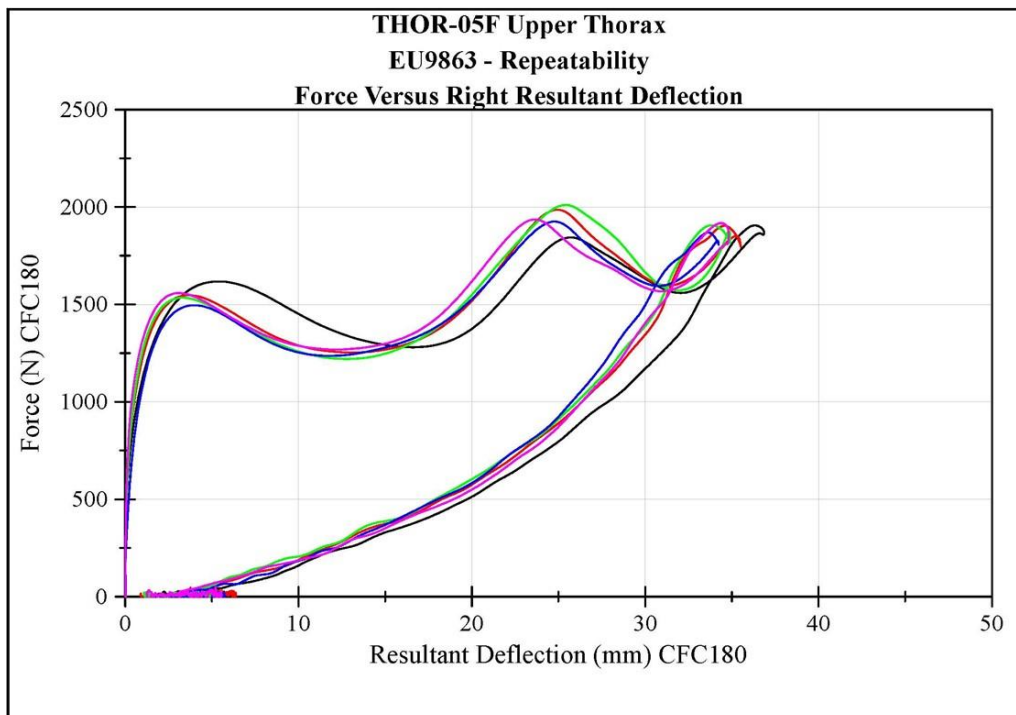


Figure 10-6. VRTC force vs. right resultant deflection for upper thorax impact repeatability tests for EU9863

10.2.2 THOR-05F EU3430 Testing at VRTC

Repeatability results for upper thorax testing on EU3430 at VRTC yielded CV values below 5 percent (Table 10-2, Figure 10-7 through Figure 10-11).

Table 10-2. VRTC THOR-05F Upper Thorax Repeatability Results for EU3430

Test Number	Maximum Probe Force (N)	Maximum Upper Left Resultant Deflection (mm)	Maximum Upper Right Resultant Deflection (mm)	Difference Between Max Left & Right Resultant Deflections (mm)	Force at Left Max Resultant Deflection (N)	Force at Right Max Resultant Deflection (N)
240814-9	2,081	38.1	38.5	0.4	1,735	1,762
240814-11	2,036	37.6	38.0	0.4	1,723	1,732
240815-1	1,991	36.6	38.3	1.7	1,738	1,742
240815-2	2,074	37.5	38.0	0.5	1,741	1,717
240815-3	2,039	38.4	37.0	-1.4	1,753	1,764
Mean	2,044	37.8		N/A	1,741	
Standard Deviation	35.9	0.6		N/A	15.5	
CV	1.8%	1.6%		N/A	0.9%	

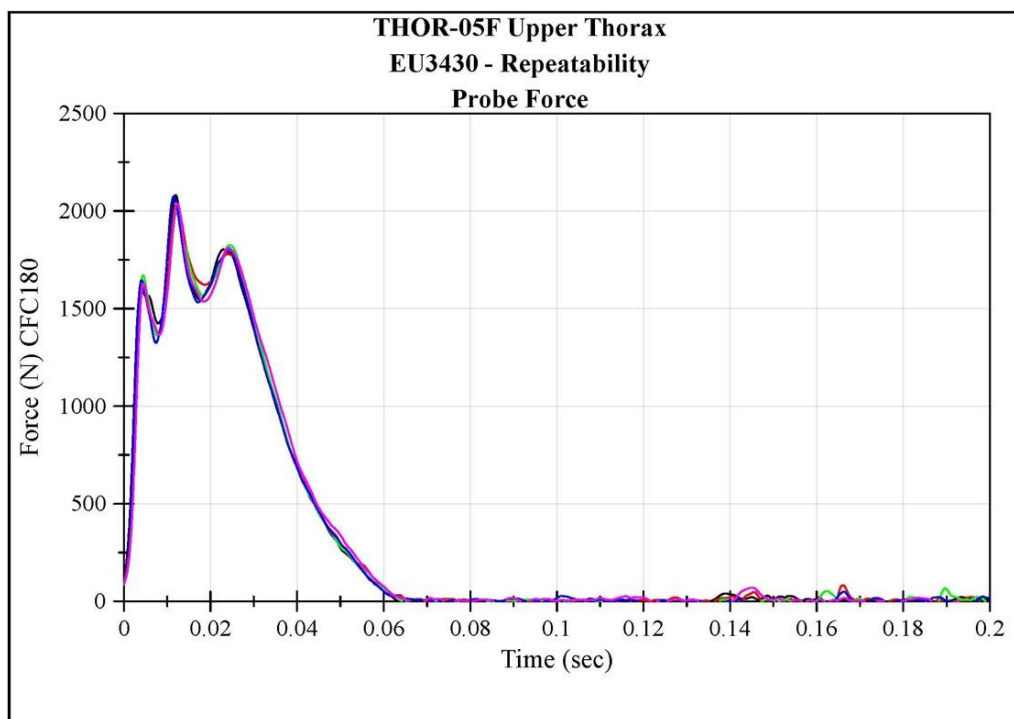


Figure 10-7. VRTC probe force for upper thorax impact repeatability tests for EU3430

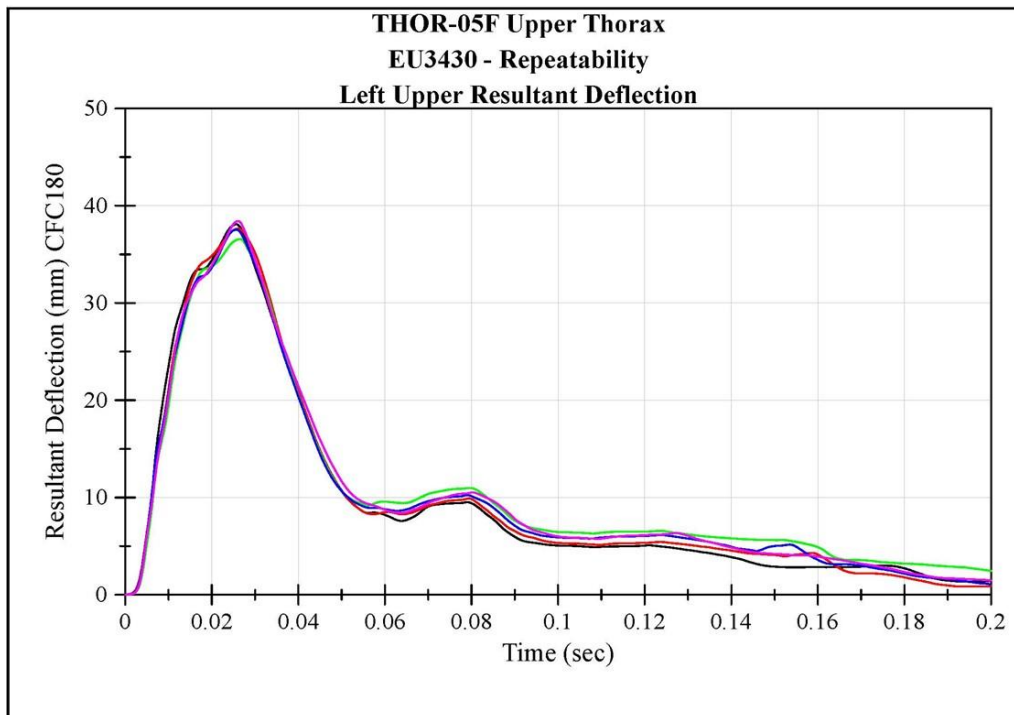


Figure 10-8. VRTC upper left resultant deflection for upper thorax impact repeatability tests for EU3430

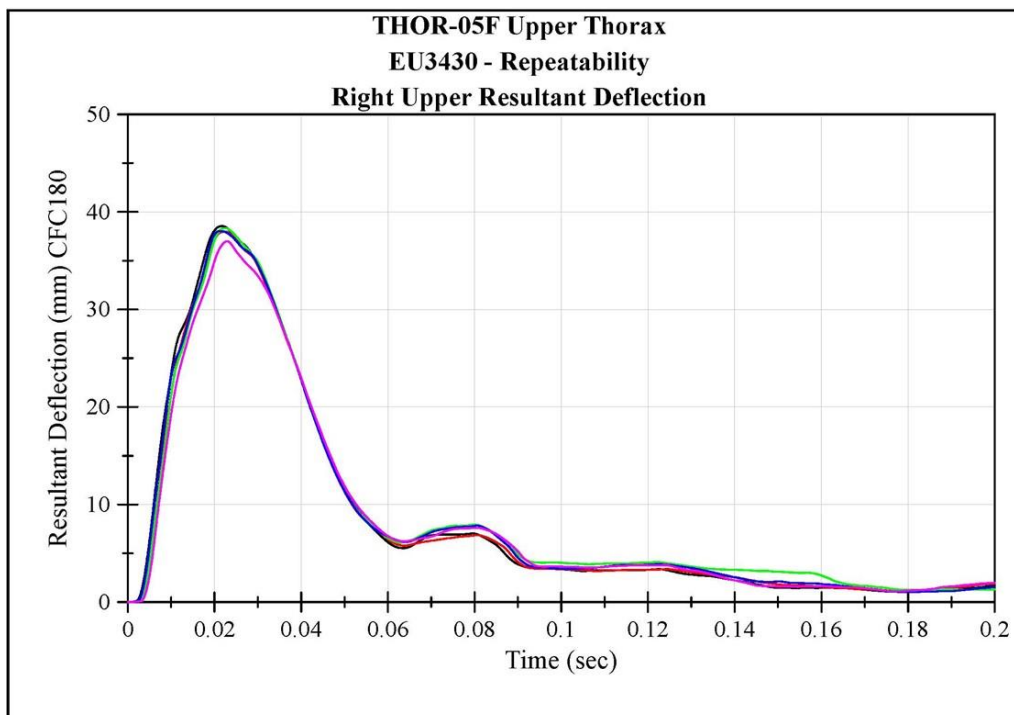


Figure 10-9. VRTC upper right resultant deflection for upper thorax impact repeatability tests for EU3430

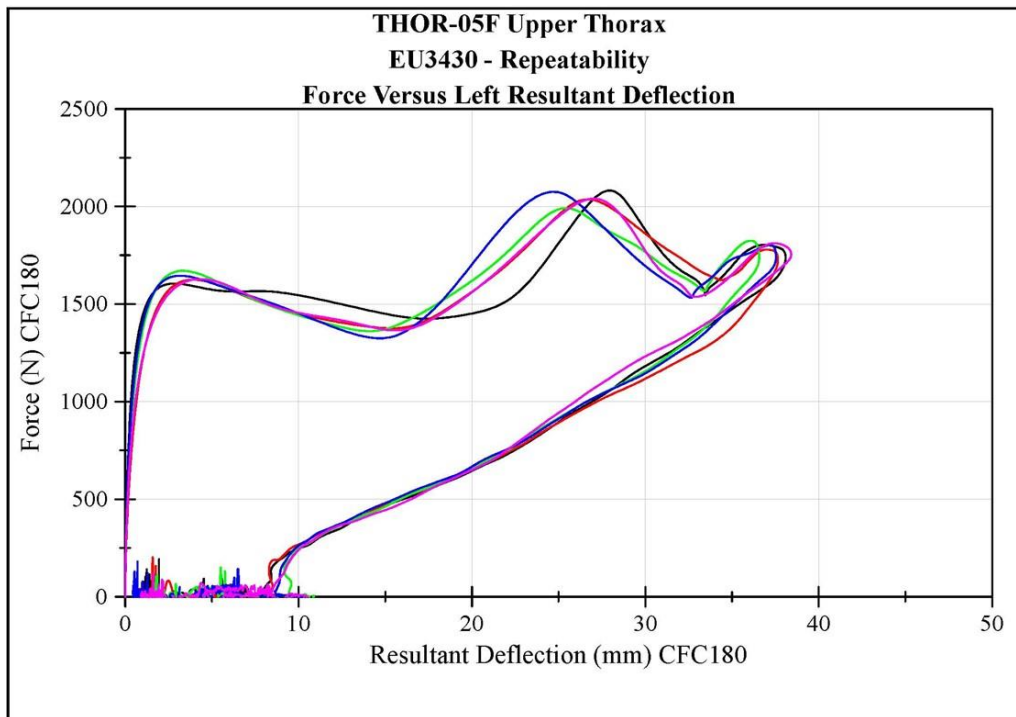


Figure 10-10. VRTC force versus left resultant deflection for upper thorax repeatability tests for EU3430

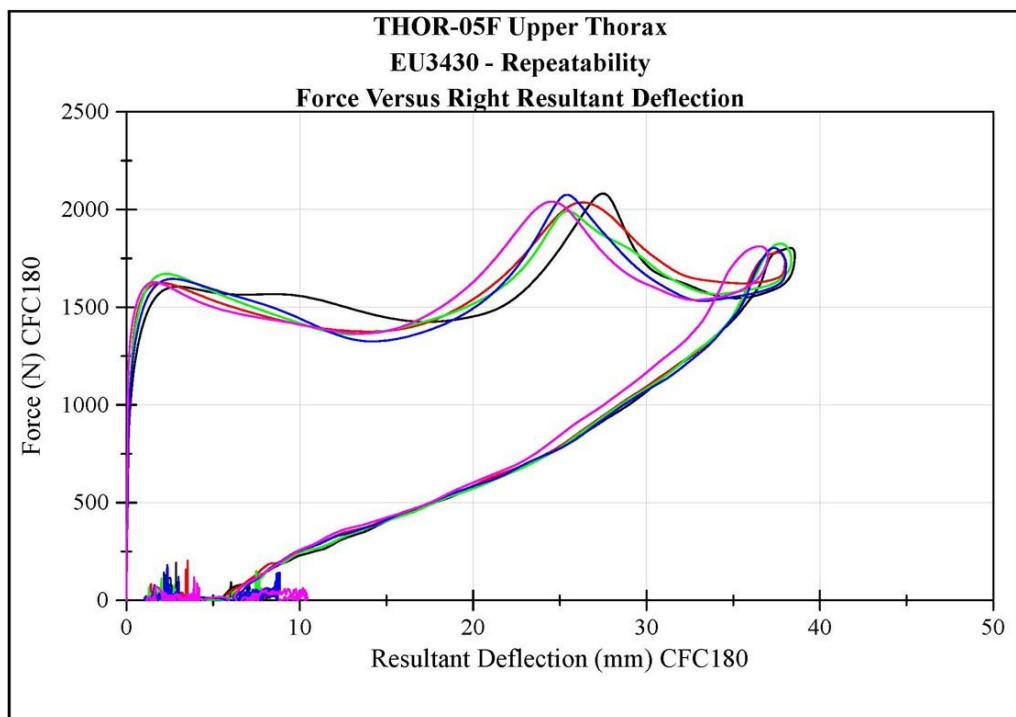


Figure 10-11. VRTC force versus right resultant deflection for upper thorax repeatability tests for EU3430

10.2.3 THOR-05F EV4675 Testing at VRTC

Repeatability results for upper thorax testing on EV4675 at VRTC yielded CV values below 5 percent (Table 10-3, Figure 10-12 through Figure 10-16).

Table 10-3. VRTC THOR-05F Upper Thorax Repeatability Results for EV4675

Test Number	Maximum Probe Force (N)	Maximum Upper Left Resultant Deflection (mm)	Maximum Upper Right Resultant Deflection (mm)	Difference Between Max Left & Right Resultant Deflections (mm)	Force at Left Max Resultant Deflection (N)	Force at Right Max Resultant Deflection (N)
240617-4	1,904	32.8	35.6	2.8	1,688	1,703
240617-8	1,916	34.5	34.4	-0.1	1,748	1,698
240617-9	1,869	34.5	34.1	-0.4	1,663	1,632
240617-10	2,033	35.0	31.8	-3.2	1,755	1,699
240618-1	1,915	35.1	33.6	-1.4	1,750	1,711
Mean	1,927	34.1		N/A	1,705	
Standard Deviation	62.0	1.1		N/A	39.5	
CV	3.2%	3.3%		N/A	2.3%	

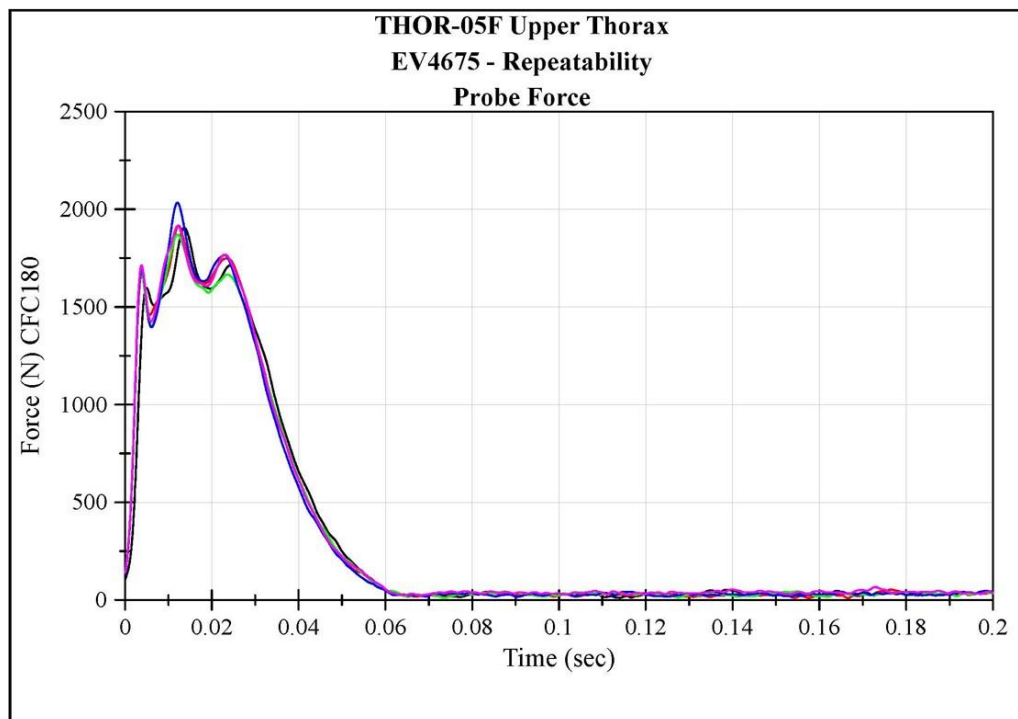


Figure 10-12. VRTC probe fore for upper thorax impact repeatability tests for EV4675

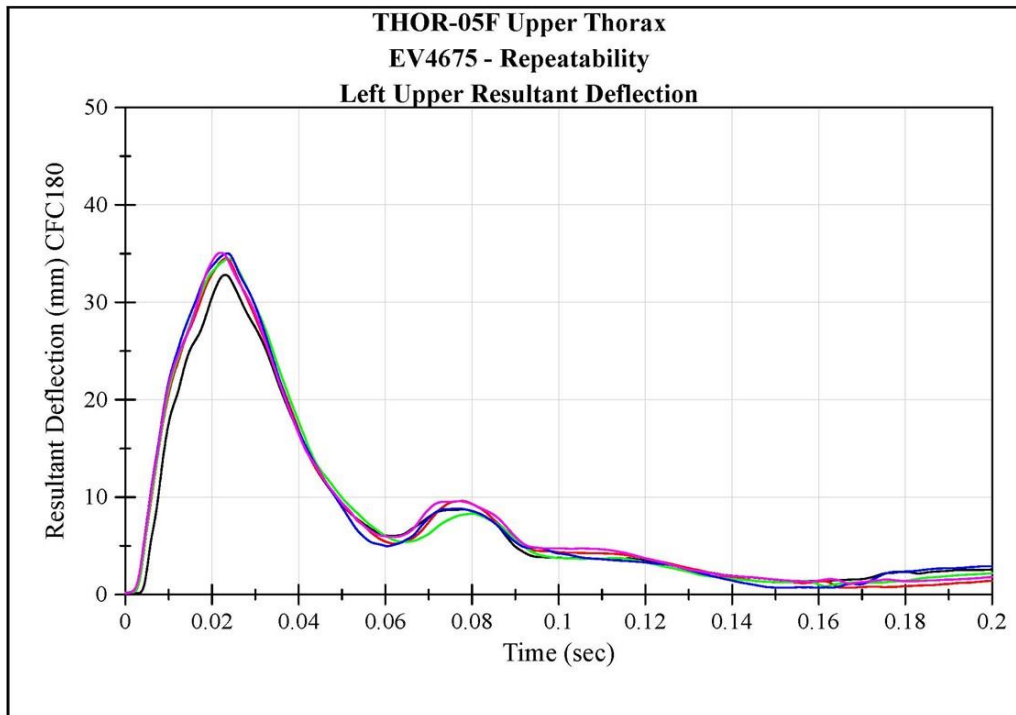


Figure 10-13. VRTC upper left resultant deflection for upper thorax impact repeatability tests for EV4675

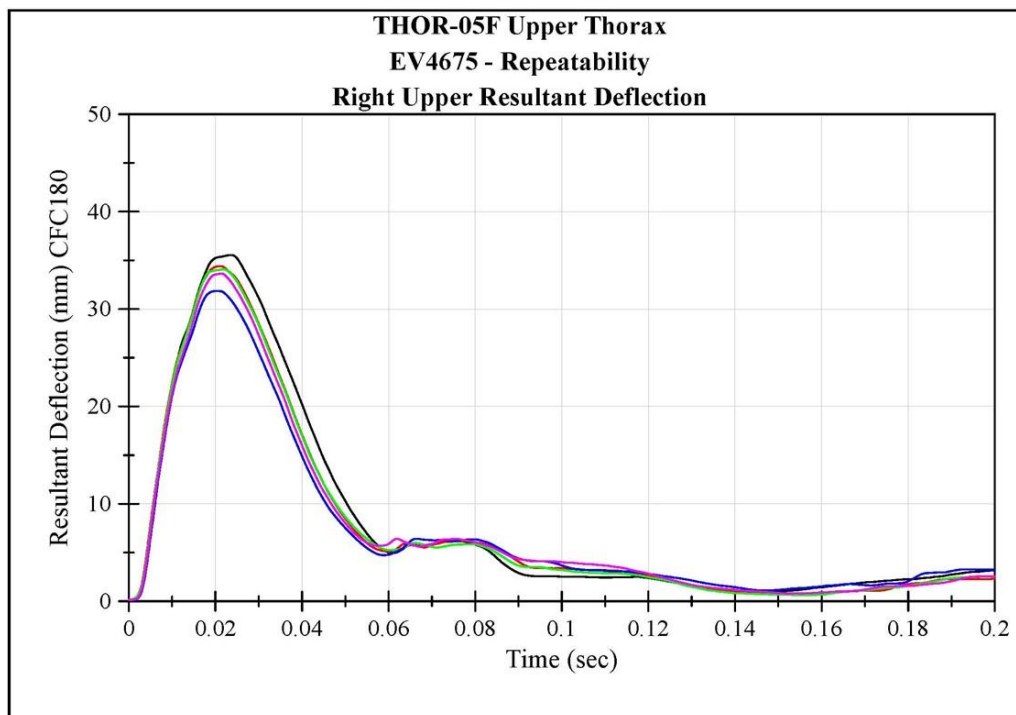


Figure 10-14. VRTC upper right resultant deflection for upper thorax impact repeatability tests for EV4675

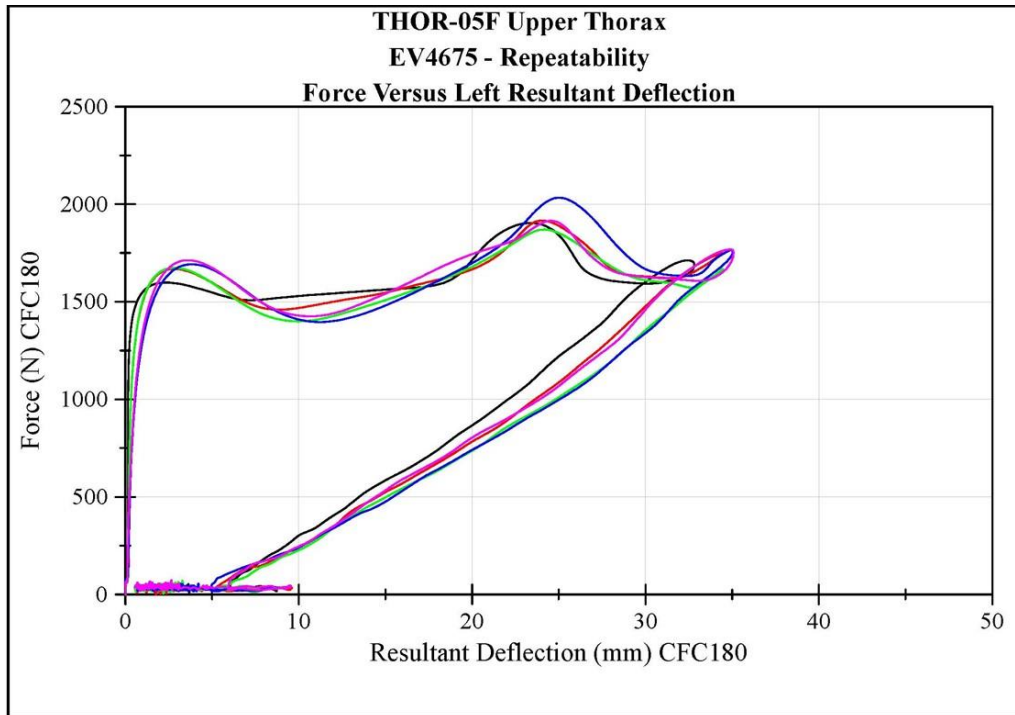


Figure 10-15. VRTC force versus left resultant deflection for upper thorax repeatability tests for EV4675

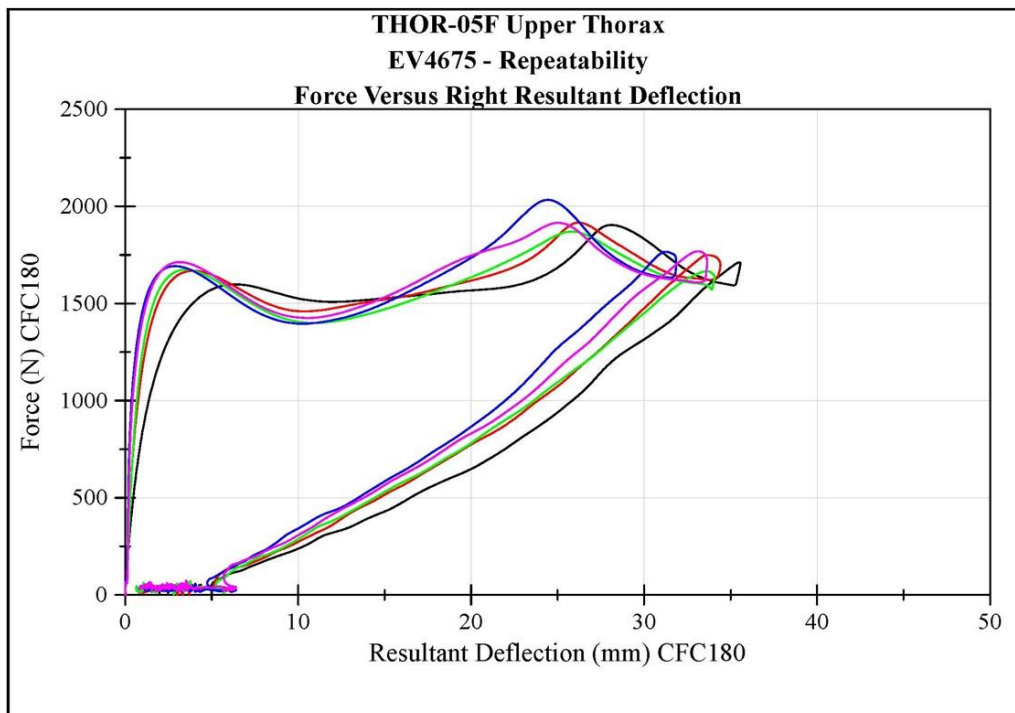


Figure 10-16. VRTC force versus right resultant deflection for upper thorax repeatability tests for EV4675

10.2.4 THOR-05F EV4675 Testing at Humanetics

Repeatability results for upper thorax testing on EV4675 at Humanetics yielded CV values below 5 percent (Table 10-4, Figure 10-17 through Figure 10-21).

Table 10-4. Humanetics THOR-05F Upper Thorax Repeatability Results for EV4675

Test Number	Maximum Probe Force (N)	Maximum Upper Left Resultant Deflection (mm)	Maximum Upper Right Resultant Deflection (mm)	Difference Between Max Left & Right Resultant Deflections (mm)	Force at Left Max Resultant Deflection (N)	Force at Right Max Resultant Deflection (N)
688653	1,913	38.2	37.0	-1.2	1,846	1,821
688619	2,012	39.0	38.0	-1.0	1,723	1,798
688608	1,990	38.5	36.9	-1.6	1,896	1,889
688117	2,034	34.9	35.7	0.8	1,884	1,872
687990	2,033	35.5	35.2	-0.3	1,861	1,868
Mean	1,996	36.9		N/A	1,846	
Standard Deviation	49.9	1.5		N/A	53.1	
CV	2.5%	4.1%		N/A	2.9%	

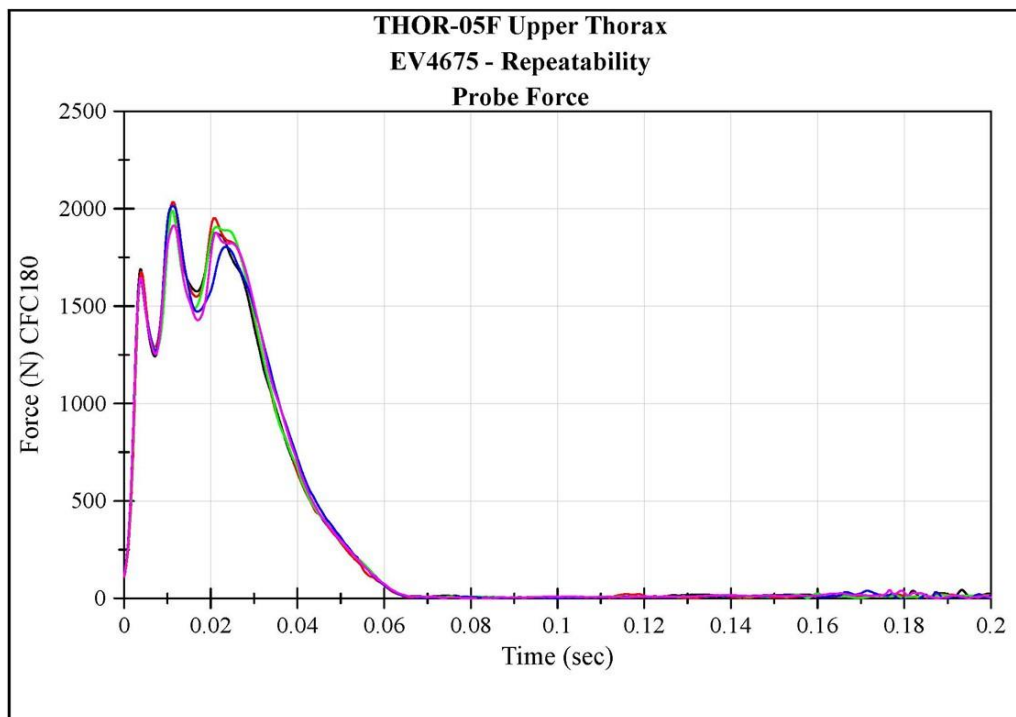


Figure 10-17. Humanetics probe force for upper thorax impact repeatability tests for EV4675

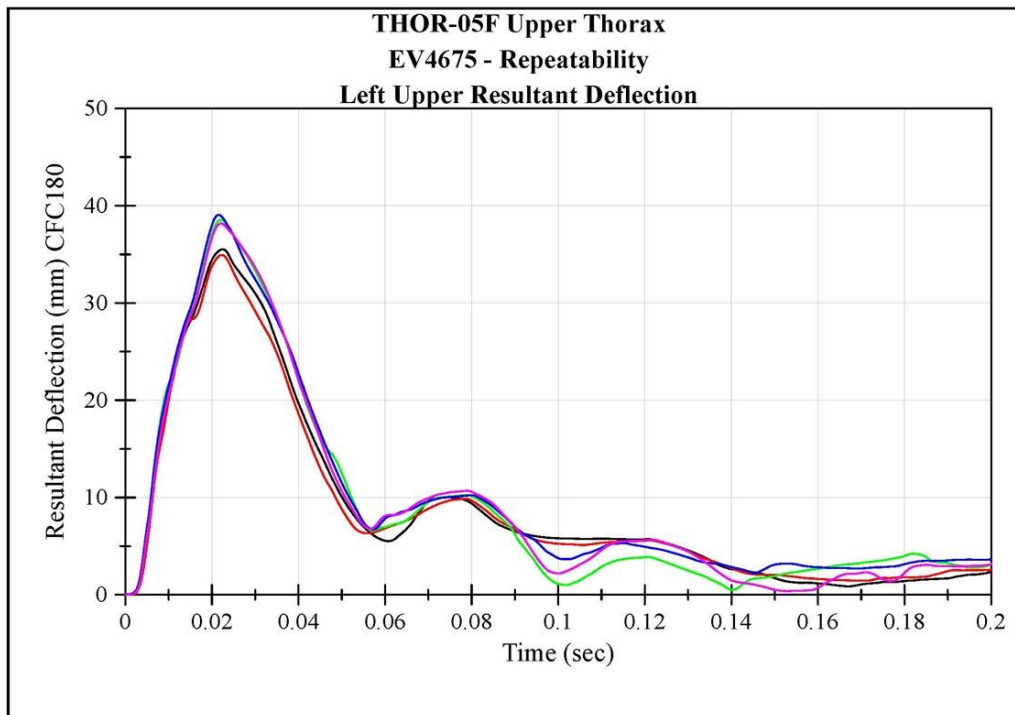


Figure 10-18. Humanetics upper left resultant deflection for upper thorax impact repeatability tests for EV4675

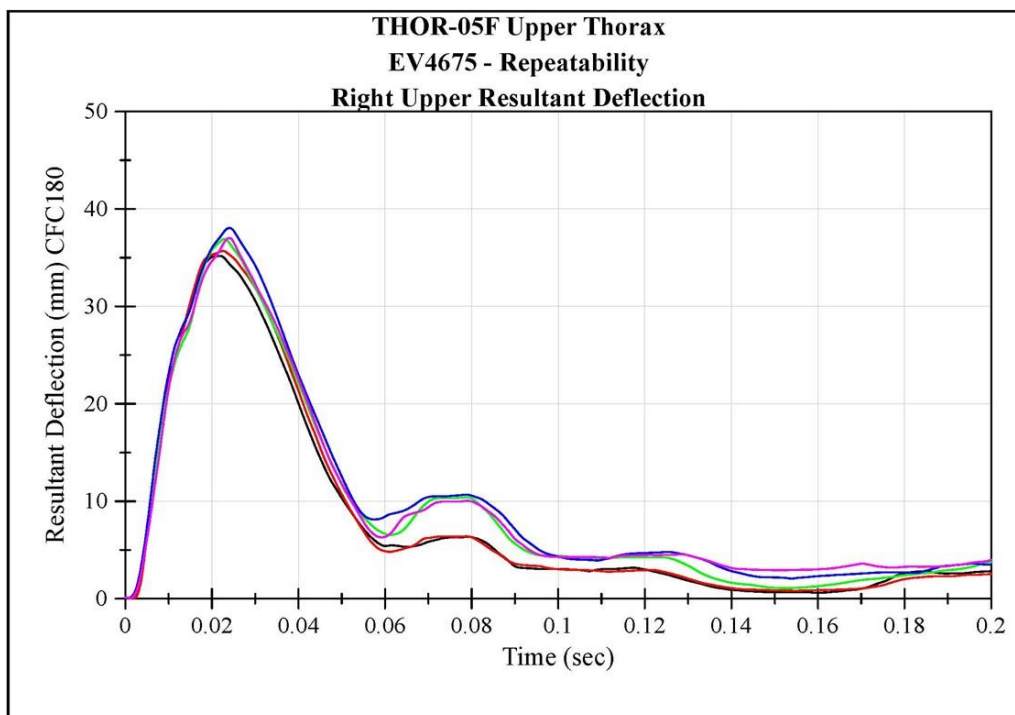


Figure 10-19. Humanetics upper right resultant deflection for upper thorax impact repeatability tests for EV4675

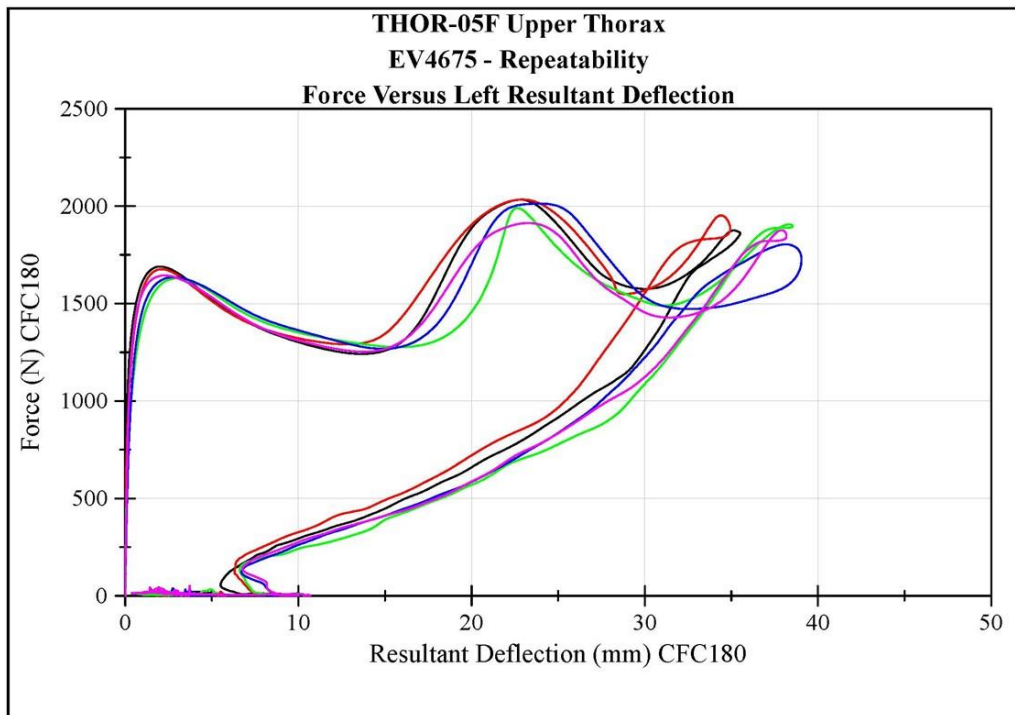


Figure 10-20. Humanetics force versus left resultant deflection for upper thorax repeatability tests for EV4675

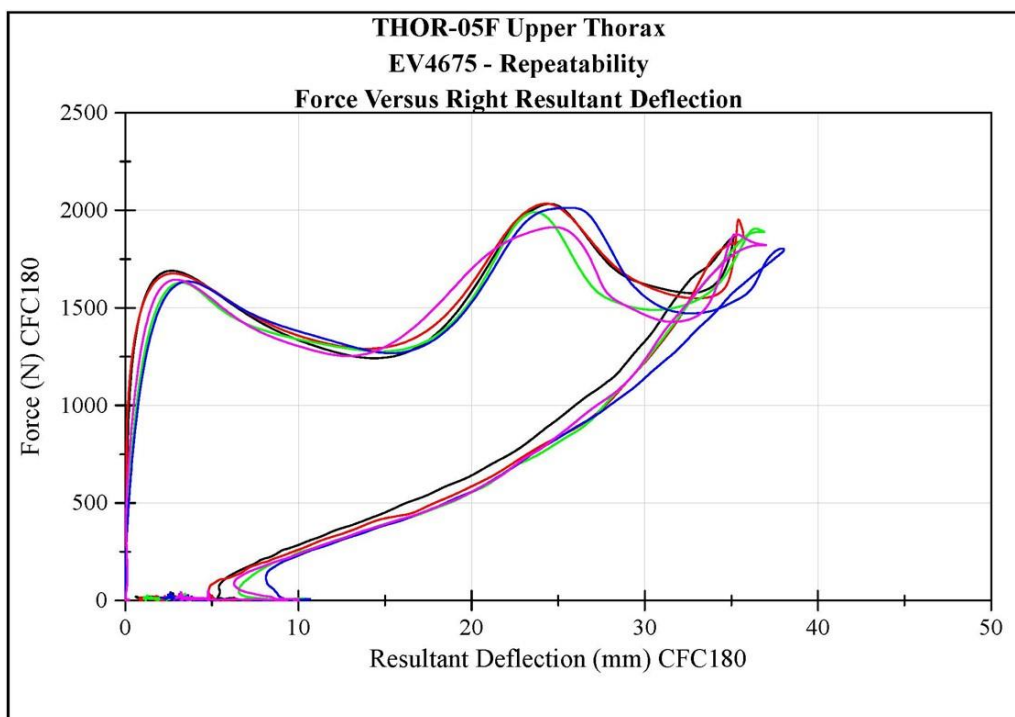


Figure 10-21. Humanetics force versus right resultant deflection for upper thorax impact repeatability tests for EV4675

10.2.5 THOR-05F EV4675 Testing at Calspan

Repeatability results for upper thorax testing on EV4675 at Calspan yielded CV values below 5 percent (Table 10-5, Figure 10-22 through Figure 10-26).

Table 10-5. Calspan THOR-05F Upper Thorax Repeatability Results for EV4675

Test Number	Maximum Probe Force (N)	Maximum Upper Left Resultant Deflection (mm)	Maximum Upper Right Resultant Deflection (mm)	Difference Between Max Left & Right Resultant Deflections (mm)	Force at Left Max Resultant Deflection (N)	Force at Right Max Resultant Deflection (N)
2025_03_19_07_47	2,017	33.2	35.4	2.2	1,911	1,860
2025_03_19_09_26	1,904	36.5	34.7	-1.8	1,895	1,896
2025_03_19_10_05	1,921	37.1	34.9	-2.2	1,805	1,876
2025_03_19_10_38	1,926	38.2	35.5	-2.7	1,843	1,881
2025_03_19_11_14	1,956	37.5	38.2	0.7	1,819	1,938
Mean	1,945	36.1		N/A	1,872	
Standard Deviation	44.4	1.7		N/A	41.4	
CV	2.3%	4.6%		N/A	2.2%	

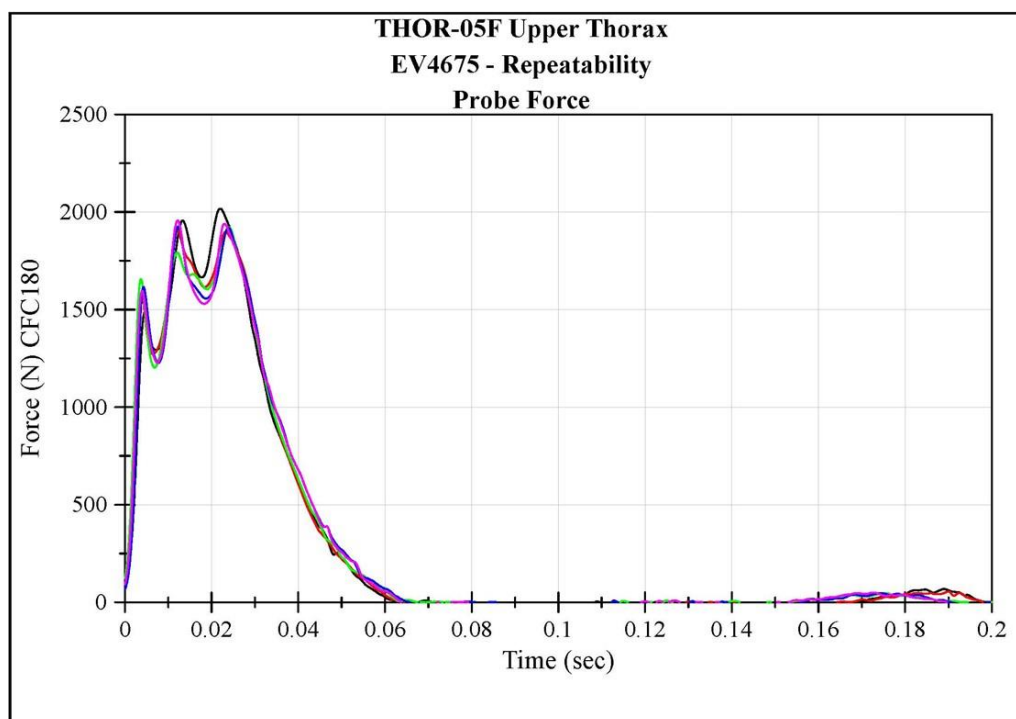


Figure 10-22. Calspan probe force for upper thorax impact repeatability tests for EV4675

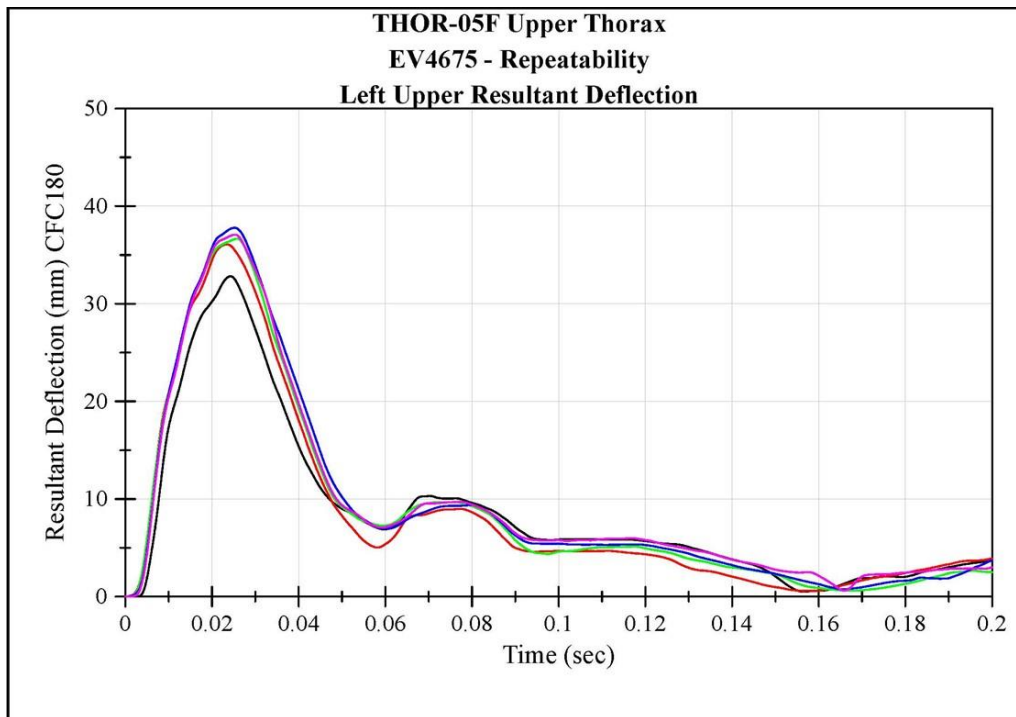


Figure 10-23. Calspan upper left resultant deflection for upper thorax impact repeatability tests for EV4675

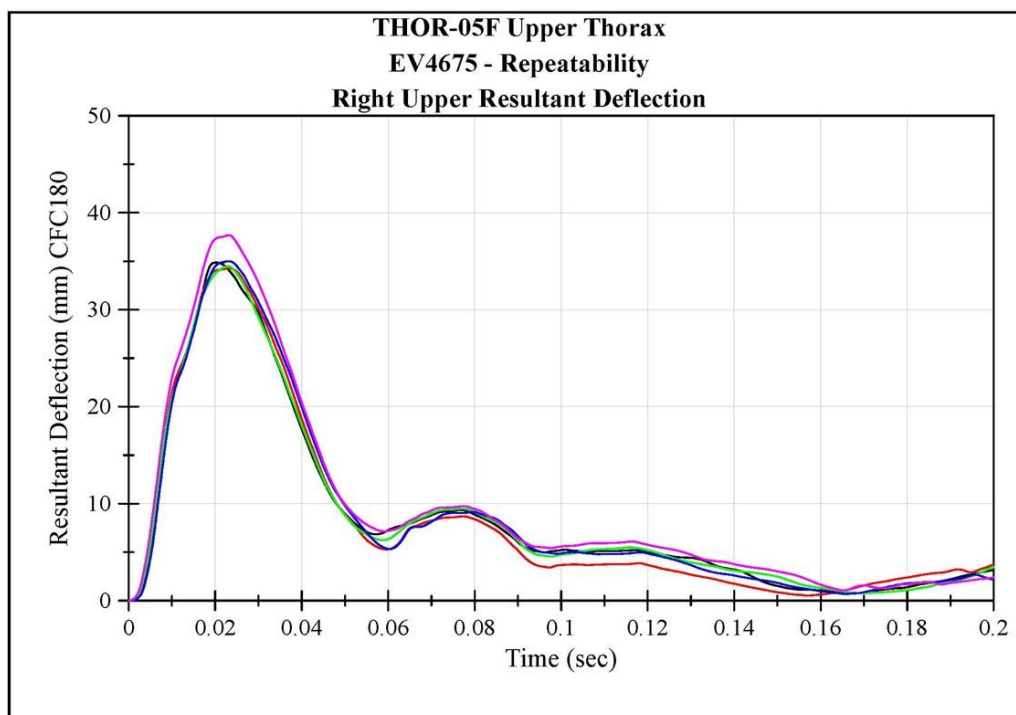


Figure 10-24. Calspan upper right resultant deflection for upper thorax impact repeatability tests for EV4675

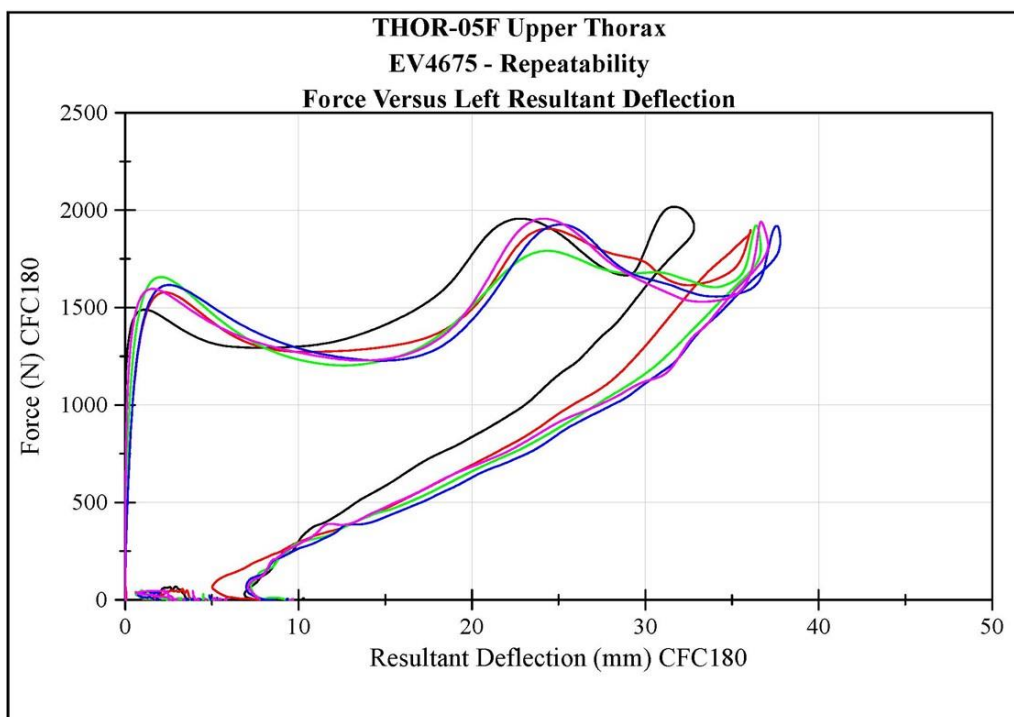


Figure 10-25. Calspan force versus left resultant deflection for upper thorax repeatability tests for EV4675

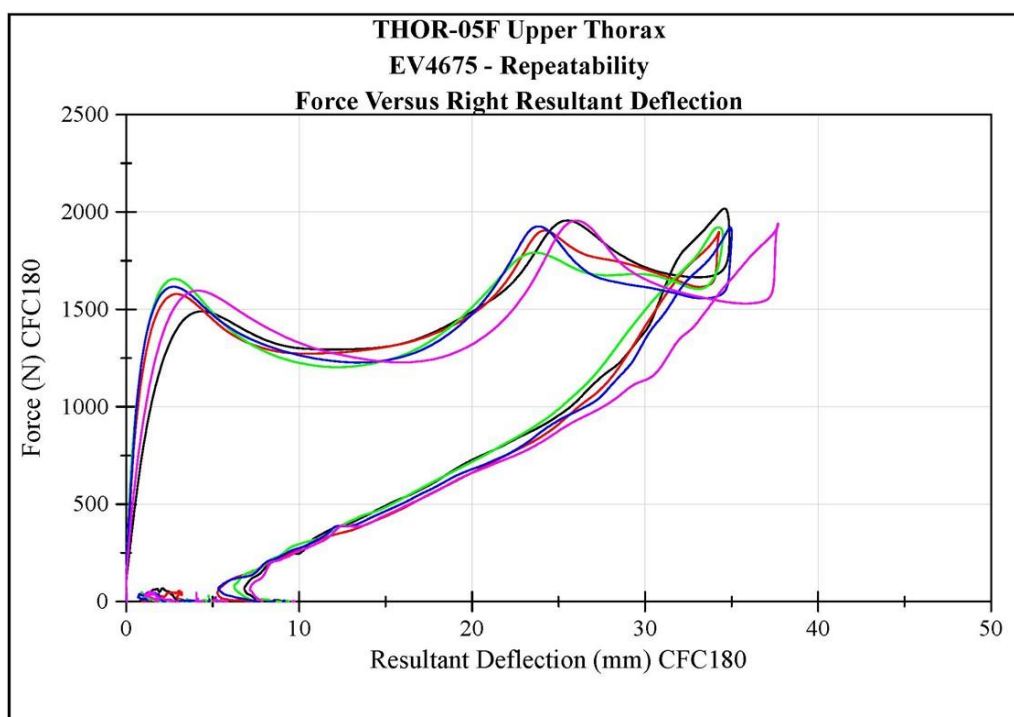


Figure 10-26. Calspan force versus right resultant deflection for upper thorax impact repeatability tests for EV4675

10.2.6 THOR-05F EV4675 Testing at TRC

Repeatability results for upper thorax testing at TRC on EV4675 yielded CV values below 5 percent, except for probe force which was above 5 percent, but under 10 percent (Table 10-6, Figure 10-27 through Figure 10-31).

Table 10-6. TRC THOR-05F Upper Thorax Repeatability Results for EV4675

Test Number	Maximum Probe Force (N)	Maximum Upper Left Resultant Deflection (mm)	Maximum Upper Right Resultant Deflection (mm)	Difference Between Max Left & Right Resultant Deflections (mm)	Force at Left Max Resultant Deflection (N)	Force at Right Max Resultant Deflection (N)
2025_05_13 13_56	2,221	30.4	32.6	2.2	1,805	1,841
2025_05_14 10_42	1,965	30.0	31.6	1.6	1,723	1,734
2025_05_15 09_33	2,198	32.0	30.9	-1.1	1,766	1,783
2025_05_15 10_52	2,182	32.0	32.6	0.6	1,770	1,738
2025_05_15 11_24	1,967	33.5	34.9	1.4	1,841	1,818
Mean	2,107	32.1		N/A	1,782	
Standard Deviation	129	1.5		N/A	43.3	
CV	6.1%	4.6%		N/A	2.4%	

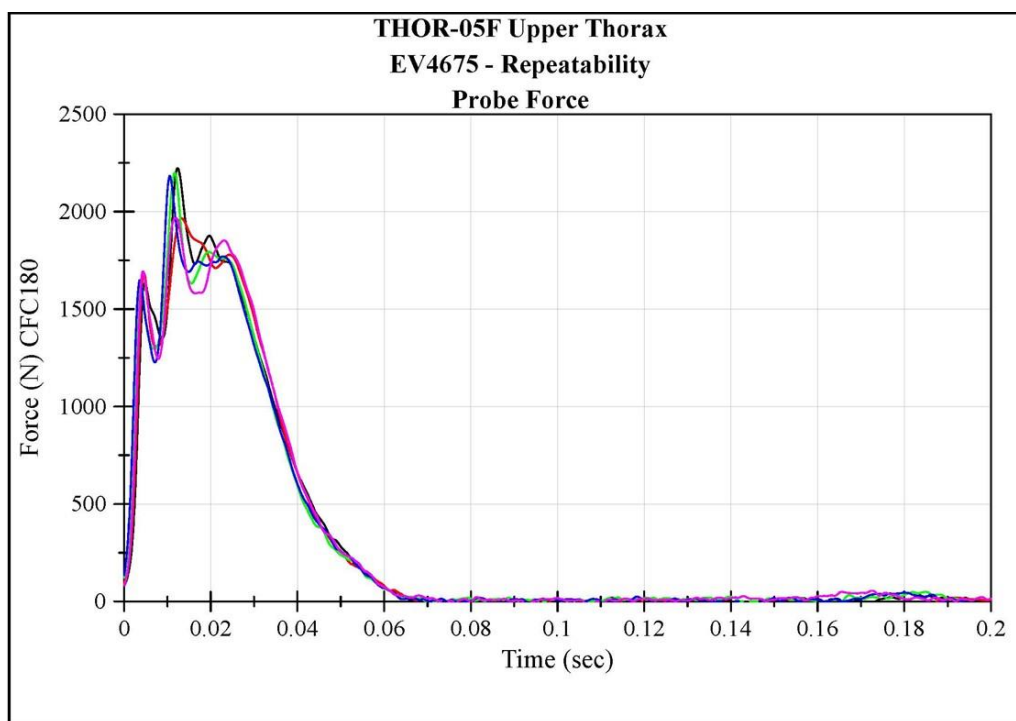


Figure 10-27. TRC probe force for upper thorax impact repeatability tests for EV4675

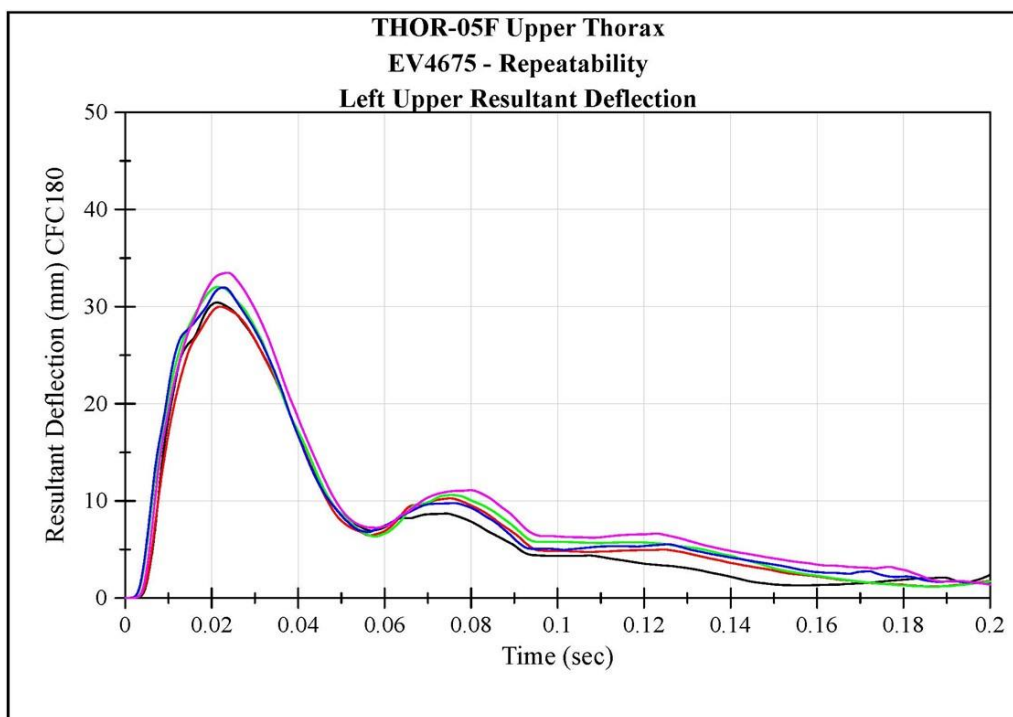


Figure 10-28. TRC upper left resultant deflection for upper thorax impact repeatability tests for EV4675

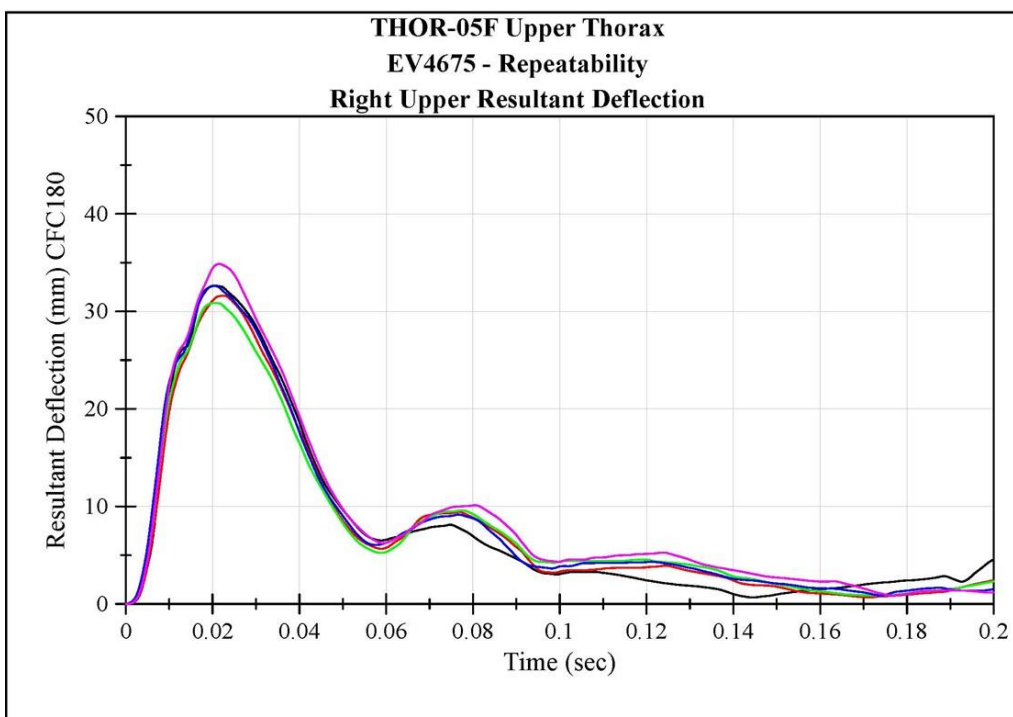


Figure 10-29. TRC upper right resultant deflection for upper thorax impact repeatability tests for EV4675

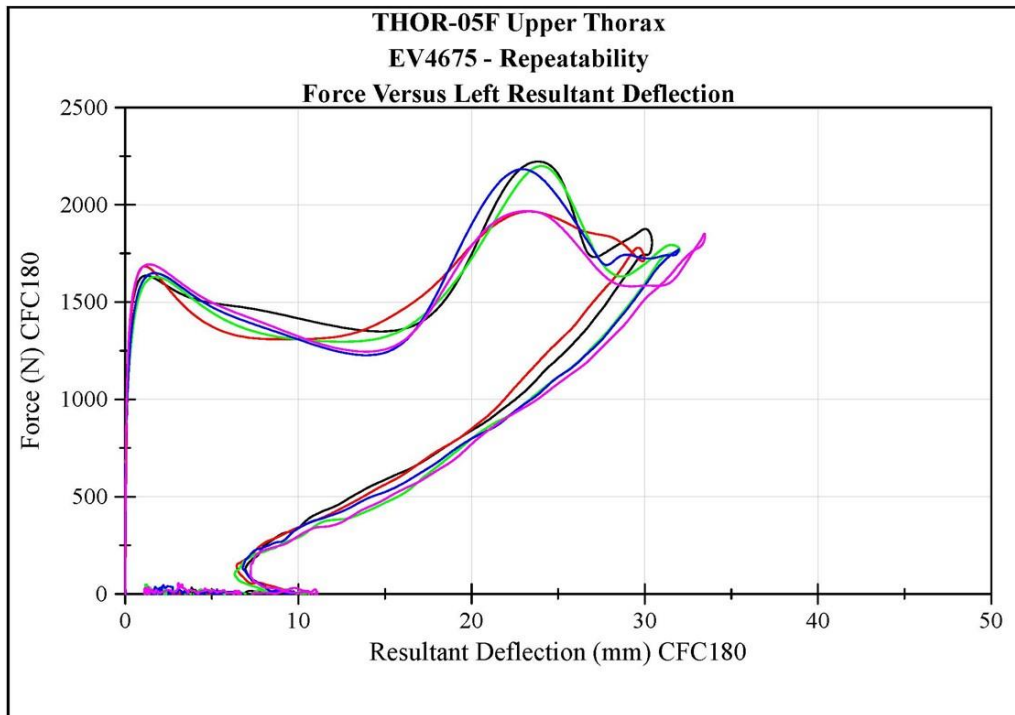


Figure 10-30. TRC force versus left resultant deflection for upper thorax repeatability tests for EV4675

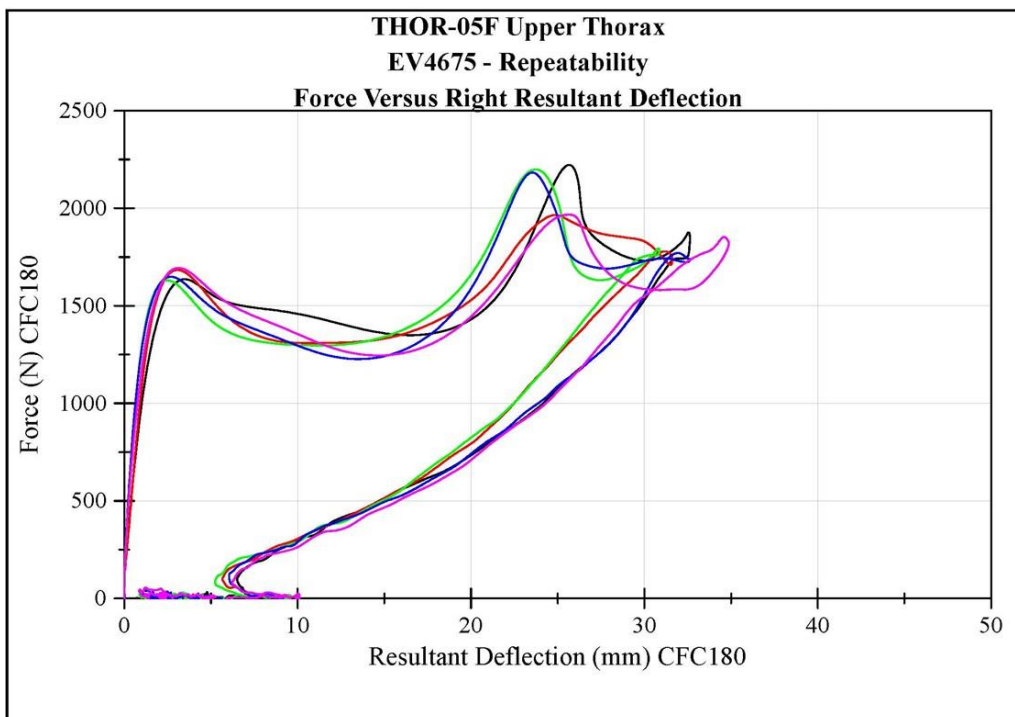


Figure 10-31. TRC force versus right resultant deflection for upper thorax impact repeatability tests for EV4675

10.3 Upper Thorax Dummy Reproducibility Results

Dummy Reproducibility results at VRTC for the upper thorax qualification yielded CV values below 5 percent for probe force and force at maximum deflection, while deflections were above 5 percent, but under 10 percent (Table 10-7).

Table 10-7. THOR-05F Upper Thorax Reproducibility Results

Dummy	Test Number	Maximum Probe Force (N)	Maximum Upper Left Resultant Deflection (mm)	Maximum Upper Right Resultant Deflection (mm)	Difference Between Max Left & Right Resultant Deflections (mm)	Force at Left Max Resultant Deflection (N)	Force at Right Max Resultant Deflection (N)
VRTC EU9863	240212-1	1,905	32.6	36.8	4.2	1,881	1,868
	240212-6	1,986	34.2	35.5	1.3	1,803	1,795
	240212-7	2,010	33.4	34.9	1.5	1,819	1,830
	240213-1	1,925	34.1	34.2	0.1	1,823	1,807
	240213-2	1,936	34.5	34.8	0.4	1,830	1,854
VRTC EU3430	240814-9	2,081	38.1	38.5	0.4	1,735	1,762
	240814-11	2,036	37.6	38.0	0.4	1,723	1,732
	240815-1	1,991	36.6	38.3	1.7	1,738	1,742
	240815-2	2,074	37.5	38.0	0.5	1,741	1,717
	240815-3	2,039	38.4	37.0	-1.4	1,753	1,764
VRTC EV4675	240617-4	1,904	32.8	35.6	2.8	1,688	1,703
	240617-8	1,916	34.5	34.4	-0.1	1,748	1,698
	240617-9	1,869	34.5	34.1	-0.4	1,663	1,632
	240617-10	2,033	35.0	31.8	-3.2	1,755	1,699
	240618-1	1,915	35.1	33.6	-1.4	1,750	1,711
Mean		1,975	35.5		N/A	1,759	
Standard Deviation		68.7	1.9		N/A	61.1	
CV		3.5%	5.4%		N/A	3.5%	

10.4 Lab-to-Lab Variability Analysis

The results of the upper thorax qualification tests from each lab are presented in Table 10-8. The repeatability within each lab is indicated by CV values below 5 percent (Table 10-3 through Table 10-6). The last three rows of the table show the *Test Reproducibility* results when data from all four labs are combined. The force at maximum deflection CV is below 5 percent while the maximum probe force and the upper thoracic resultant deflection CV values were greater than 5 percent, but under 10 percent.

Table 10-8. THOR-05F Upper Thorax Lab-to-Lab Variability Results

Dummy	Test Number	Maximum Probe Force (N)	Maximum Upper Left Resultant Deflection (mm)	Maximum Upper Right Resultant Deflection (mm)	Difference Between Max Left & Right Resultant Deflections (mm)	Force at Left Max Resultant Deflection (N)	Force at Right Max Resultant Deflection (N)
VRTC EV4675	240617-4	1,904	32.8	35.6	2.8	1,688	1,703
	240617-8	1,916	34.5	34.4	-0.1	1,748	1,698
	240617-9	1,869	34.5	34.1	-0.4	1,663	1,632
	240617-10	2,033	35.0	31.8	-3.2	1,755	1,699
	240618-1	1,915	35.1	33.6	-1.4	1,750	1,711
Humanetics EV4675	688653	1,913	38.2	37.0	-1.2	1,846	1,821
	688619	2,012	39.0	38.0	-1.0	1,723	1,798
	688608	1,990	38.5	36.9	-1.6	1,896	1,889
	688117	2,034	34.9	35.7	0.8	1,884	1,872
	687990	2,033	35.5	35.2	-0.3	1,861	1,868
Calspan EV4675	2025_03_19_07_47	2,017	33.2	35.4	2.2	1,911	1,860
	2025_03_19_09_26	1,904	36.5	34.7	-1.8	1,895	1,896
	2025_03_19_10_05	1,921	37.1	34.9	-2.2	1,805	1,876
	2025_03_19_10_38	1,926	38.2	35.5	-2.7	1,843	1,881
	2025_03_19_11_14	1,956	37.5	38.2	0.7	1,819	1,938
TRC EV4675	2025_05_13_13_56	2,221	30.4	32.6	2.2	1,805	1,841
	2025_05_14_10_42	1,965	30.0	31.6	1.6	1,723	1,734
	2025_05_15_09_33	2,198	32.0	30.9	-1.1	1,766	1,783
	2025_05_15_10_52	2,182	32.0	32.6	0.6	1,770	1,738
	2025_05_15_11_24	1,967	33.5	34.9	1.4	1,841	1,818
Test Reproducibility EV4675							
Mean		1,994	34.8		N/A	1,801	
Standard Deviation		102	2.4		N/A	78.3	
CV		5.1%	6.8%		N/A	4.3%	

10.5 Corridor Development

All the data used to determine the upper thorax qualification corridors is shown in Table 10-9. The qualification corridors were calculated using the mean plus or minus 10 percent of the maximum for the specified measured or calculated channels, with the exception of the difference between the left and right thorax resultant deflections. For consistency, as established by the THOR-50M (National Highway Traffic Safety Administration, 2022), a difference of ± 5 mm between left and right thorax deflections indicates an acceptable symmetrical impact.

Table 10-9. THOR-05F Upper Thorax Qualification Corridor Results
(Highlighted values fell outside average $\pm 10\%$.)

Dummy	Test Number	Maximum Probe Force (N)	Maximum Upper Left Resultant Deflection (mm)	Maximum Upper Right Resultant Deflection (mm)	Difference Between Max Left & Right Resultant Deflections (mm)	Force at Left Max Resultant Deflection (N)	Force at Right Max Resultant Deflection (N)
VRTC EU9863	240212-1	1,905	32.6	36.8	4.2	1,881	1,868
	240212-6	1,986	34.2	35.5	1.3	1,803	1,795
	240212-7	2,010	33.4	34.9	1.5	1,819	1,830
	240213-1	1,925	34.1	34.2	0.1	1,823	1,807
	240213-2	1,936	34.5	34.8	0.4	1,830	1,854
VRTC EU3430	240814-9	2,081	38.1	38.5	0.4	1,735	1,762
	240814-11	2,036	37.6	38.0	0.4	1,723	1,732
	240815-1	1,991	36.6	38.3	1.7	1,738	1,742
	240815-2	2,074	37.5	38.0	0.5	1,741	1,717
	240815-3	2,039	38.4	37.0	-1.4	1,753	1,764
VRTC EV4675	240617-4	1,904	32.8	35.6	2.8	1,688	1,703
	240617-8	1,916	34.5	34.4	-0.1	1,748	1,698
	240617-9	1,869	34.5	34.1	-0.4	1,663	1,632
	240617-10	2,033	35.0	31.8	-3.2	1,755	1,699
	240618-1	1,915	35.1	33.6	-1.4	1,750	1,711
Humanetics EV4675	688653	1,913	38.2	37.0	-1.2	1,846	1,821
	688619	2,012	39.0	38.0	-1.0	1,723	1,798
	688608	1,990	38.5	36.9	-1.6	1,896	1,889
	688117	2,034	34.9	35.7	0.8	1,884	1,872
	687990	2,033	35.5	35.2	-0.3	1,861	1,868
Calspan EV4675	2025_03_19 07_47	2,017	33.2	35.4	2.2	1,911	1,860
	2025_03_19 09_26	1,904	36.5	34.7	-1.8	1,895	1,896
	2025_03_19 10_05	1,921	37.1	34.9	-2.2	1,805	1,876
	2025_03_19 10_38	1,926	38.2	35.5	-2.7	1,843	1,881
	2025_03_19 11_14	1,956	37.5	38.2	0.7	1,819	1,938
TRC EV4675	2025_05_13 13_56	2,221	30.4	32.6	2.2	1,805	1,841
	2025_05_14 10_42	1,965	30.0	31.6	1.6	1,723	1,734
	2025_05_15 09_33	2,198	32.0	30.9	-1.1	1,766	1,783
	2025_05_15 10_52	2,182	32.0	32.6	0.6	1,770	1,738
	2025_05_15 11_24	1,967	33.5	34.9	1.4	1,841	1,818
Mean		1,995	35.3		N/A	1,796	
Standard Deviation		89.4	2.3		N/A	70.4	
CV		4.5%	6.5%		N/A	3.9%	

Table 10-10. Upper Thorax Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Impact Velocity	m/s	4.25	4.35	4.30	
Maximum Probe Force	N	1,796	2,195	1,995	10%
Maximum Upper Left Resultant Deflection	mm	31.7	38.8	35.3	10%
Maximum Upper Right Resultant Deflection	mm				
Difference Between Maximum Left & Right Resultant Deflections	mm	N/A	< 5	0	
Force at Left & Right Maximum Resultant Deflection	N	1,616	1,976	1,796	10%

Discussion. Highlighted cells in Table 10-9 indicate test values that did not meet the respective target response $\pm 10\%$ in Table 10-10. Humanetics testing yielded one non-conformity and TRC had three tests with 6 non-conformities.

Repeatability CV values were all below 5 percent with the exception of maximum probe force on the first test at TRC, resulting in a CV value of 6.1%.

Dummy Reproducibility results showed CV values below 5 percent for probe force and force at maximum resultant deflection. The CV value for maximum resultant deflection was just above 5 percent at 5.4%.

The lab-to-lab *Test Reproducibility* revealed CV values below 5 percent for force at resultant deflection, and over 5 percent for maximum probe force (5.1%) and maximum resultant deflection (6.8%).

11 LOWER THORAX

11.1 Methodology

Lower thorax repeatability and reproducibility tests followed the qualification procedures described in the *THOR-05F Qualification Procedures and Requirements*. This test mode impacts 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 13.97 ± 0.02 kg and a 152.4 ± 0.25 mm diameter rigid disk impact surface which contacts the THOR-05F 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 probe force and resultant deflection at max 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.

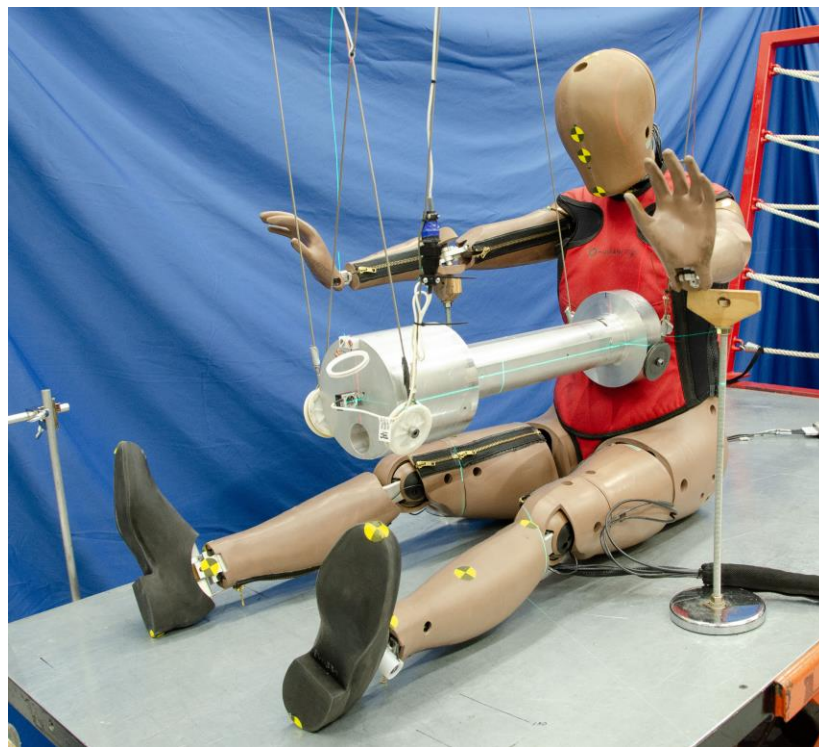


Figure 11-1. Lower thorax impact test setup

11.2 Lower Thorax Repeatability Results

Sections 11.2.1 through 11.2.6 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 four 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-05F EU9863 Testing at VRTC

Repeatability results for left lower thorax testing on EU9863 at VRTC yielded CV values between 5 and 10 percent for both probe force and deflection at maximum force. For right side impacts, CV values were below 5 percent for probe force and between 5 and 10 percent for resultant deflection at maximum force (Table 11-1, Figure 11-2 through Figure 11-5). When combining left and right sides, CV values were above 5 percent, but below 10% for all specifications. Although the target CV for a given dummy tested in a given lab is under 5 percent, it is important to note that this was the first THOR-05F lower thorax R&R test series, and elevated variation is not unusual since sensitivity to test setup was unknown at the time of testing.

Table 11-1. VRTC THOR-05F Lower Thorax Repeatability Results for EU9863

Test Number	Impact Side	Left or Right Resultant Deflection at Max Force (mm)	Maximum Probe Force (N)
240215-7	Left Side	46.1	1,886
240215-14		49.6	1,652
240215-15		47.7	1,809
240216-1		40.7	2,025
240216-2		41.6	1,950
Mean		45.1	1,864
Standard Deviation		3.9	143
CV		8.6%	7.7%
240216-3	Right Side	45.3	1,937
240222-2		45.8	1,959
240222-3		42.8	1,995
240222-4		42.2	2,023
240222-5		39.7	2,163
Mean		43.2	2,015
Standard Deviation		2.5	88.6
CV		5.7%	4.4%
Mean	Combined Left & Right Sides	44.2	1,940
Standard Deviation		3.2	137
CV		7.3%	7.1%

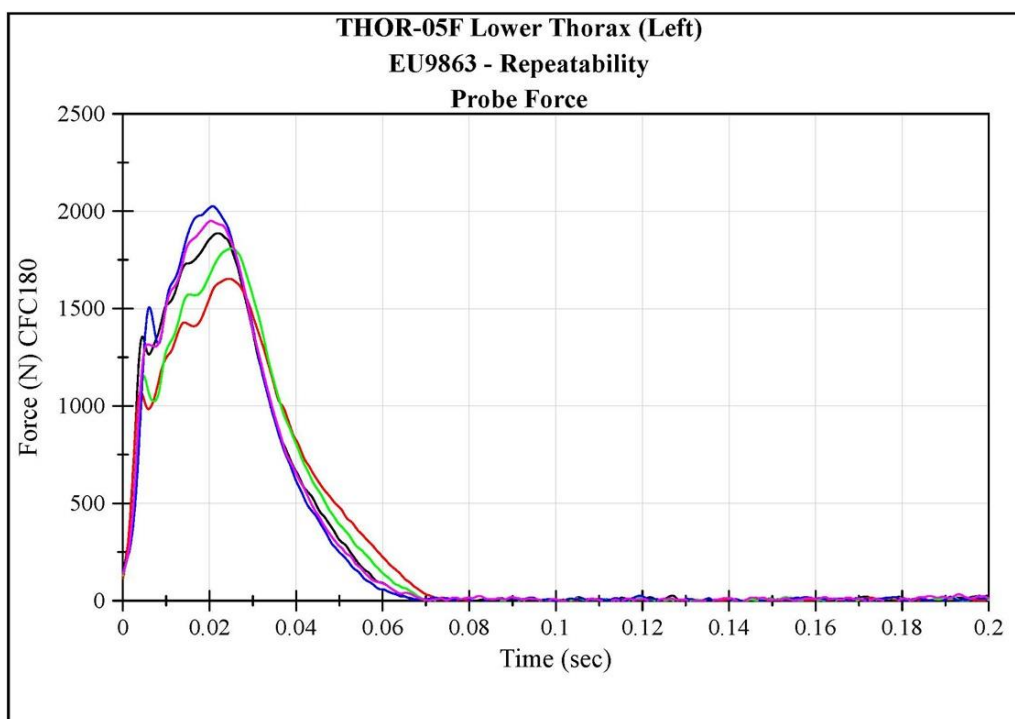


Figure 11-2. VRTC probe force for left lower thorax impact repeatability tests for EU9863

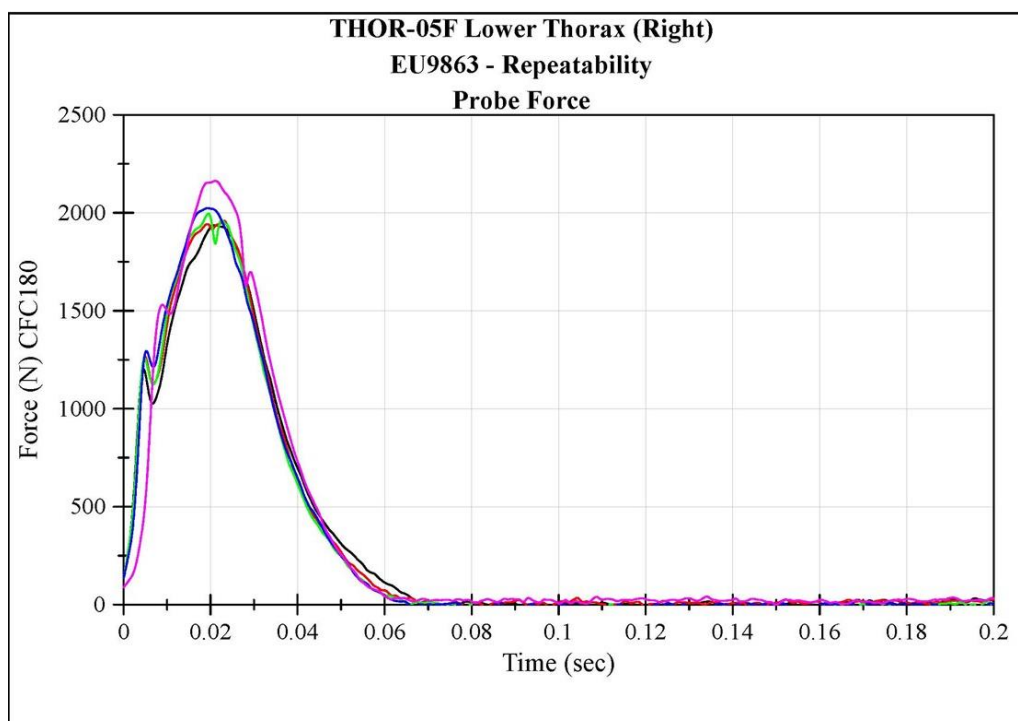


Figure 11-3. VRTC probe force for right lower thorax impact repeatability tests for EU9863

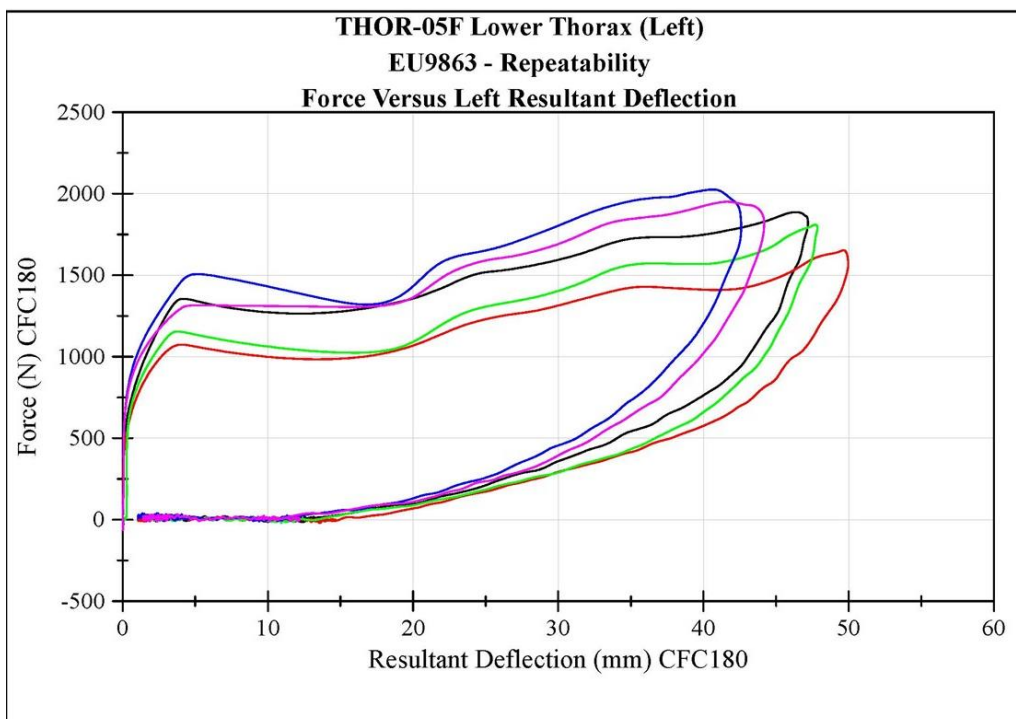


Figure 11-4. VRTC probe force vs. resultant deflection for left lower thorax impact repeatability tests for EU9863

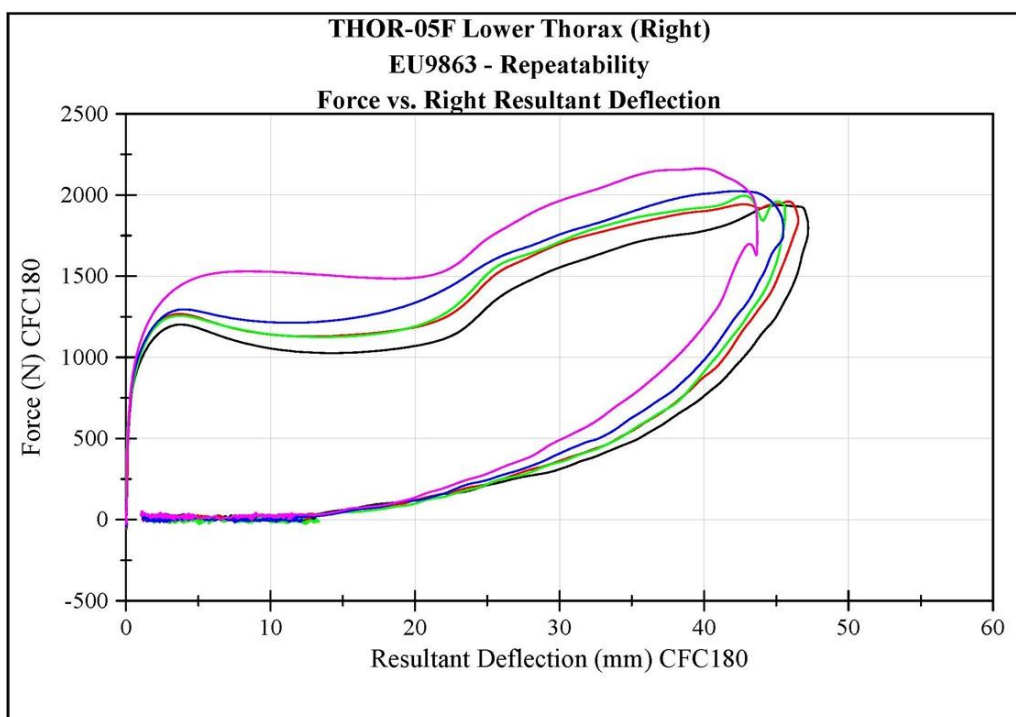


Figure 11-5. VRTC probe force vs. resultant deflection for right lower thorax impact repeatability tests for EU9863

11.2.2 THOR-05F EU3430 Testing at VRTC

Repeatability results for lower thorax testing on EU3430 at VRTC yielded CV values below 5 percent for both left and right sides as well as combined (Table 11-2, Figure 11-6 through Figure 11-9).

Table 11-2. VRTC THOR-05F Lower Thorax Repeatability Results for EU3430

Test Number	Impact Side	Left or Right Resultant Deflection at Max Force (mm)	Maximum Probe Force (N)
241106-2	Left Side	41.8	2,026
241106-7		40.6	1,985
241107-3		41.1	2,025
241107-4		39.7	2,029
241107-5		40.1	2,029
Mean		40.7	2,019
Standard Deviation		0.8	19.0
CV		2.0%	0.9%
240815-17	Right Side	41.8	2,113
240819-2		40.9	2,053
240819-4		41.2	2,101
240819-5		39.7	2,065
240819-6		41.3	2,125
Mean		41.0	2,091
Standard Deviation		0.8	31.1
CV		1.9%	1.5%
Mean	Combined Left & Right Sides	40.8	2,055
Standard Deviation		0.8	45.3
CV		1.9%	2.2%

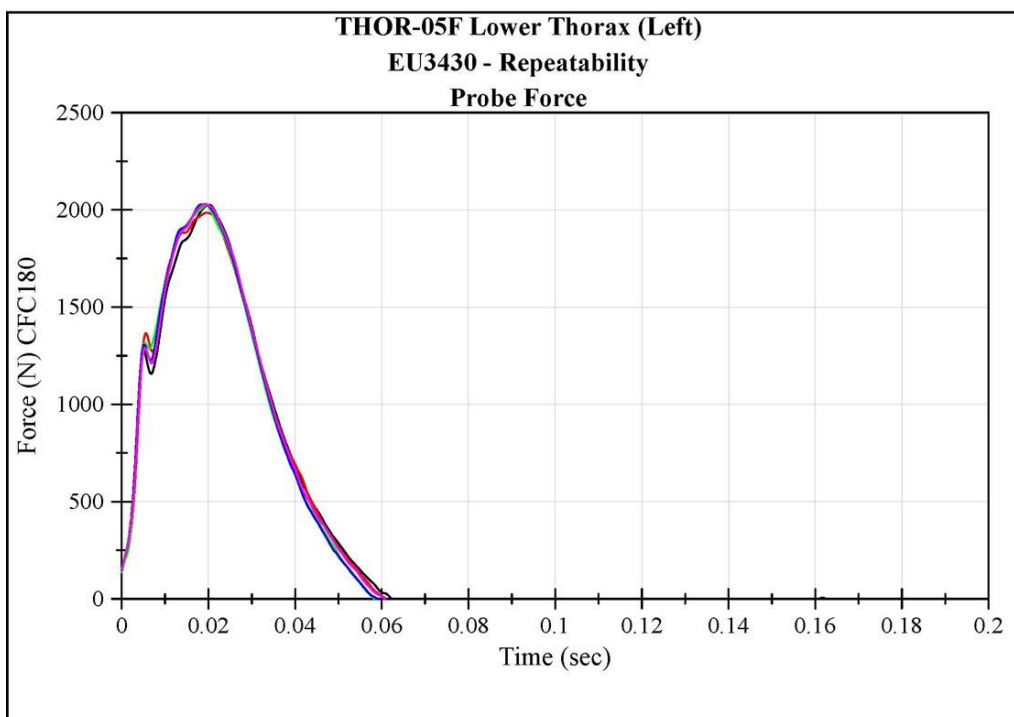


Figure 11-6. VRTC probe force for left lower thorax impact repeatability tests for EU3430

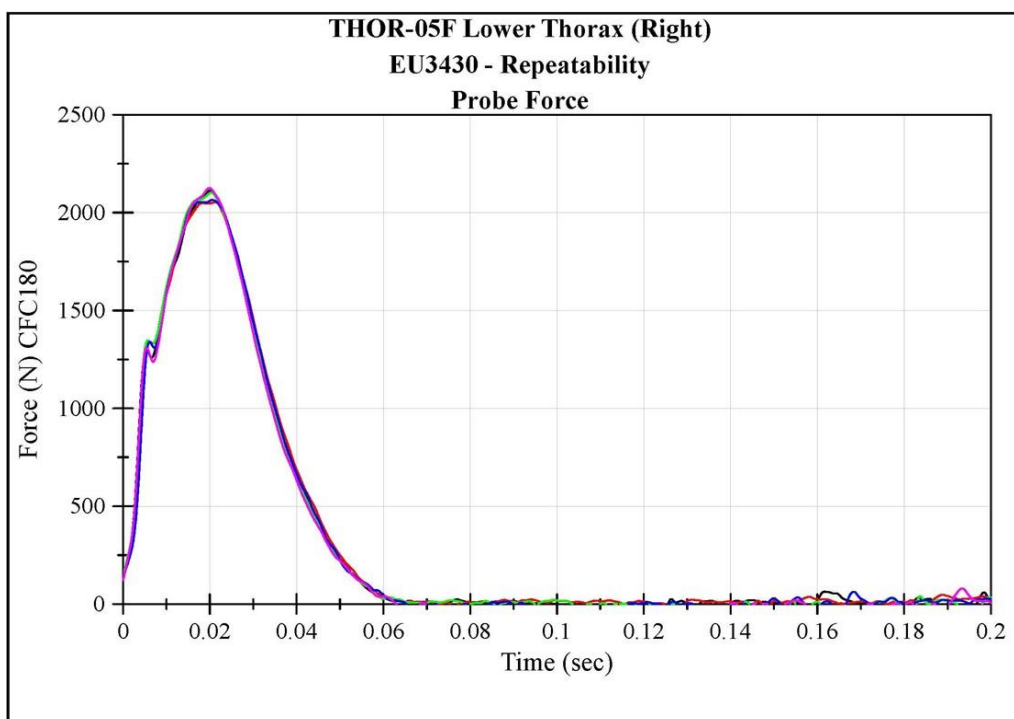


Figure 11-7. VRTC probe force for right lower thorax impact repeatability tests for EU3430

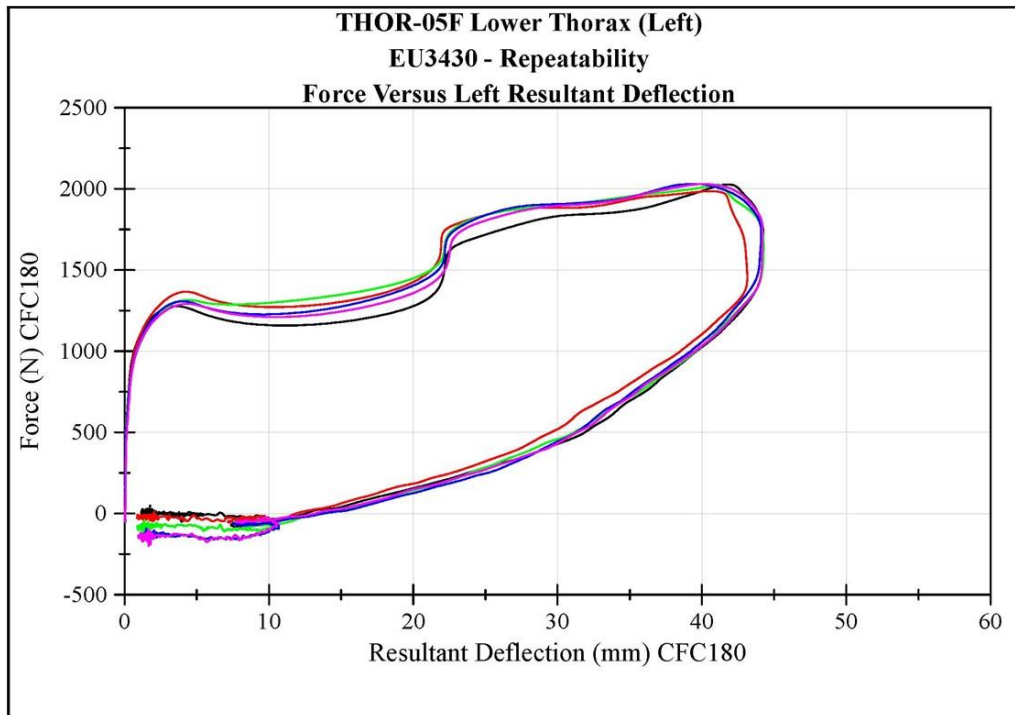


Figure 11-8. VRTC probe force vs. resultant deflection for left lower thorax impact repeatability tests for EU3430

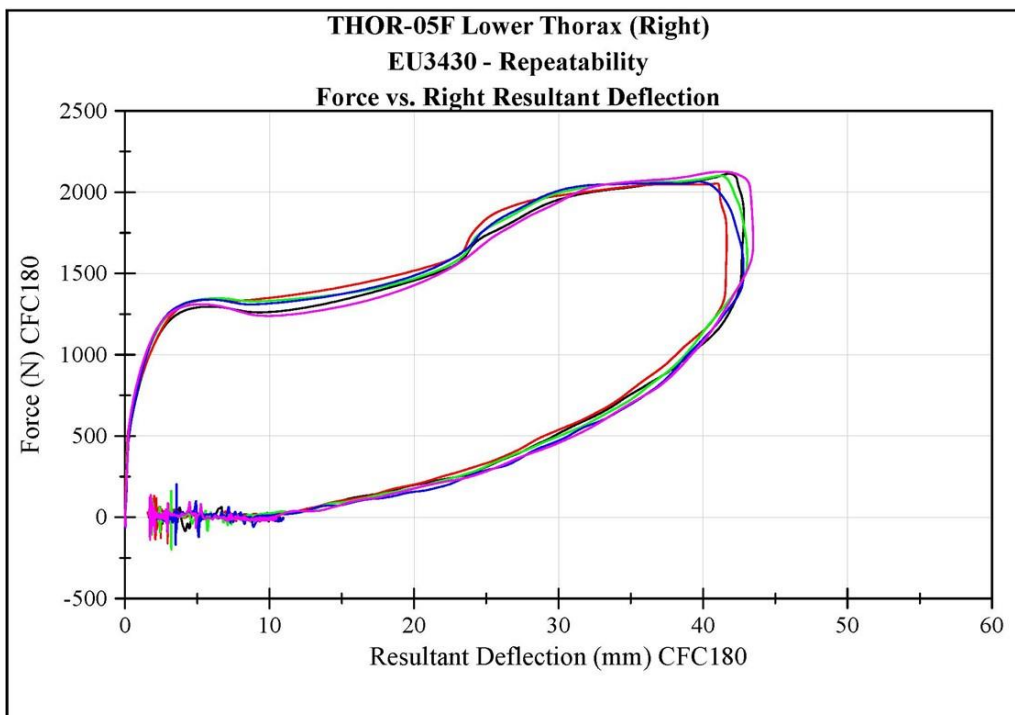


Figure 11-9. VRTC probe force vs. resultant deflection for right lower thorax impact repeatability tests for EU3430

11.2.3 THOR-05F EV4675 Testing at VRTC

Repeatability results for lower thorax testing on EV4675 at VRTC yielded CV values below 5 percent for both left and right sides as well as combined (Table 11-3, Figure 11-10 through Figure 11-13).

Table 11-3. VRTC THOR-05F Lower Thorax Repeatability Results for EV4675

Test Number	Impact Side	Left or Right Resultant Deflection at Max Force (mm)	Maximum Probe Force (N)
240618-4	Left Side	38.5	2,147
240618-8		38.8	2,143
240618-9		38.6	2,165
240624-1		38.2	2,084
240624-4		36.5	2,134
Mean		38.1	2,134
Standard Deviation		0.9	30.4
CV		2.5%	1.4%
240624-12	Right Side	37.8	2,135
240624-13		42.3	2,113
240624-14		40.2	2,088
240624-15		38.6	2,066
240624-17		41.0	2,099
Mean		40.0	2,100
Standard Deviation		1.8	25.7
CV		4.5%	1.2%
Mean	Combined Left & Right Sides	39.1	2,117
Standard Deviation		1.7	32.1
CV		4.3%	1.5%

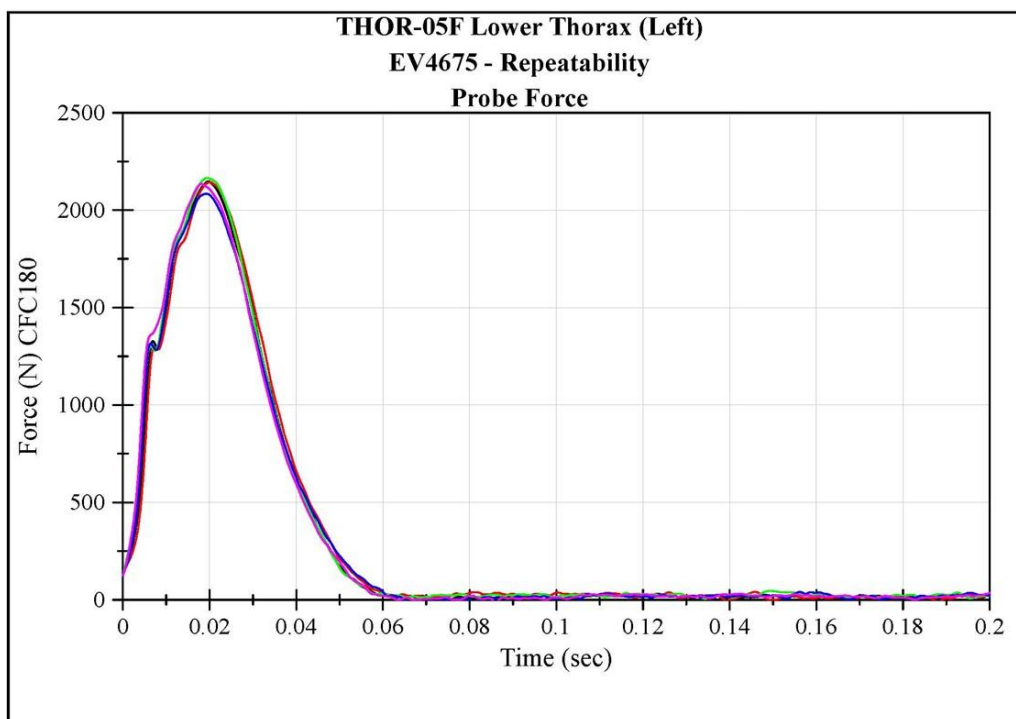


Figure 11-10. VRTC probe force for left lower thorax impact repeatability tests for EV4675

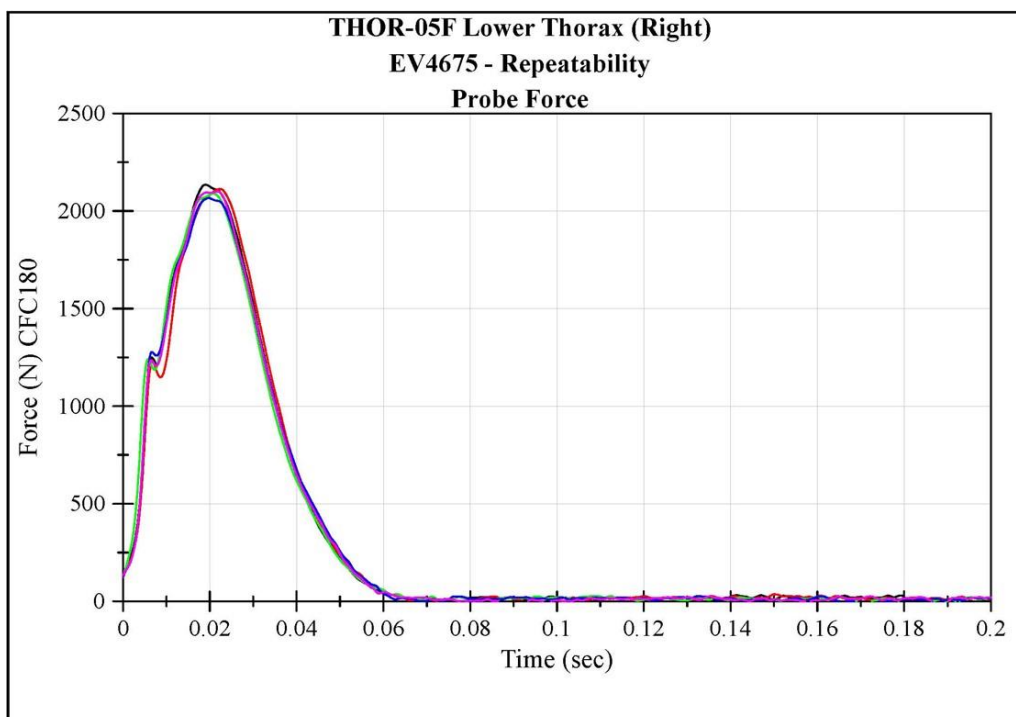


Figure 11-11. VRTC probe force for right lower thorax impact repeatability tests for EV4675

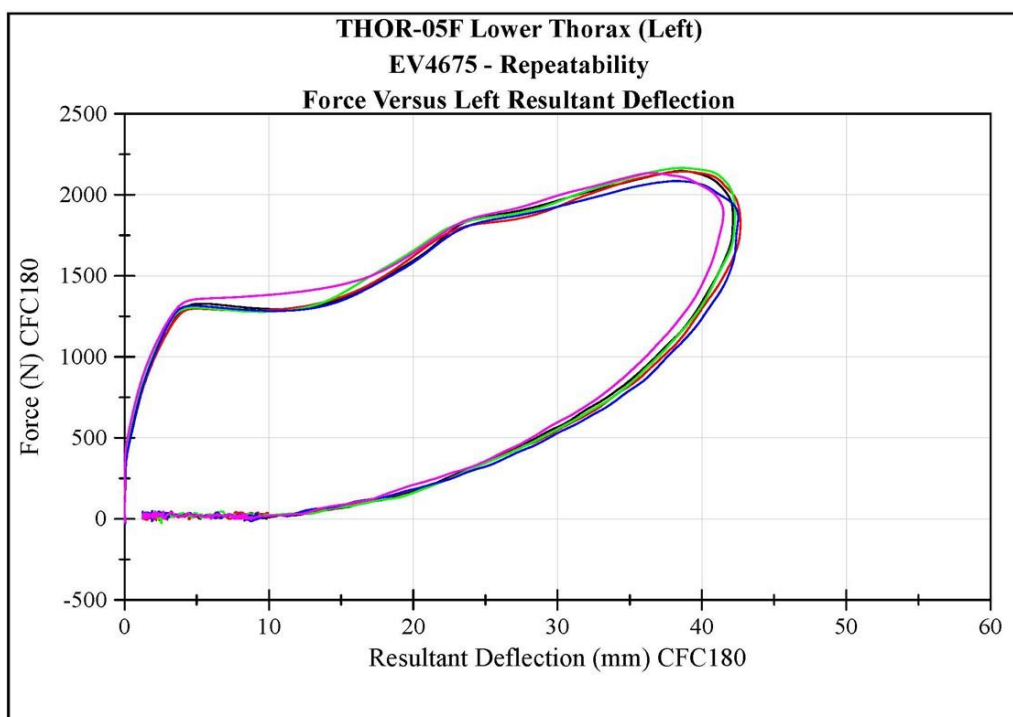


Figure 11-12. VRTC probe force vs. resultant deflection for left lower thorax impact repeatability tests for EV4675

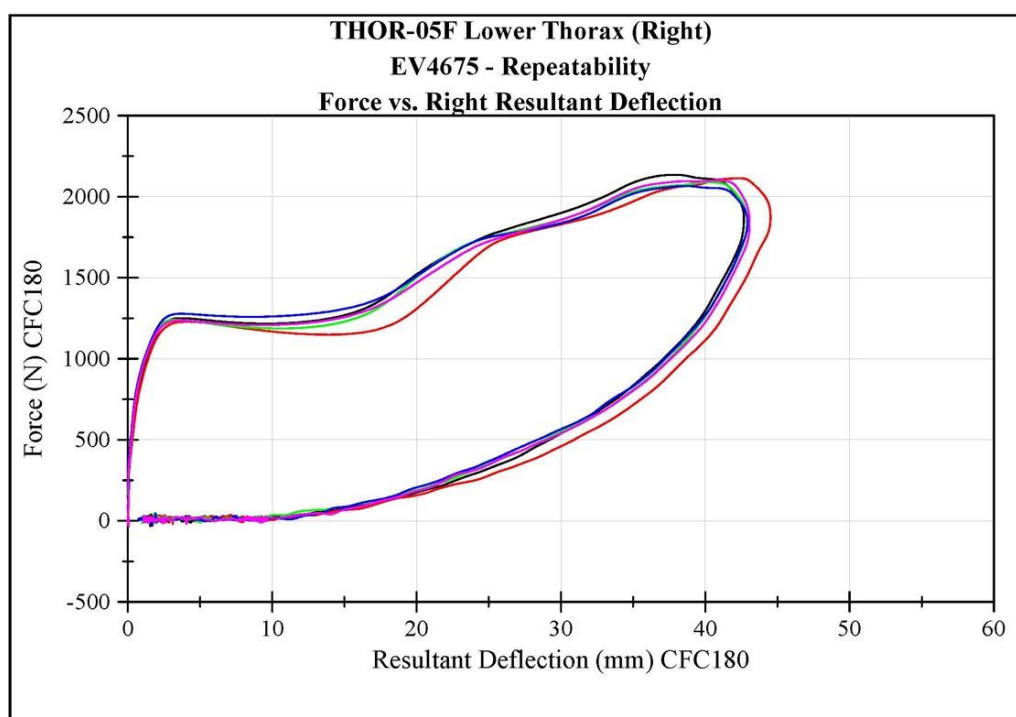


Figure 11-13. VRTC probe force vs. resultant deflection for right lower thorax impact repeatability tests for EV4675

11.2.4 THOR-05F EV4675 Testing at Humanetics

Repeatability results for lower thorax testing on EV4675 at Humanetics yielded CV values below 5 percent on both left and right sides; for combined left and right data, the resultant deflection at maximum force was above 5 percent, but under 10 percent while the probe force was below 5 percent (Table 11-4, Figure 11-14 through Figure 11-17).

Table 11-4. Humanetics THOR-05F Lower Thorax Repeatability Results for EV4675

Test Number	Impact Side	Left or Right Resultant Deflection at Max Force (mm)	Maximum Probe Force (N)
689945	Left Side	45.6	1,947
690303		45.4	1,954
690381		46.0	1,918
690311		48.4	1,900
690366		46.8	1,882
Mean		46.4	1,920
Standard Deviation		1.2	30.5
CV		2.6%	1.6%
690470	Right Side	51.8	2,008
690482		46.0	1,925
690461		51.2	1,978
690444		50.3	1,933
690489		50.7	1,945
Mean		50.0	1,958
Standard Deviation		2.3	34.6
CV		4.6%	1.8%
Mean	Combined Left & Right Sides	48.2	1,939
Standard Deviation		2.6	36.5
CV		5.3%	1.9%

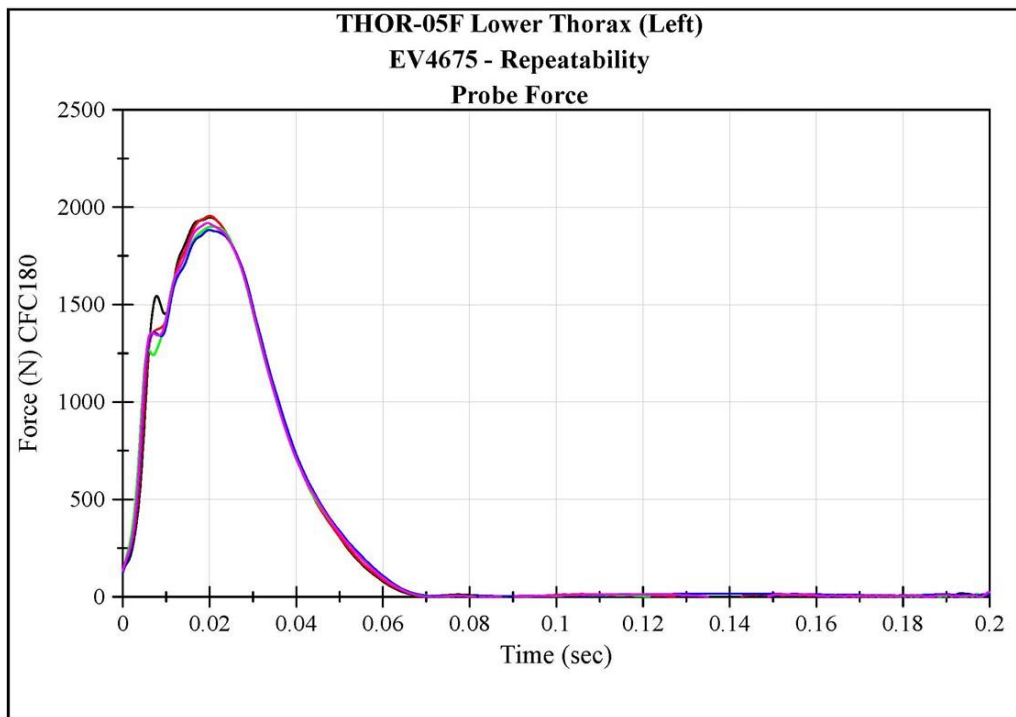


Figure 11-14. Humanetics probe force for left lower thorax impact repeatability tests for EV4675

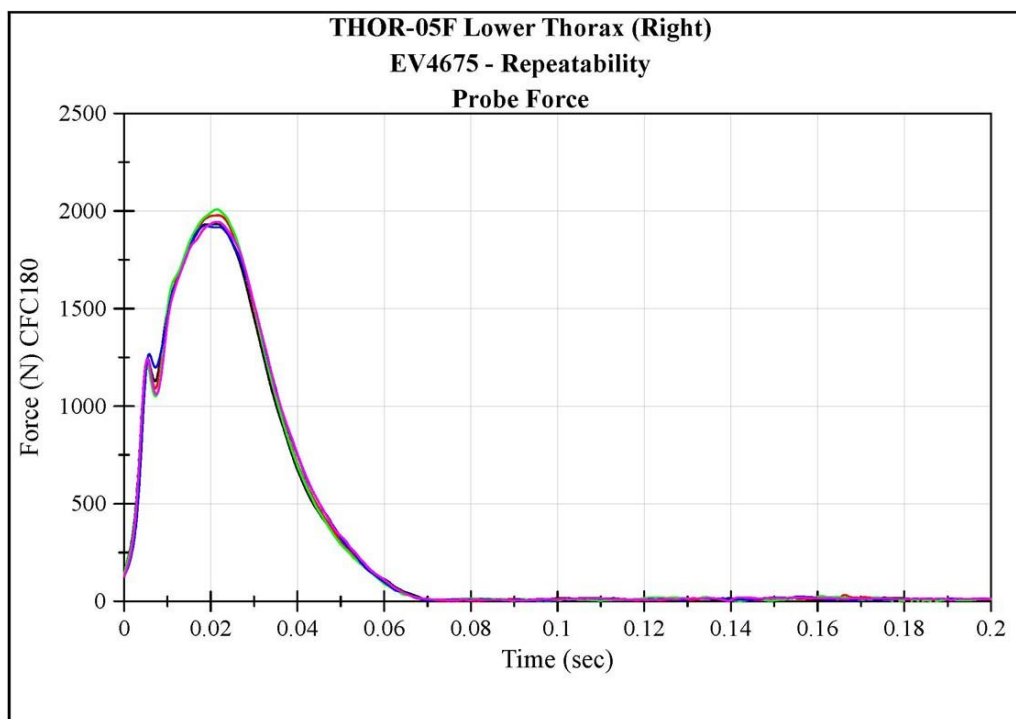


Figure 11-15. Humanetics probe force for right lower thorax impact repeatability tests for EV4675

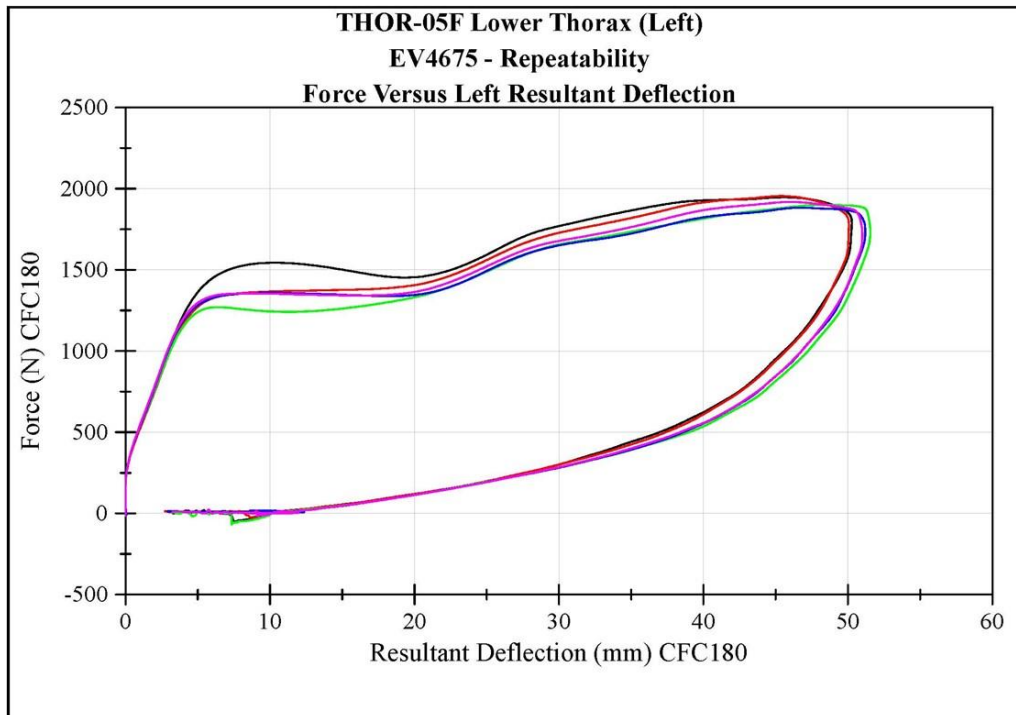


Figure 11-16. Humanetics probe force vs. resultant deflection for left lower thorax impact repeatability tests for EV4675

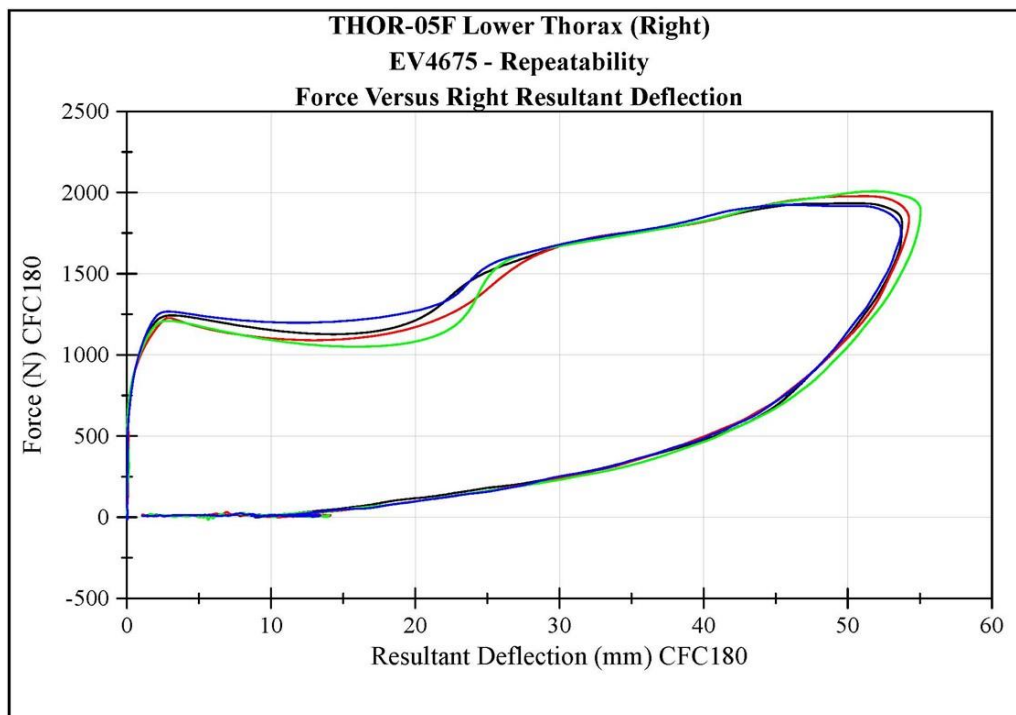


Figure 11-17. Humanetics probe force vs. resultant deflection for right lower thorax impact repeatability tests for EV4675

11.2.5 THOR-05F EV4675 Testing at Calspan

Repeatability results for lower thorax testing on EV4675 at Calspan yielded CV values below 5 percent on both left and right sides as well as combined (Table 11-5, Figure 11-18 through Figure 11-21).

Table 11-5. Calspan THOR-0F Lower Thorax Repeatability Results for EV4675

Test Number	Impact Side	Left or Right Resultant Deflection at Max Force (mm)	Maximum Probe Force (N)
2025_03_19 08_29	Left Side	37.6	2,036
2025_03_19 11_32		41.9	2,042
2025_03_19 13_08		39.8	2,056
2025_03_19 13_58		41.6	1,961
2025_03_19 14_45		39.0	2,000
Mean		40.0	2,019
Standard Deviation		1.8	38.3
CV		4.9%	1.9%
2025_03_19 08_50	Right Side	40.4	2,103
2025_03_19 15_07		39.1	2,020
2025_03_19 15_43		43.4	1,998
2025_03_19 16_15		39.7	1,967
2025_03_19 16_48		41.5	2,004
Mean		40.8	2,019
Standard Deviation		1.7	51.0
CV		4.2%	2.5%
Mean	Combined Left & Right Sides	40.4	2,019
Standard Deviation		1.7	42.5
CV		4.2%	2.1%

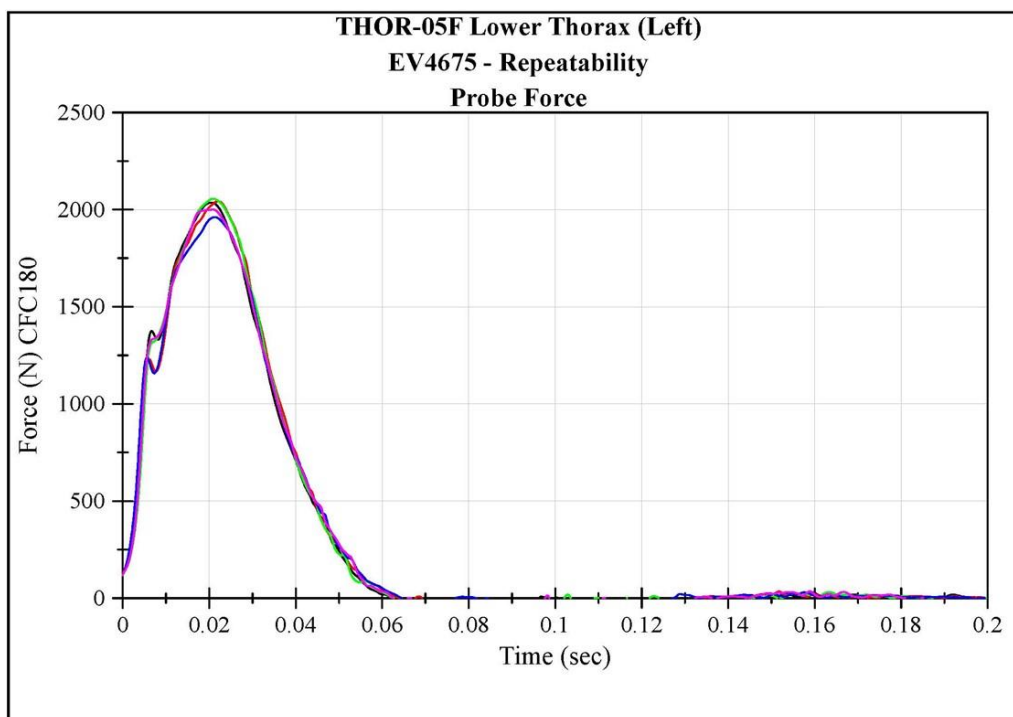


Figure 11-18. Calspan probe force for left lower thorax impact repeatability tests for EV4675

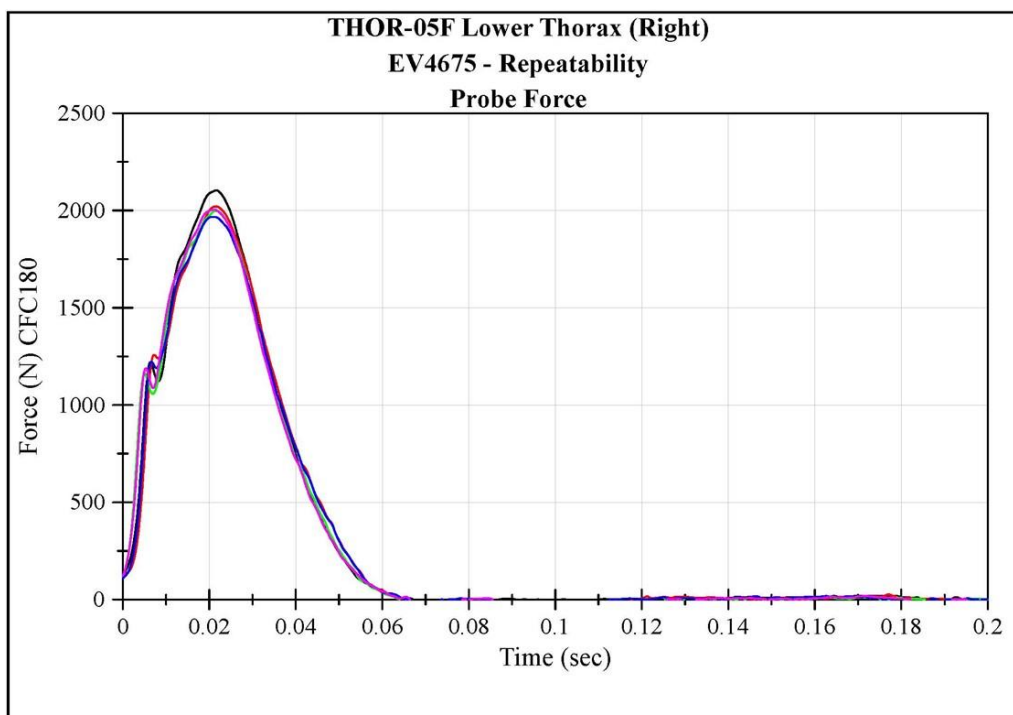


Figure 11-19. Calspan probe force for right lower thorax impact repeatability tests for EV4675

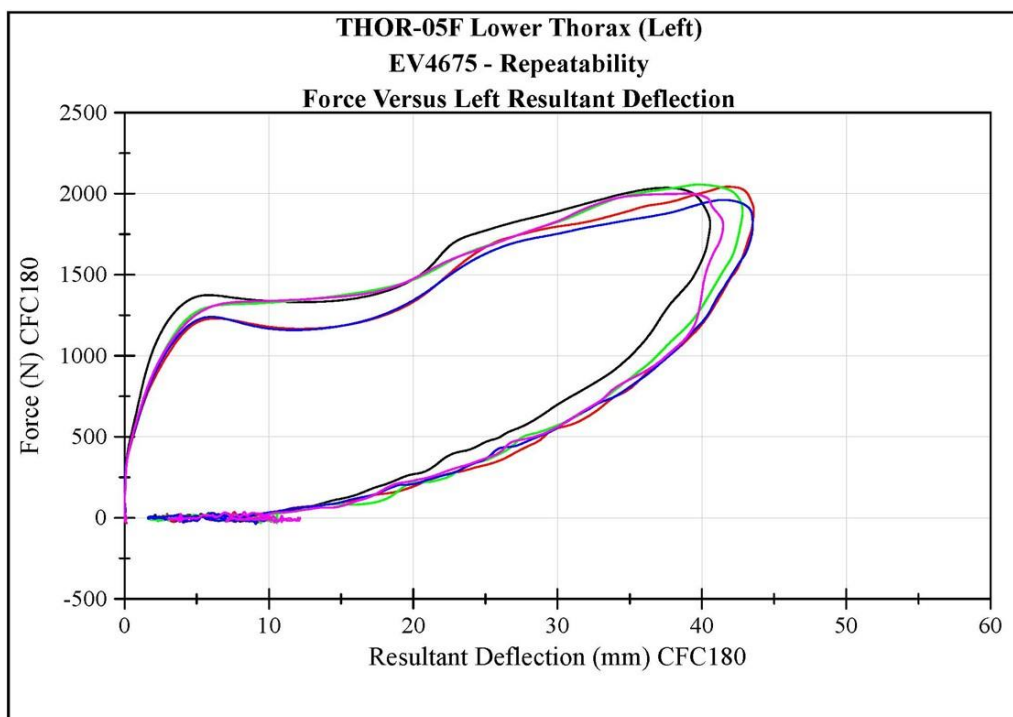


Figure 11-20. Calspan probe force vs. resultant deflection for left lower thorax impact repeatability tests for EV4675

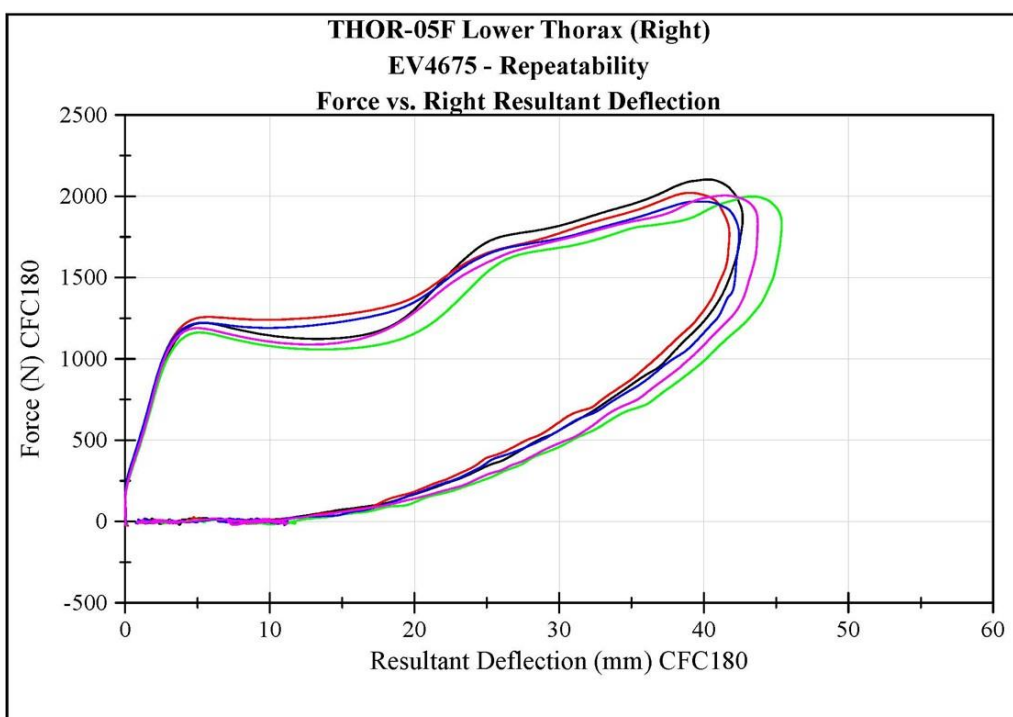


Figure 11-21. Calspan probe force vs. resultant deflection for right lower thorax impact repeatability tests for EV4675

11.2.6 THOR-05F EV4675 Testing at TRC

Repeatability results at TRC for lower thorax testing on EV4675 yielded CV values below 5 percent for both left and right sides as well as combined (Table 11-6, Figure 11-22 through Figure 11-25).

Table 11-6. TRC THOR-0F Lower Thorax Repeatability Results for EV4675

Test Number	Impact Side	Left or Right Resultant Deflection at Max Force (mm)	Maximum Probe Force (N)
2025_05_15 14_49	Left Side	42.6	1,976
2025_05_16 07_59		41.3	2,083
2025_05_16 08_11		42.1	2,043
2025_05_16 08_53		42.6	2,025
2025_05_16 09_30		42.8	1,980
Mean		42.3	2,022
Standard Deviation		0.6	44.7
CV		1.5%	2.2%
2025_05_16 10_07	Right Side	45.7	1,936
2025_05_16 10_56		43.6	1,938
2025_05_16 11_25		42.9	1,933
2025_05_16 12_33		45.3	1,961
2025_05_16 13_09		44.2	1,908
Mean		44.3	1,935
Standard Deviation		1.2	18.8
CV		2.6%	1.0%
Mean	Combined Left & Right Sides	43.3	1,978
Standard Deviation		1.4	55.8
CV		3.2%	2.8%

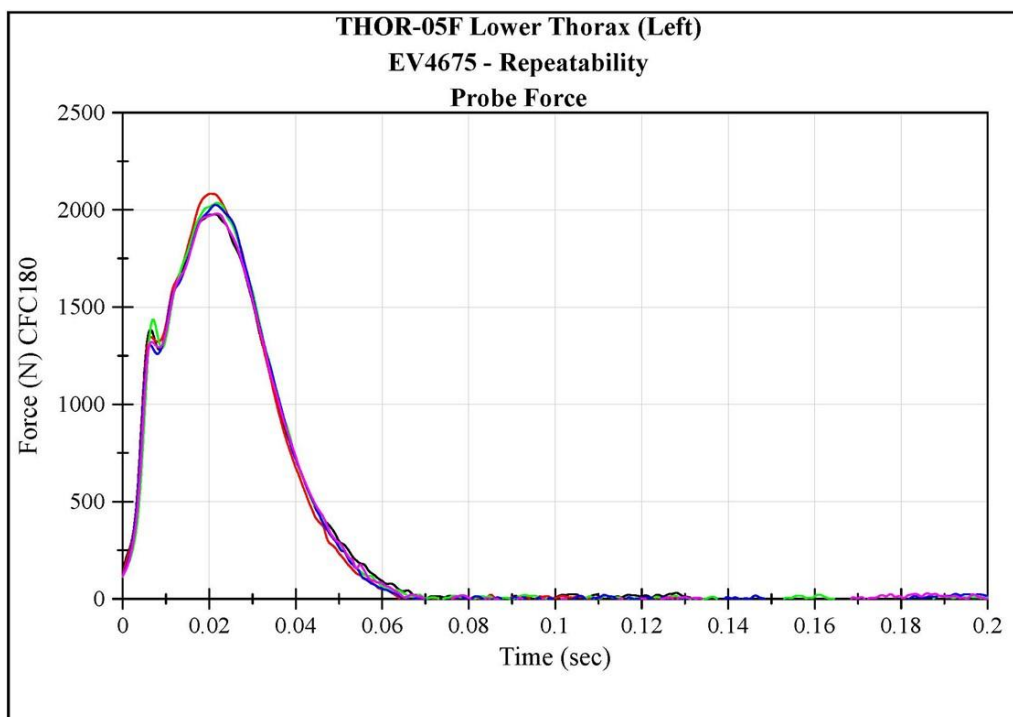


Figure 11-22. TRC probe force for left lower thorax impact repeatability tests for EV4675

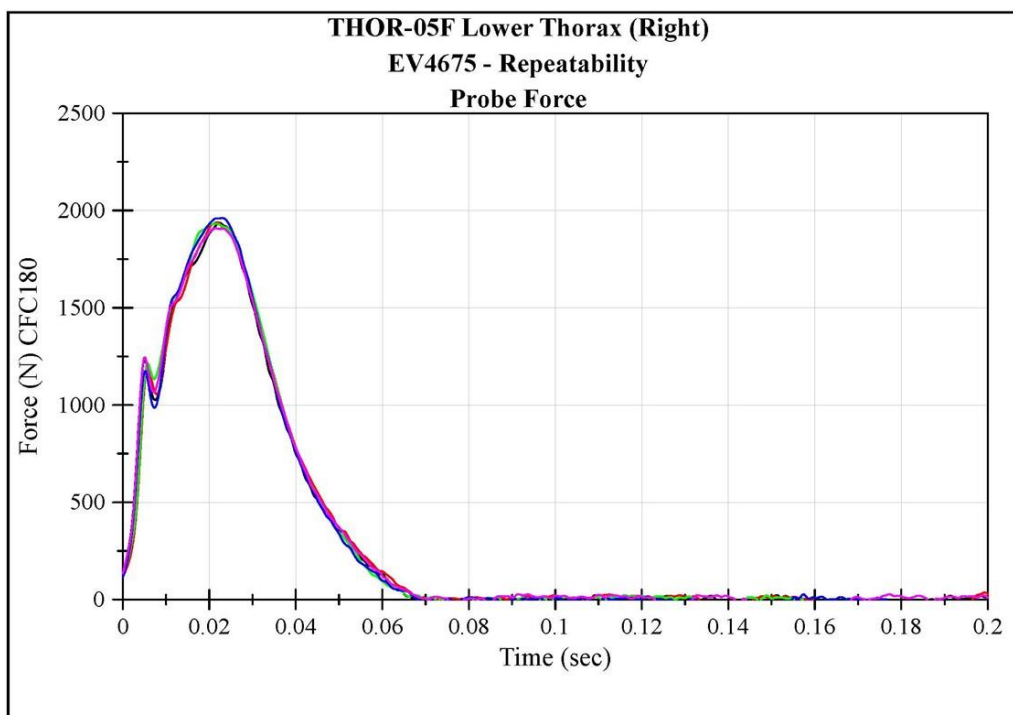


Figure 11-23. TRC probe force for right lower thorax impact repeatability tests for EV4675

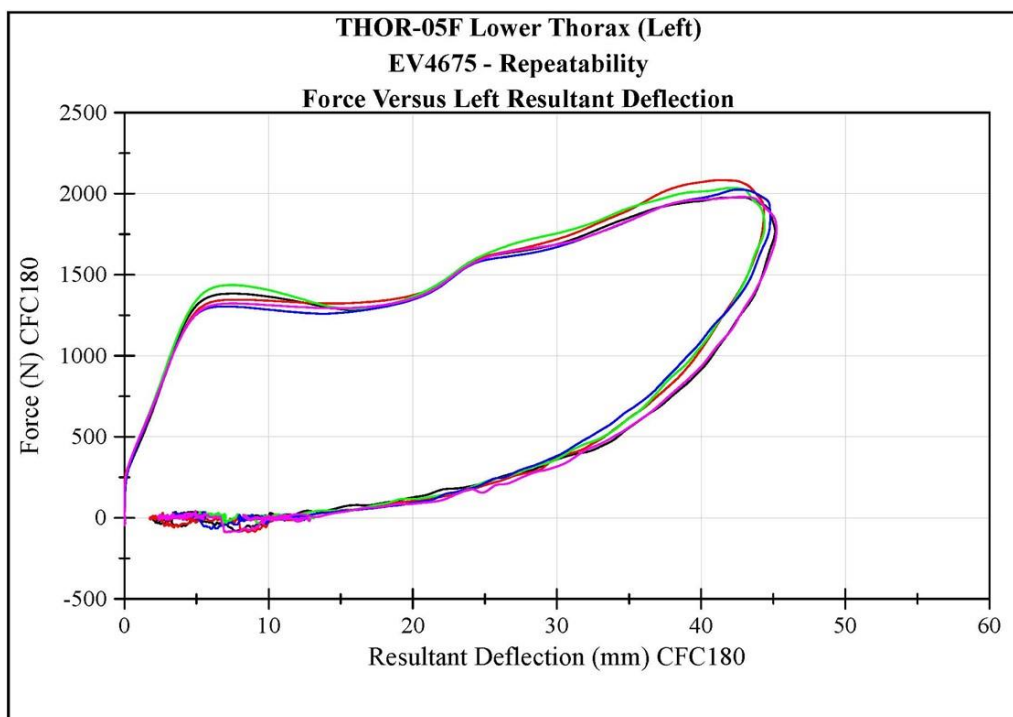


Figure 11-24. TRC probe force vs. resultant deflection for left lower thorax impact repeatability tests for EV4675

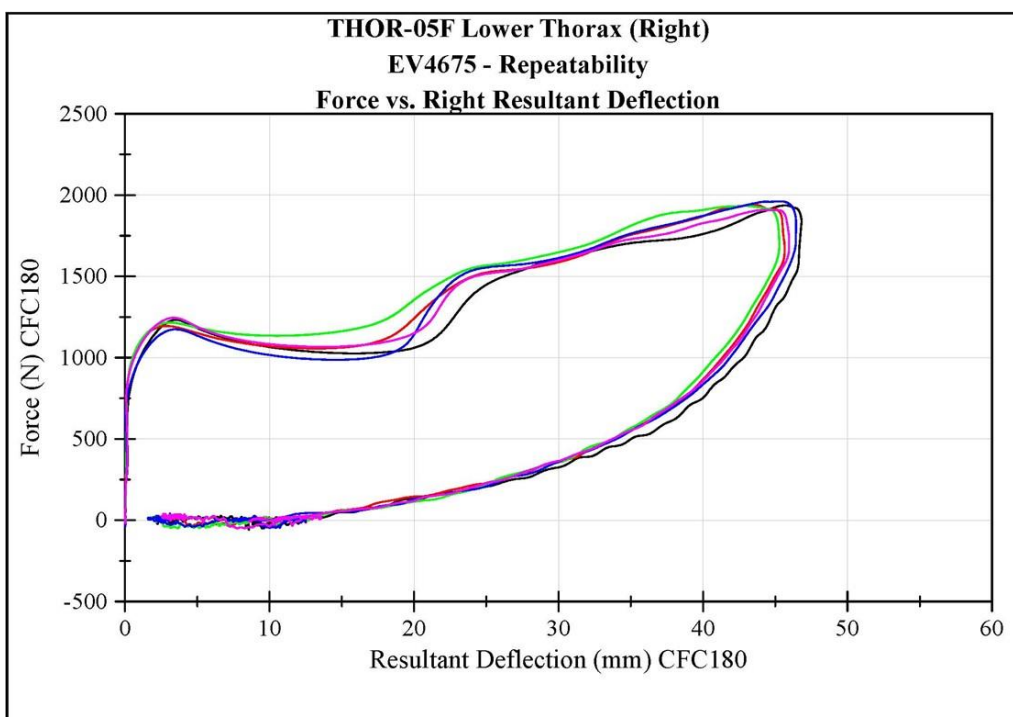


Figure 11-25. TRC probe force vs. resultant deflection for right lower thorax impact repeatability tests for EV4675

11.3 Lower Thorax Impact Dummy Reproducibility Results

Dummy Reproducibility results at VRTC for lower thorax impact qualification tests yielded CV values above 5 percent, but under 10 percent for both the left and right sides (Table 11-7).

Table 11-7. THOR-05F Lower Thorax reproducibility Results

Dummy	Impact Side	Test Number	Left or Right Resultant Deflection at Max Force (mm)	Maximum Probe Force (N)
VRTC EU9863	Left Side	240215-7	46.1	1,886
		240215-14	49.6	1,652
		240215-15	47.7	1,809
		240216-1	40.7	2,025
		240216-2	41.6	1,950
	Right Side	240216-3	45.3	1,937
		240222-2	45.8	1,959
		240222-3	42.8	1,995
		240222-4	42.2	2,023
		240222-5	39.7	2,163
VRTC EU3430	Left Side	241106-2	41.8	2,026
		241106-7	40.6	1,985
		241107-3	41.1	2,025
		241107-4	39.7	2,029
		241107-5	40.1	2,029
	Right Side	240815-17	41.8	2,113
		240819-2	40.9	2,053
		240819-4	41.2	2,101
		240819-5	39.7	2,065
		240819-6	41.3	2,125
VRTC EV4675	Left Side	240618-4	38.5	2,147
		240618-8	38.8	2,143
		240618-9	38.6	2,165
		240624-1	38.2	2,084
		240624-4	36.5	2,134
	Right Side	240624-12	37.8	2,135
		240624-13	42.3	2,113
		240624-14	40.2	2,088
		240624-15	38.6	2,066
		240624-17	41.0	2,099
Mean			41.3	2,037
Standard Deviation			3.0	111
CV			7.2%	5.5%

11.4 Lab-to-Lab Variability Analysis

Test Reproducibility results at all four labs for lower thorax impact qualification tests yielded CV values below 5 percent for probe force and above 5 percent, but under 10 percent for deflection at maximum force (Table 11-8).

Table 11-8. THOR-05F Lower Thorax Reproducibility Results

Dummy	Impact Side	Test Number	Left or Right Resultant Deflection at Max Force (mm)	Maximum Probe Force (N)
VRTC EV4675	Left Side	240618-4	38.5	2,147
		240618-8	38.8	2,143
		240618-9	38.6	2,165
		240624-1	38.2	2,084
		240624-4	36.5	2,134
	Right Side	240624-12	37.8	2,135
		240624-13	42.3	2,113
		240624-14	40.2	2,088
		240624-15	38.6	2,066
		240624-17	41.0	2,099
Humanetics EV4675	Left Side	689945	45.6	1,947
		690303	45.4	1,954
		690381	46.0	1,918
		690311	48.4	1,900
		690366	46.8	1,882
	Right Side	690470	51.8	2,008
		690482	46.0	1,925
		690461	51.2	1,978
		690444	50.3	1,933
		690489	50.7	1,945
Calspan EV4675	Left Side	2025_03_19 08_29	37.6	2,036
		2025_03_19 11_32	41.9	2,042
		2025_03_19 13_08	39.8	2,056
		2025_03_19 13_58	41.6	1,961
		2025_03_19 14_45	39.0	2,000
	Right Side	2025_03_19 08_50	40.4	2,103
		2025_03_19 15_07	39.1	2,020
		2025_03_19 15_43	43.4	1,998
		2025_03_19 16_15	39.7	1,967
		2025_03_19 16_48	41.5	2,004
TRC EV4675	Left Side	2025_05_15 14_49	42.6	1,976
		2025_05_16 07_59	41.3	2,083
		2025_05_16 08_11	42.1	2,043
		2025_05_16 08_53	42.6	2,025
		2025_05_16 09_30	42.8	1,980
	Right Side	2025_05_16 10_07	45.7	1,936
		2025_05_16 10_56	43.6	1,938
		2025_05_16 11_25	42.9	1,933
		2025_05_16 12_33	45.3	1,961
		2025_05_16 13_09	44.2	1,908

Test Reproducibility EV4675			
Mean		42.7	2,013
Standard Deviation		4.0	78.7
CV		9.3%	3.9%

11.5 Corridor Development

All the data used to determine the lower thorax qualification corridors is 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-05F Lower Thorax Qualification Corridor Results
(Highlighted values fell outside average $\pm 10\%$.)

Dummy		Test Number	Left or Right Resultant Deflection at Max Force (mm)	Maximum Probe Force (N)
VRTC EU9863	Left	240215-7	46.1	1,886
		240215-14	49.6	1,652
		240215-15	47.7	1,809
		240216-1	40.7	2,025
		240216-2	41.6	1,950
	Right	240216-3	45.3	1,937
		240222-2	45.8	1,959
		240222-3	42.8	1,995
		240222-4	42.2	2,023
		240222-5	39.7	2,163
VRTC EU3430	Left	241106-2	41.8	2,026
		241106-7	40.6	1,985
		241107-3	41.1	2,025
		241107-4	39.7	2,029
		241107-5	40.1	2,029
	Right	240815-17	41.8	2,113
		240819-2	40.9	2,053
		240819-4	41.2	2,101
		240819-5	39.7	2,065
		240819-6	41.3	2,125
VRTC EV4675	Left	240618-4	38.5	2,147
		240618-8	38.8	2,143
		240618-9	38.6	2,165
		240624-1	38.2	2,084
		240624-4	36.5	2,134
	Right	240624-12	37.8	2,135
		240624-13	42.3	2,113
		240624-14	40.2	2,088
		240624-15	38.6	2,066
		240624-17	41.0	2,099

Humanetics EV4675	Left	689945	45.6	1,947
		690303	45.4	1,954
		690381	46.0	1,918
		690311	48.4	1,900
		690366	46.8	1,882
	Right	690470	51.8	2,008
		690482	46.0	1,925
		690461	51.2	1,978
		690444	50.3	1,933
		690489	50.7	1,945
Calspan EV4675	Left	2025_03_19 08_29	37.6	2,036
		2025_03_19 11_32	41.9	2,042
		2025_03_19 13_08	39.8	2,056
		2025_03_19 13_58	41.6	1,961
		2025_03_19 14_45	39.0	2,000
	Right	2025_03_19 08_50	40.4	2,103
		2025_03_19 15_07	39.1	2,020
		2025_03_19 15_43	43.4	1,998
		2025_03_19 16_15	39.7	1,967
		2025_03_19 16_48	41.5	2,004
TRC EV4675	Left	2025_05_15 14_49	42.6	1,976
		2025_05_16 07_59	41.3	2,083
		2025_05_16 08_11	42.1	2,043
		2025_05_16 08_53	42.6	2,025
		2025_05_16 09_30	42.8	1,980
	Right	2025_05_16 10_07	45.7	1,936
		2025_05_16 10_56	43.6	1,938
		2025_05_16 11_25	42.9	1,933
		2025_05_16 12_33	45.3	1,961
		2025_05_16 13_09	44.2	1,908
Mean			42.7	2,008
Standard Deviation			3.6	92.0
CV			8.5%	4.6%

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	
Maximum Probe Force	N	1,807	2,209	2,008	10%
Left or Right Resultant Deflection at Max Force	mm	38.4	46.9	42.7	10%

Discussion. Highlighted cells in Table 11-9 indicate test values that did not meet the respective target response ± 10 percent in Table 11-10. Deflection at maximum force was most likely to fall outside the corridors; 17% of the tests show a non-conformity due to this specification. Only one test was out of range for maximum probe force.

Repeatability All CV values were below 5 percent with the exception of EU9863, which was only tested at VRTC. For EU9863, left-side responses were between 5 percent and 10 percent; on the right, resultant deflection at maximum force was also between 5 and 10 percent, while maximum probe force was below 5 percent. A careful review of EU9863's data suggests test setup variation caused the higher response variability, which was not apparent at the time of testing since it was the first series in this mode. Since the R&R test series, 11 additional lower thorax tests on EU9863 demonstrated reduced CVs of less than 5 percent for all measures. Including those 11 tests in the larger dataset altered average deflection and probe force values by less than 0.2 percent, indicating the initial VRTC variability, though larger than ideal, did not warrant exclusion or retesting.

Given that the probe alignment is offset from the centerline of the dummy, test labs may need to be diligent to ensure the dummy is not rotated about the Z-axis on the test table when aligning the dummy with the impact probe. Otherwise, they may experience *Dummy/Test Repeatability* difficulties.

Dummy Reproducibility CV values were between 5 and 10 percent for all specifications. Five tests (17%) were non-conforming, with all but one of the non-conformities due to out of range deflection at maximum force.

With respect to lab-to-lab variability, *Test Repeatability* CV values were between 5 and 10 percent, for deflection at maximum probe force; probe force CV values were below 5 percent.

12 ABDOMEN

12.1 Methodology

Abdomen repeatability and reproducibility tests followed the qualification procedures described in the *THOR-05F Qualification Procedures and Requirements*. These tests utilize a horizontally oriented, rigid, rectangular bar attached to an impact probe (total mass of 16.00 ± 0.02 kg) (Figure 12-1). The 6.10 ± 0.05 m/s impact probe is positioned such that the center of the rectangular bar is 20.7 mm below the umbilicus (belly button) landmark on the abdomen. During the tests, the probe force and left and right abdominal pressures were measured.

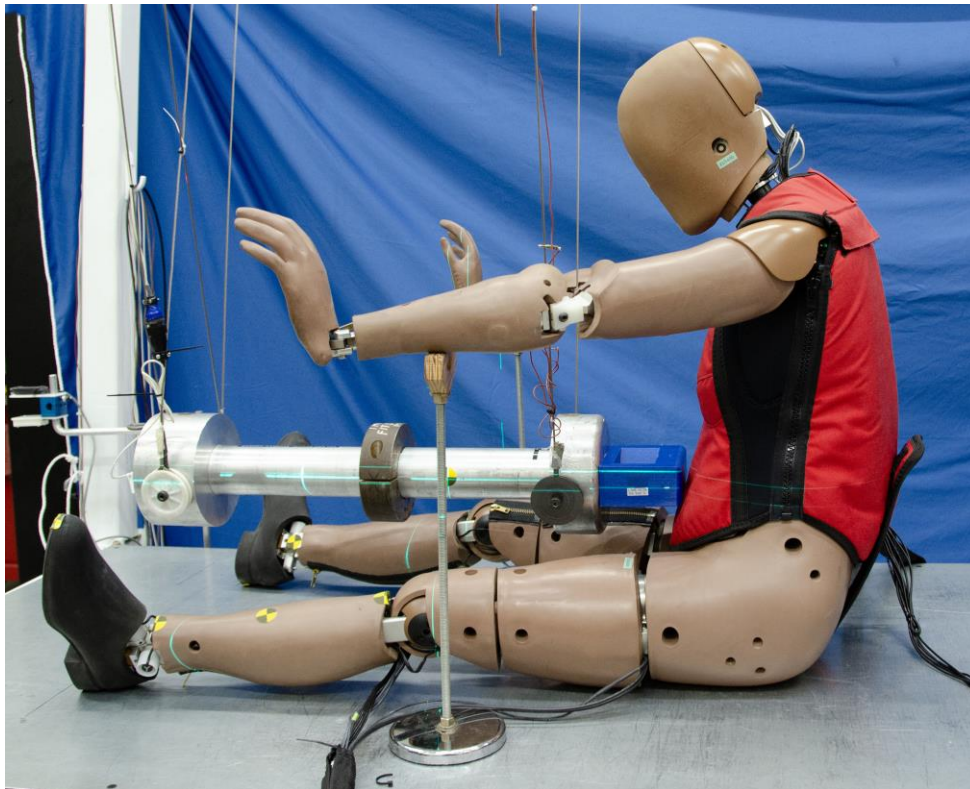


Figure 12-1. Abdomen test setup

12.2 Abdomen Repeatability Results

Sections 12.2.1 through 12.2.3 illustrate the results of the 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 four 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-05F EU9863 Testing at VRTC

Repeatability results for abdomen testing on EU9863 at VRTC yielded CV values below 5 percent (Table 12-1, Figure 12-2 through Figure 12-3).

Table 12-1. VRTC THOR-05F Abdomen Repeatability Results for EU9863

Test Number	Maximum Probe Force (N)	Left Abdomen Max Pressure (kPa)	Right Abdomen Max Pressure (kPa)	Difference Between Max Left & Right Pressures (kPa)
240815-13	4,321	201	196	5
240815-15	4,366	201	195	6
240819-3	4,418	201	202	1
240819-9	4,549	212	203	9
240819-10	4,508	211	199	12
Mean	4,432	202		N/A
Standard Deviation	95.3	5.6		N/A
CV	2.2%	2.8%		N/A

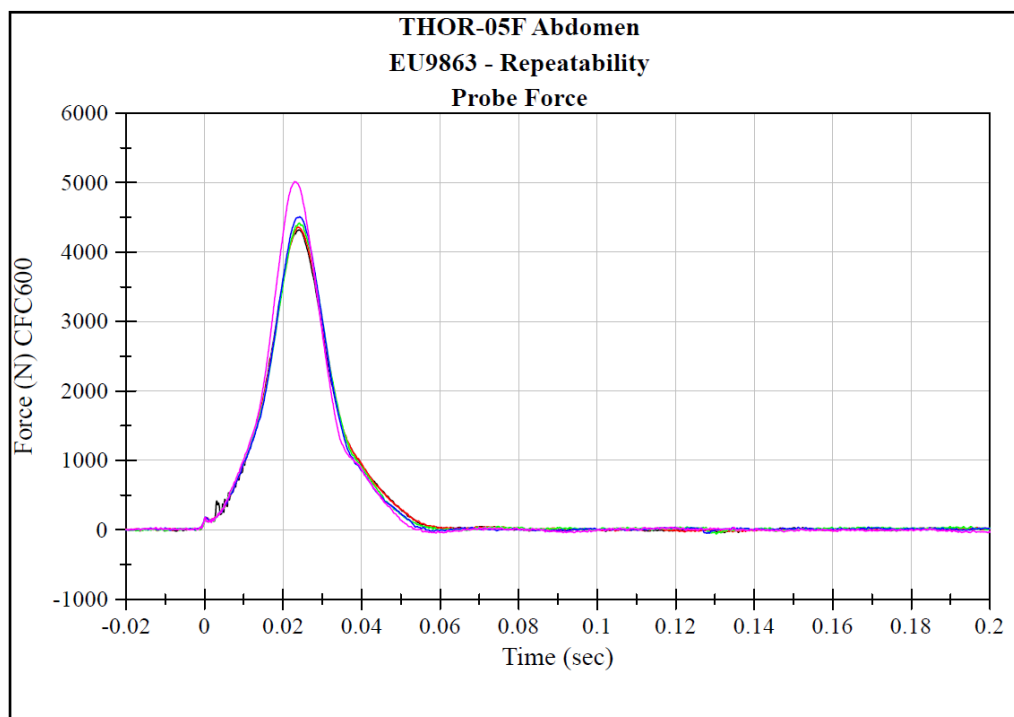


Figure 12-2 VRTC probe force for abdomen impact repeatability tests for EU9863

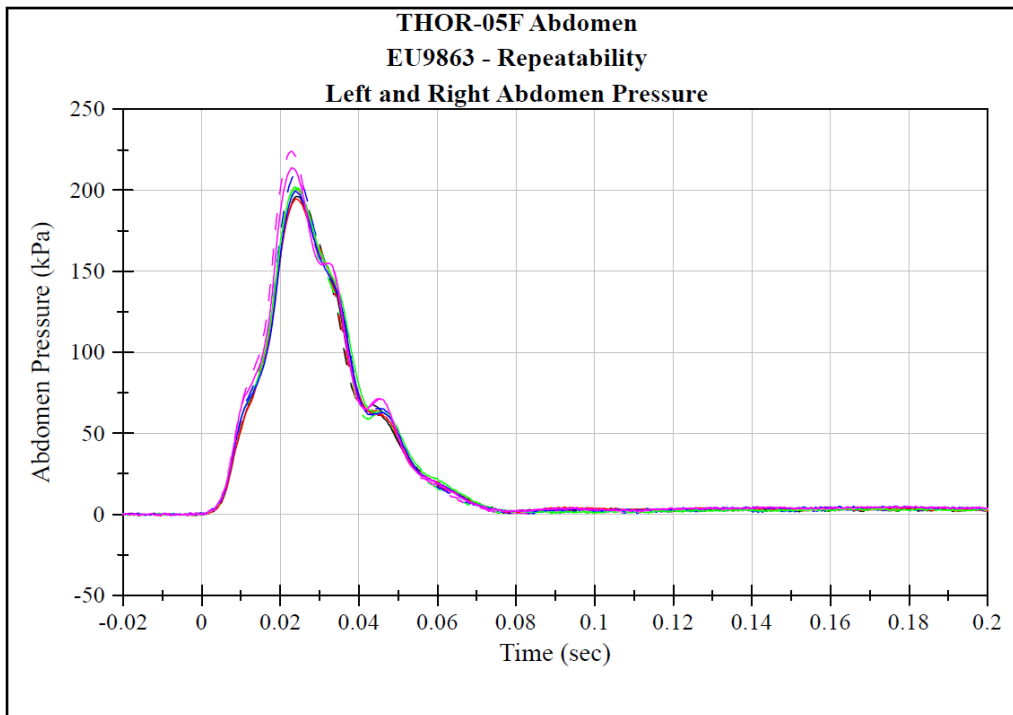


Figure 12-3. VRTC left and right abdomen pressure for abdomen impact repeatability tests for EU9863

12.2.2 THOR-05F EU3430 Testing at VRTC

Repeatability results for abdomen testing on EU3430 at VRTC yielded CV values below 5 percent (Table 12-2, Figure 12-4 through Figure 12-5).

Table 12-2. VRTC THOR-05F Abdomen Repeatability Results for EU3430

Test Number	Maximum Probe Force (N)	Left Abdomen Max Pressure (kPa)	Right Abdomen Max Pressure (kPa)	Difference Between Max Left & Right Pressures (kPa)
240813-11	4,400	207	213	6
240813-13	4,521	215	211	4
240813-14	4,543	214	214	0
240813-16	4,619	209	220	11
240814-1	4,520	208	214	6
Mean	4,521	213		N/A
Standard Deviation	78.6	3.9		N/A
CV	1.7%	1.8%		N/A

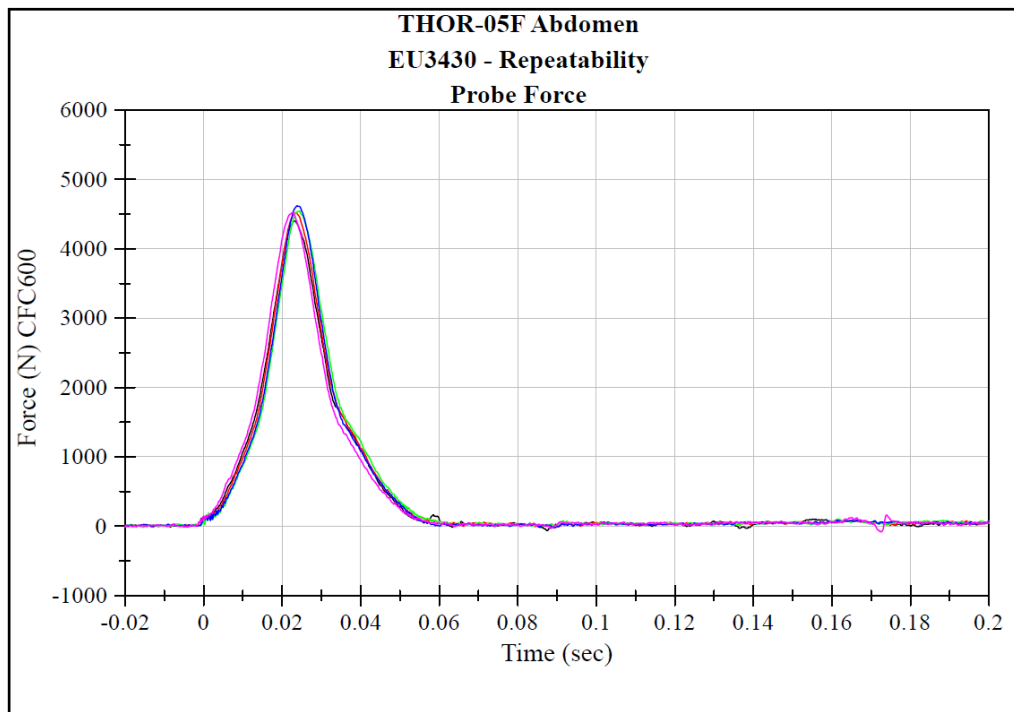


Figure 12-4 VRTC probe force for abdomen impact repeatability tests for EU3430

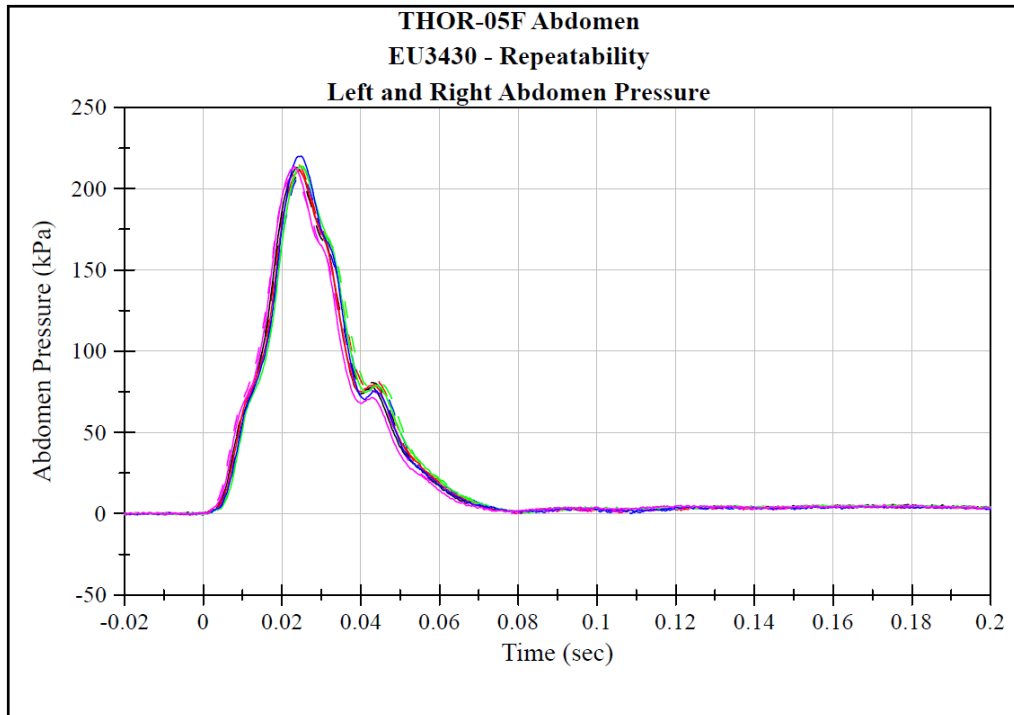


Figure 12-5. VRTC left and right abdomen pressure for abdomen impact repeatability tests for EU3430

12.2.3 THOR-05F EV4675 Testing at VRTC

Repeatability results for abdomen testing on EV4675 at VRTC yielded CV values below 5 percent (Table 12-3, Figure 12-6 through Figure 12-7).

Table 12-3. VRTC THOR-05F Abdomen Repeatability Results for EV4675

Test Number	Maximum Probe Force (N)	Left Abdomen Max Pressure (kPa)	Right Abdomen Max Pressure (kPa)	Difference Between Max Left & Right Pressures (kPa)
240708-2	4,472	199	204	5
240709-2	4,410	209	197	12
240709-4	4,513	205	209	4
240709-7	4,498	206	206	1
240709-8	4,646	210	209	1
Mean	4,508	205		N/A
Standard Deviation	86.9	4.3		N/A
CV	1.9%	2.1%		N/A

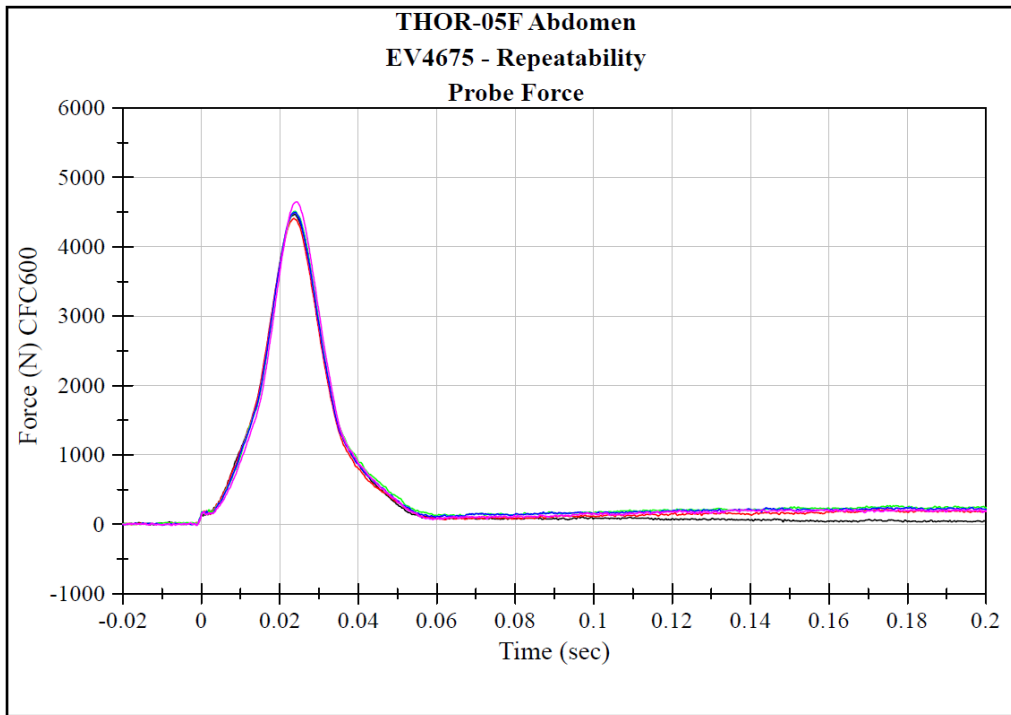


Figure 12-6 VRTC probe force for abdomen impact repeatability tests for EV4675

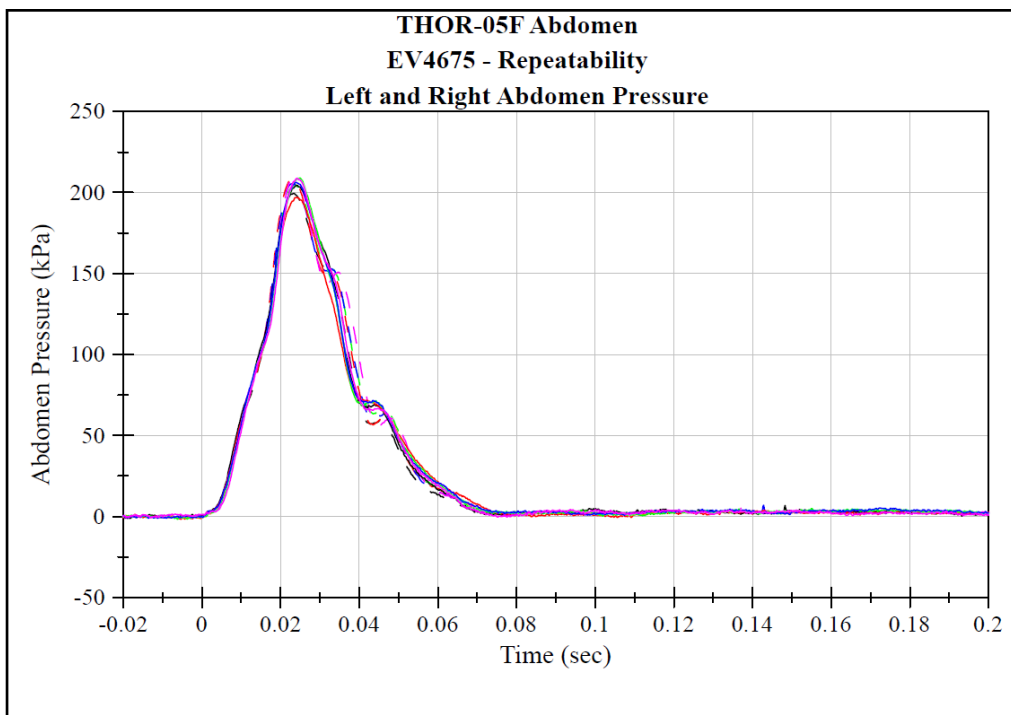


Figure 12-7. VRTC left and right abdomen pressure for abdomen impact repeatability tests for EV4675

12.2.4 THOR-05F EV4675 Testing at Humanetics

Repeatability results for abdomen testing on EV4675 at Humanetics yielded CV values below 5 percent (Table 12-4, Figure 12-8 through Figure 12-9).

Table 12-4. Humanetics THOR-05F Abdomen Repeatability Results for ED7448

Test Number	Maximum Probe Force (N)	Left Abdomen Max Pressure (kPa)	Right Abdomen Max Pressure (kPa)	Difference Between Max Left & Right Pressures (kPa)
689345	4,610	204	204	0
689327	4,696	210	211	1
689355	4,534	208	194	14
689318	4,641	207	200	7
689339	4,629	205	207	2
Mean	4,622	205		N/A
Standard Deviation	58.6	4.9		N/A
CV	1.3%	2.4%		N/A

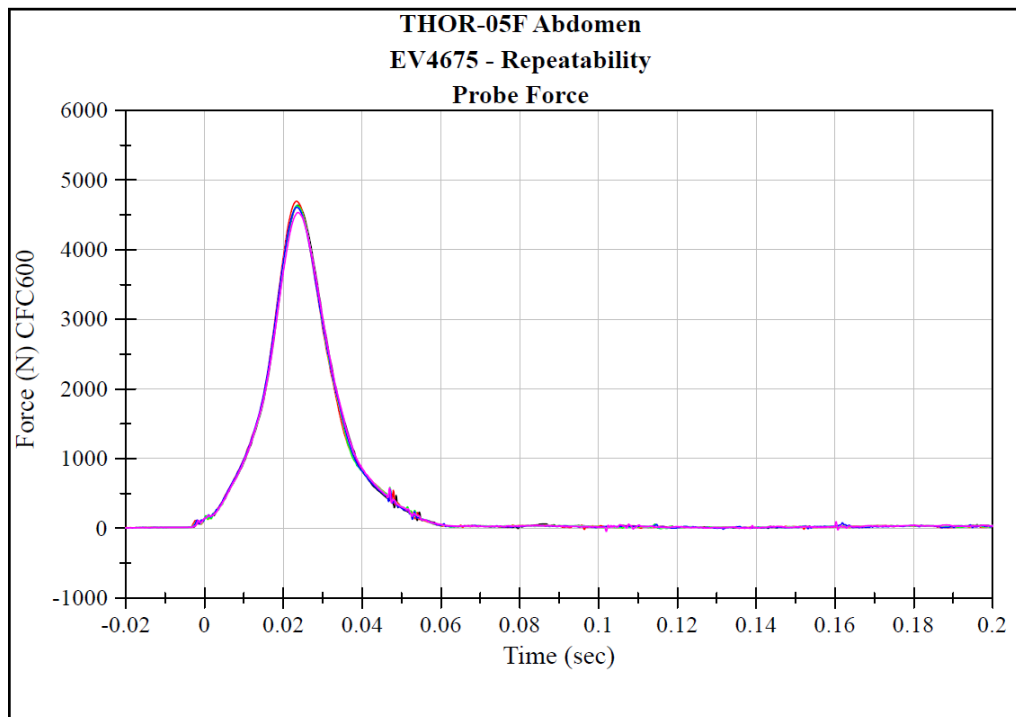


Figure 12-8 Humanetics probe force for abdomen impact repeatability tests for EV4675

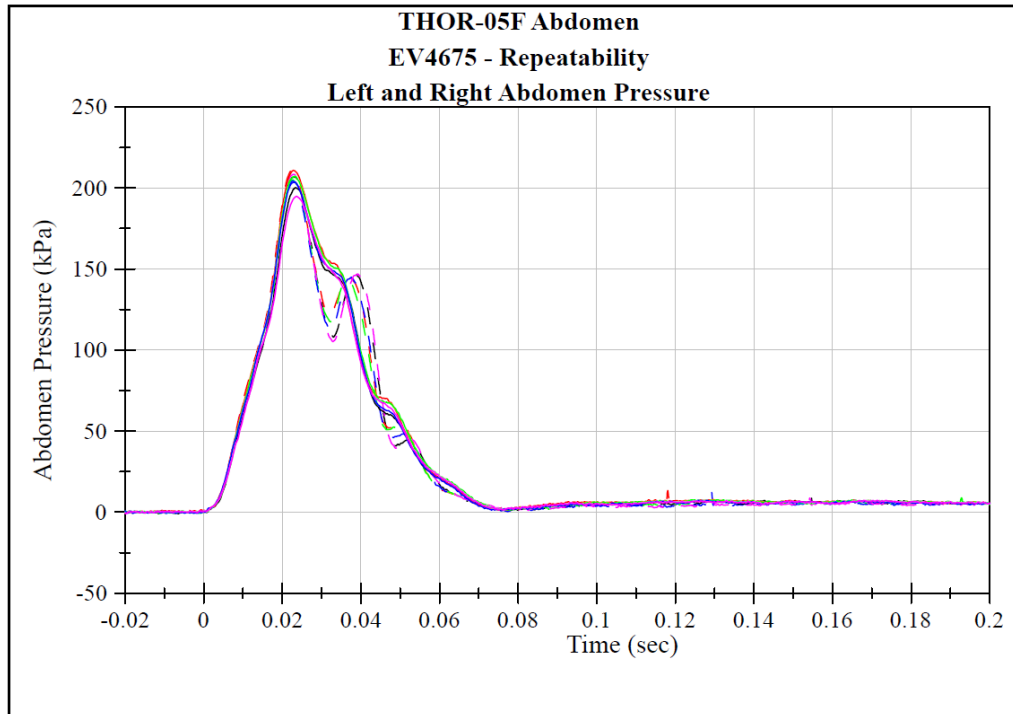


Figure 12-9. Humanetics left and right abdomen pressure for abdomen impact repeatability tests for EV4675

12.2.5 THOR-05F EV4675 Testing at Calspan

Repeatability results for abdomen testing on EV4675 at Calspan yielded CV values below 5 percent (Table 12-5, Figure 12-10 through Figure 12-11).

Table 12-5. Calspan THOR-05F Abdomen Repeatability Results for EV4675

Test Number	Maximum Probe Force (N)	Left Abdomen Max Pressure (kPa)	Right Abdomen Max Pressure (kPa)	Difference Between Max Left & Right Pressures (kPa)
2025_03_24_12_54	4,450	224	227	3
2025_03_24_15_36	4,465	218	215	2
2025_03_24_17_09	4,515	227	219	7
2025_03_24_17_47	4,344	219	212	7
2025_03_24_18_51	4,341	216	207	9
Mean	4,423	218		N/A
Standard Deviation	77.5	6.4		N/A
CV	1.8%	2.9%		N/A

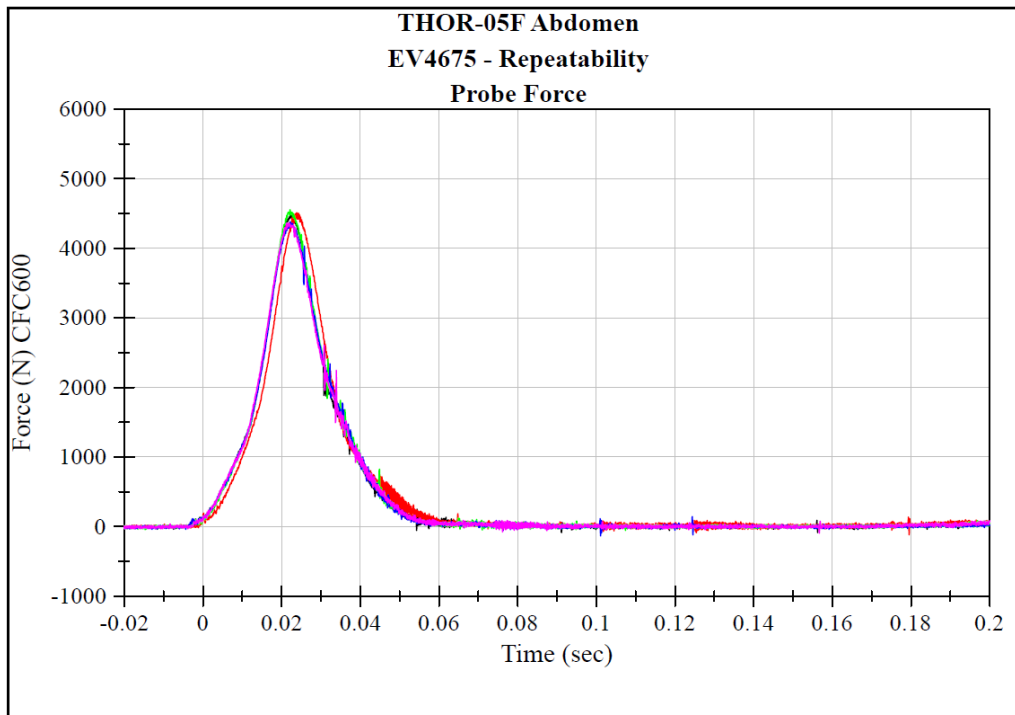


Figure 12-10 Calspan probe force for abdomen impact repeatability tests for EV4675

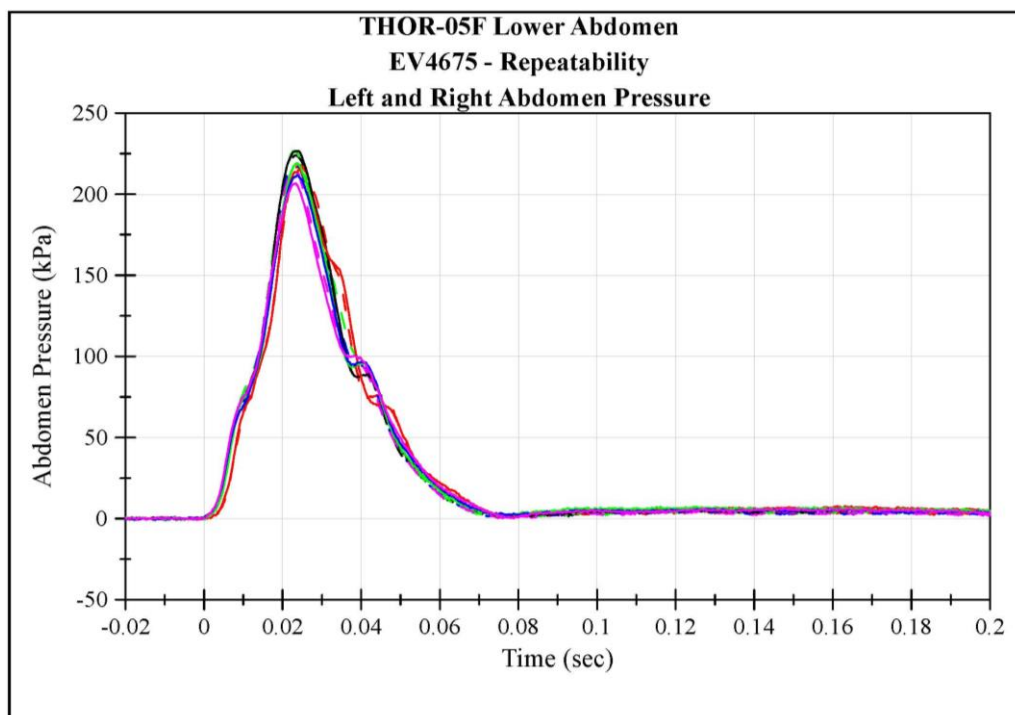


Figure 12-11. Calspan left and right abdomen pressure for abdomen impact repeatability tests for EV4675

12.2.6 THOR-05F EV4675 Testing at TRC

Repeatability results for abdomen testing on EV4675 at TRC yielded CV values below 5 percent (Table 12-6, Figure 12-12 through Figure 12-13).

Table 12-6. TRC THOR-05F Abdomen Repeatability Results for EV4675

Test Number	Maximum Probe Force (N)	Left Abdomen Max Pressure (kPa)	Right Abdomen Max Pressure (kPa)	Difference Between Max Left & Right Pressures (kPa)
2025_05_20_09_57	4,465	207	222	15
2025_05_20_11_19	4,472	213	219	6
2025_05_20_16_13	4,584	217	224	7
2025_05_21_08_56	4,554	215	223	9
2025_05_21_10_43	4,447	216	213	3
Mean	4,504	217		N/A
Standard Deviation	60.8	5.3		N/A
CV	1.3%	2.4%		N/A

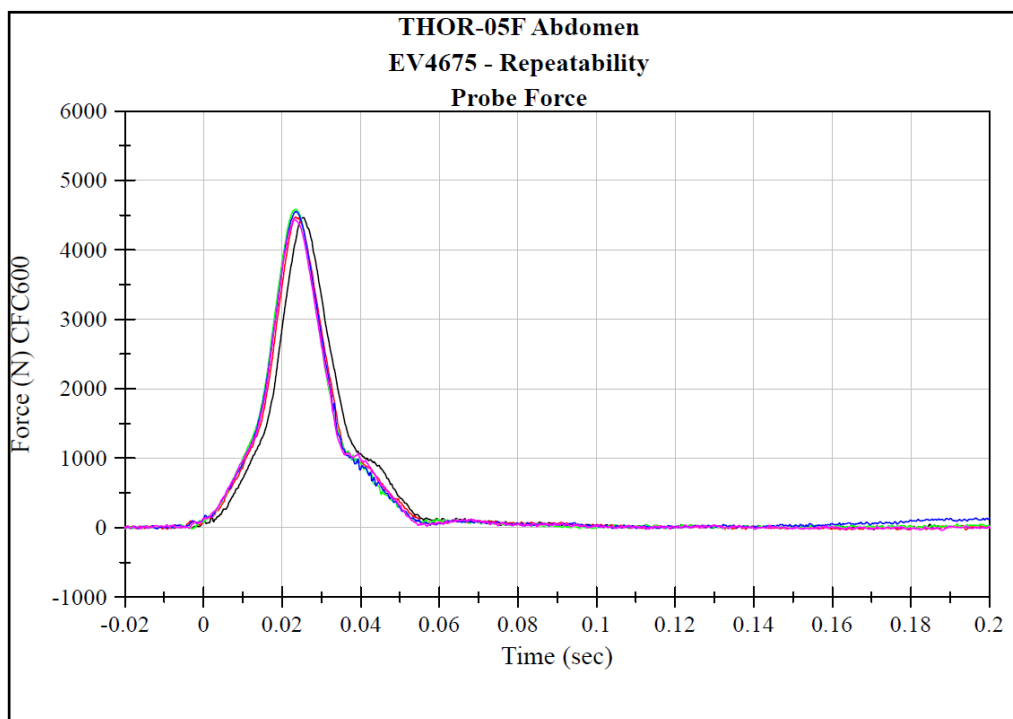


Figure 12-12 TRC probe force for abdomen impact repeatability tests for EV4675

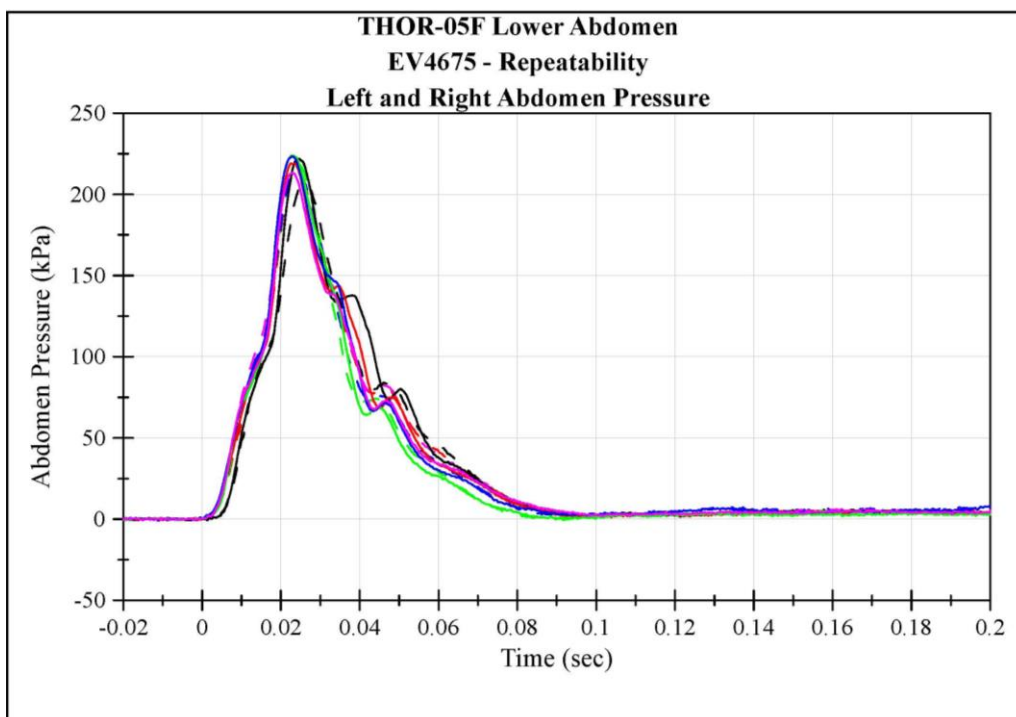


Figure 12-13. TRC left and right abdomen pressure for abdomen impact repeatability tests for EV4675

12.3 Abdomen Impact Dummy Reproducibility Results

Dummy Reproducibility results for the VRTC abdomen qualification yielded CV values below 5 percent (Table 12-7).

Table 12-7. THOR-05F Abdomen Reproducibility Results

Dummy	Test Number	Maximum Probe Force (N)	Left Abdomen Max Pressure (kPa)	Right Abdomen Max Pressure (kPa)	Difference Between Max Left & Right Pressures (kPa)
VRTC EU9863	240815-13	4,321	201	196	5
	240815-15	4,366	201	195	6
	240819-3	4,418	201	202	1
	240819-9	4,549	212	203	9
	240819-10	4,508	211	199	12
VRTC EU3430	240813-11	4,400	207	213	6
	240813-13	4,521	215	211	4
	240813-14	4,543	214	214	0
	240813-16	4,619	209	220	11
	240814-1	4,520	208	214	6
VRTC EV4675	240708-2	4,472	199	204	5
	240709-2	4,410	209	197	12
	240709-4	4,513	205	209	4
	240709-7	4,498	206	206	1
	240709-8	4,646	210	209	1
Mean		4,487	207		N/A
Standard Deviation		90.2	6.3		N/A
CV		2.0%	3.0%		N/A

12.4 Lab-to-Lab Variability Analysis

Test Reproducibility results at all four labs for abdomen qualification yielded CV values below 5 percent (Table 12-8). Additionally, the CV for combined pressures is also below 5 percent.

Table 12-8. THOR-05F Abdomen Reproducibility Results

Dummy	Test Number	Maximum Probe Force (N)	Left Abdomen Max Pressure (kPa)	Right Abdomen Max Pressure (kPa)	Difference Between Max Left & Right Pressures (kPa)
VRTC EV4675	240708-2	4,472	199	204	5
	240709-2	4,410	209	197	12
	240709-4	4,513	205	209	4
	240709-7	4,498	206	206	1
	240709-8	4,646	210	209	1
Humanetics EV4675	689345	4,610	204	204	0
	689327	4,696	210	211	1
	689355	4,534	208	194	14
	689318	4,641	207	200	7
	689339	4,629	205	207	2
Calspan EV4675	2025_03_24 12_54	4,450	224	227	3
	2025_03_24 15_36	4,465	218	215	2
	2025_03_24 17_09	4,515	227	219	7
	2025_03_24 17_47	4,344	219	212	7
	2025_03_24 18_51	4,341	216	207	9
TRC EV4675	2025_05_20 09_57	4,465	207	222	15
	2025_05_20 11_19	4,472	213	219	6
	2025_05_20 16_13	4,584	217	224	7
	2025_05_21 08_56	4,554	215	223	9
	2025_05_21 10_43	4,447	216	213	3
Test Reproducibility EV4675					
Mean		4,514	211		N/A
Standard Deviation		98.2	8.1		N/A
CV		2.2%	3.8%		N/A

12.5 Corridor Development

All the data used to determine the abdomen qualification corridors is shown in Table 12-9. The qualification corridors were calculated using the mean plus or minus 10 percent of the maximum for the specified channels, except for the difference between the left and right abdomen pressures. For consistency, similar to the THOR-50M, a difference of ± 15 kPa between left and right pressures indicates an acceptable symmetrical impact. Table 12-10 summarizes the abdomen qualification response requirements.

Table 12-9. THOR-05F Abdomen Qualification Corridor Results

Dummy	Test Number	Maximum Probe Force (N)	Left Abdomen Max Pressure (kPa)	Right Abdomen Max Pressure (kPa)	Difference Between Max Left & Right Pressures (kPa)
VRTC EU9863	240815-13	4,321	201	196	5
	240815-15	4,366	201	195	6
	240819-3	4,418	201	202	1
	240819-9	4,549	212	203	9
	240819-10	4,508	211	199	12
VRTC EU3430	240813-11	4,400	207	213	6
	240813-13	4,521	215	211	4
	240813-14	4,543	214	214	0
	240813-16	4,619	209	220	11
	240814-1	4,520	208	214	6
VRTC EV4675	240708-2	4,472	199	204	5
	240709-2	4,410	209	197	12
	240709-4	4,513	205	209	4
	240709-7	4,498	206	206	1
	240709-8	4,646	210	209	1
Humanetics EV4675	689345	4,610	204	204	0
	689327	4,696	210	211	1
	689355	4,534	208	194	14
	689318	4,641	207	200	7
	689339	4,629	205	207	2
Calspan EV4675	2025_03_24_12_54	4,450	224	227	3
	2025_03_24_15_36	4,465	218	215	2
	2025_03_24_17_09	4,515	227	219	7
	2025_03_24_17_47	4,344	219	212	7
	2025_03_24_18_51	4,341	216	207	9
TRC EV4675	2025_05_20_09_57	4,465	207	222	15
	2025_05_20_11_19	4,472	213	219	6
	2025_05_20_16_13	4,584	217	224	7
	2025_05_21_08_56	4,554	215	223	9
	2025_05_21_10_43	4,447	216	213	3
Mean		4,502	210		N/A
Standard Deviation		97.1	7.9		N/A
CV		2.2%	3.8%		N/A

Table 12-10. Abdomen Qualification Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Impact Velocity	m/s	6.05	6.15	6.10	
Maximum Probe Force	N	4,052	4,952	4,502	10%
Left Abdomen Max Pressure	kPa	189	231	210	10%
Right Abdomen Max Pressure					
Difference Between Max Left & Right Pressures	kPa	N/A	<15	0	

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

All CV values were below 5 percent for *Dummy Repeatability*, *Test Repeatability*, *Dummy Reproducibility*, and *Test Reproducibility*.

13 UPPER LEG

13.1 Methodology

Upper leg repeatability and reproducibility tests followed the qualification procedures described in the *THOR-05F Qualification Procedures and Requirements*. This test examines the response of the femur to axial impacts at the knee using a 7.26 kg impactor with a 76.2 mm diameter rigid disk impact surface at 3.65 ± 0.05 m/s. (Figure 13-1). During these tests the probe force, femur force F_z , and resultant acetabulum force were measured.



Figure 13-1. Upper leg impact test

13.2 Upper Leg Repeatability Results

Sections 13.2.1 through 13.2.12 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 all four labs. The right and left legs were tested for each of the three dummies. 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-05F EU9863 Left Upper Leg Testing at VRTC

Repeatability results for upper leg testing on EU9863 (left side) at VRTC yielded CV values below 5 percent (Table 13-1, Figure 13-2 through Figure 13-4).

Table 13-1. VRTC THOR-05F Left Upper Leg Repeatability Results for EU9863

Test Number	Maximum Probe Force (N)	Minimum Femur Force, F_z (N)	Maximum Resultant Acetabulum Force (N)
241021-1	8,126	-4,644	2,000
241021-2	8,096	-4,564	2,041
241021-3	8,110	-4,538	1,999
241021-4	8,121	-4,555	1,985
241021-5	8,031	-4,475	1,974
Mean	8,097	-4,555	2,000
Standard Deviation	38.7	60.7	25.6
CV	0.5%	1.3%	1.3%

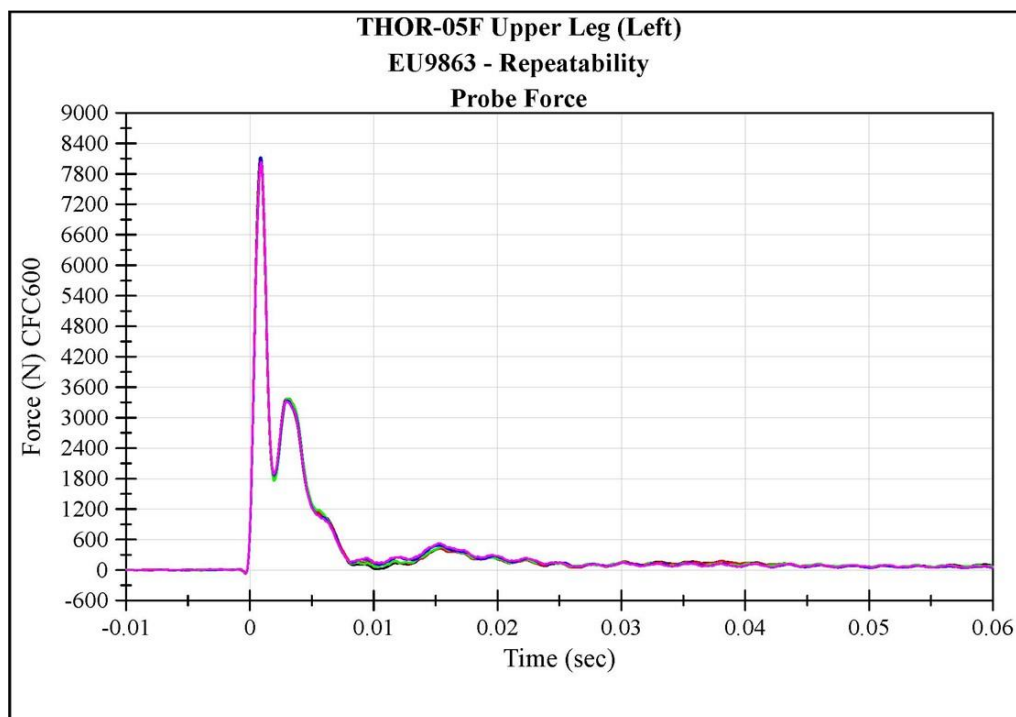


Figure 13-2. VRTC probe force for left upper leg impact repeatability tests for EU9863

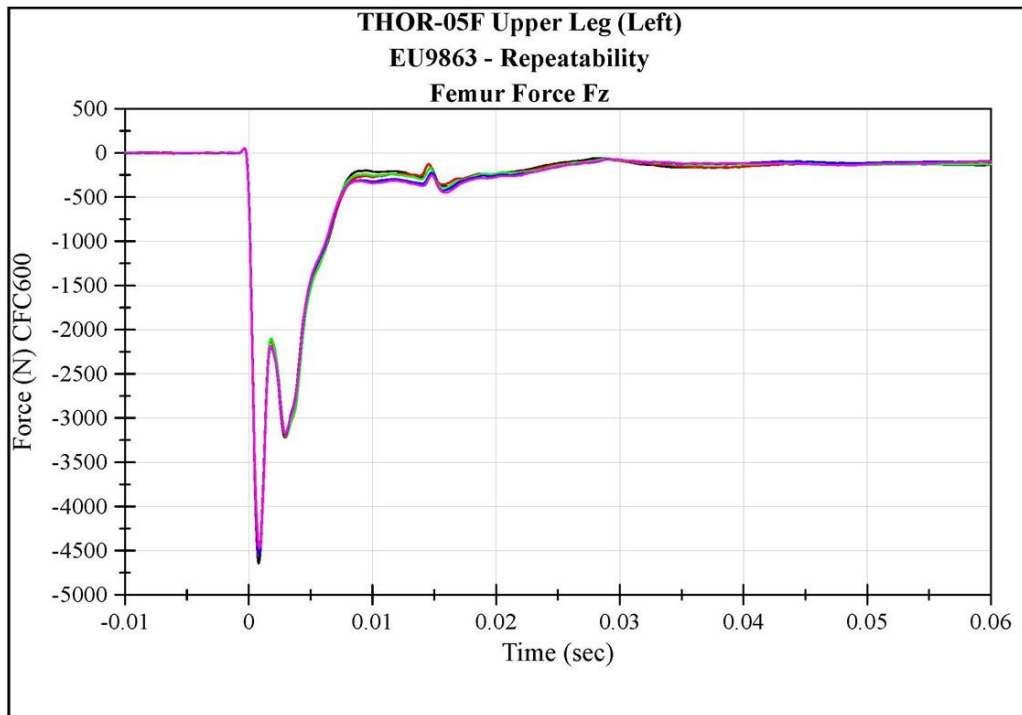


Figure 13-3. VRTC femur force Fz for left upper leg impact repeatability tests for EU9863

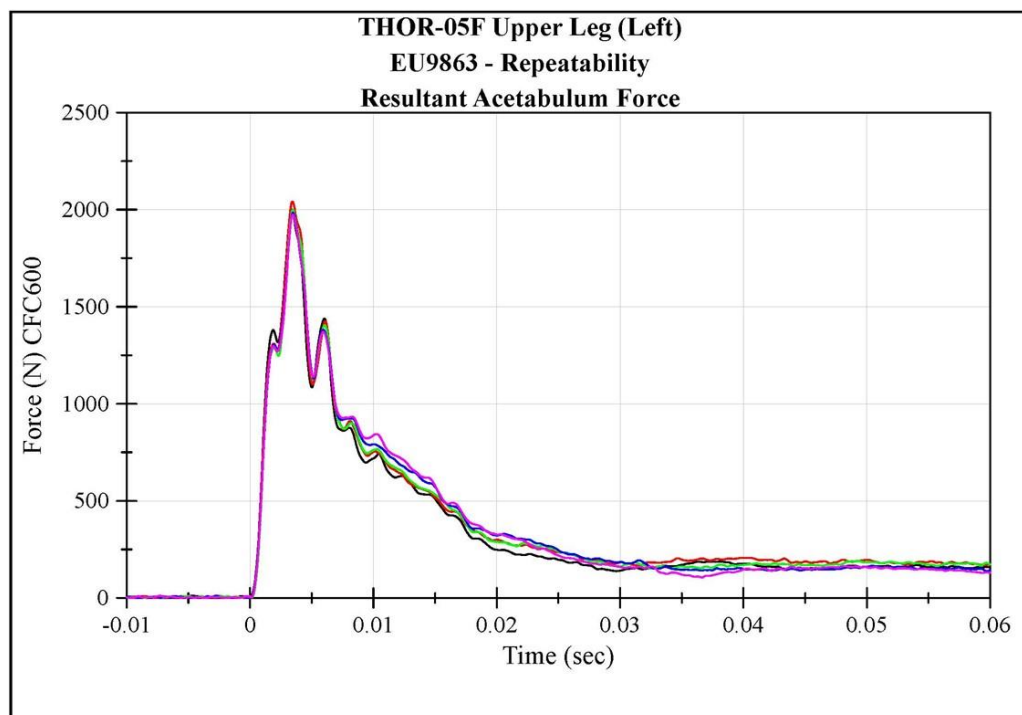


Figure 13-4. VRTC resultant acetabulum force for left upper leg impact repeatability tests for EU9863

13.2.2 THOR-05F EU9863 Right Upper Leg Testing at VRTC

Repeatability results for upper leg testing on EU9863 (right side) at VRTC yielded CV values below 5 percent (Table 13-2, Figure 13-5 through Figure 13-7).

Table 13-2. VRTC THOR-05F Right Upper Leg Repeatability Results for EU9863

Test Number	Maximum Probe Force (N)	Minimum Femur Force, F_z (N)	Maximum Resultant Acetabulum Force (N)
241017-11	7,712	-3,984	1,930
241017-12	7,692	-3,939	1,898
241017-13	7,485	-3,909	1,894
241017-14	7,423	-3,861	1,981
241017-15	7,482	-3,889	1,885
Mean	7,559	-3,916	1,918
Standard Deviation	133	47.2	39.4
CV	1.8%	1.2%	2.1%

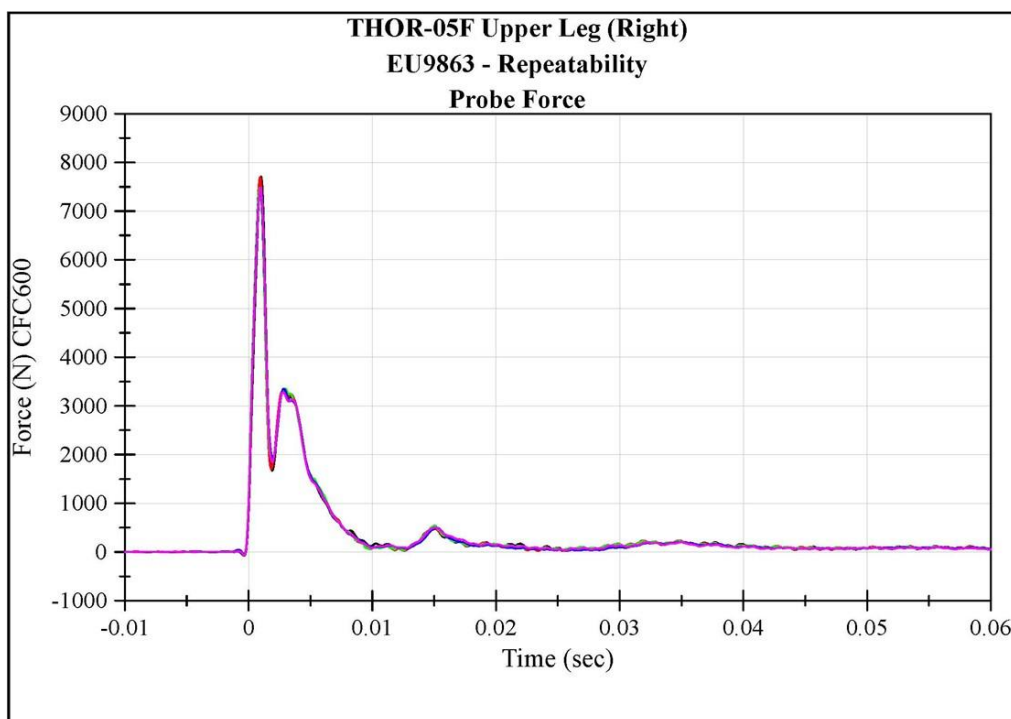


Figure 13-5. VRTC probe force for right upper leg impact repeatability tests for EU9863

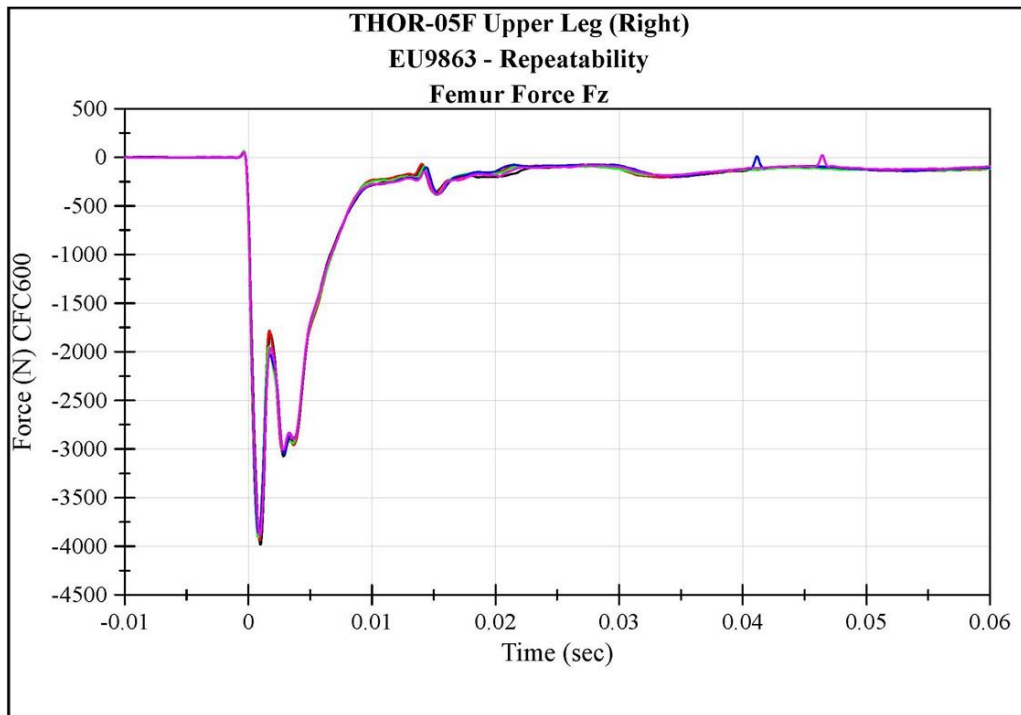


Figure 13-6. VRTC femur force Fz for right upper leg impact repeatability tests for EU9863

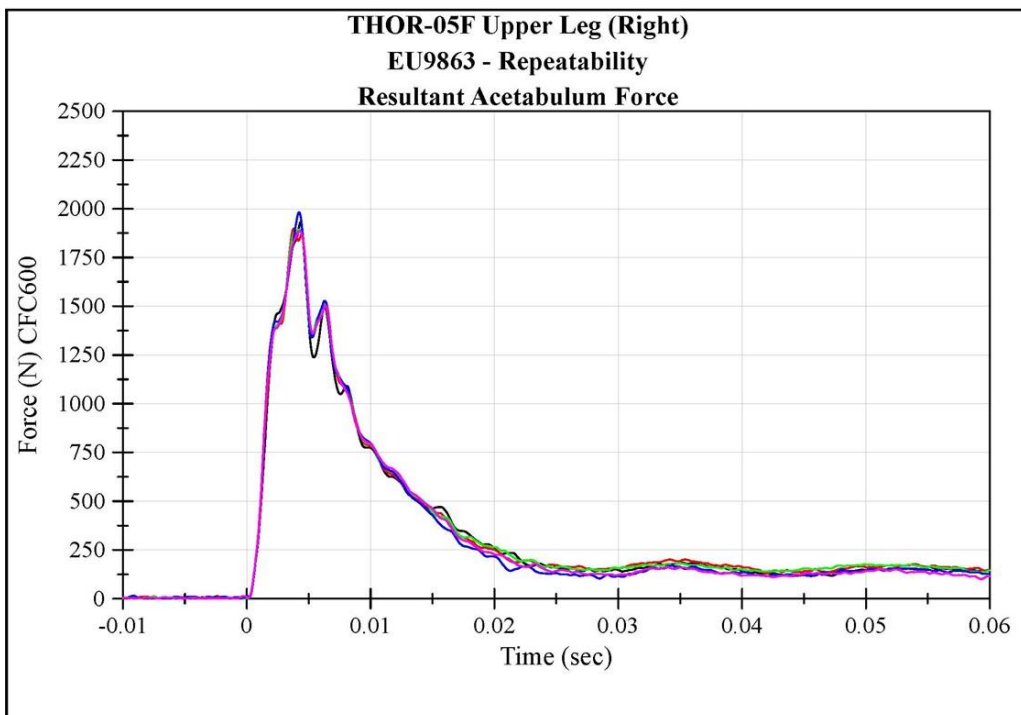


Figure 13-7. VRTC resultant acetabulum force for right upper leg impact repeatability tests for EU9863

13.2.3 THOR-05F EU3430 Left Upper Leg Testing at VRTC

Repeatability results for upper leg testing on EU3430 (left side) at VRTC yielded CV values below 5 percent (Table 13-3, Figure 13-8 through Figure 13-10).

Table 13-3. VRTC THOR-05F Left Upper Leg Repeatability Results for EU3430

Test Number	Maximum Probe Force (N)	Minimum Femur Force, F_z (N)	Maximum Resultant Acetabulum Force (N)
241016-8	8,261	-4,274	1,861
241016-9	8,648	-4,435	1,960
241016-10	8,406	-4,265	1,904
241016-11	8,158	-4,174	1,966
241016-12	7,895	-4,001	1,928
Mean	8,273	-4,230	1,924
Standard Deviation	281	159	43.0
CV	3.4%	3.8%	2.2%

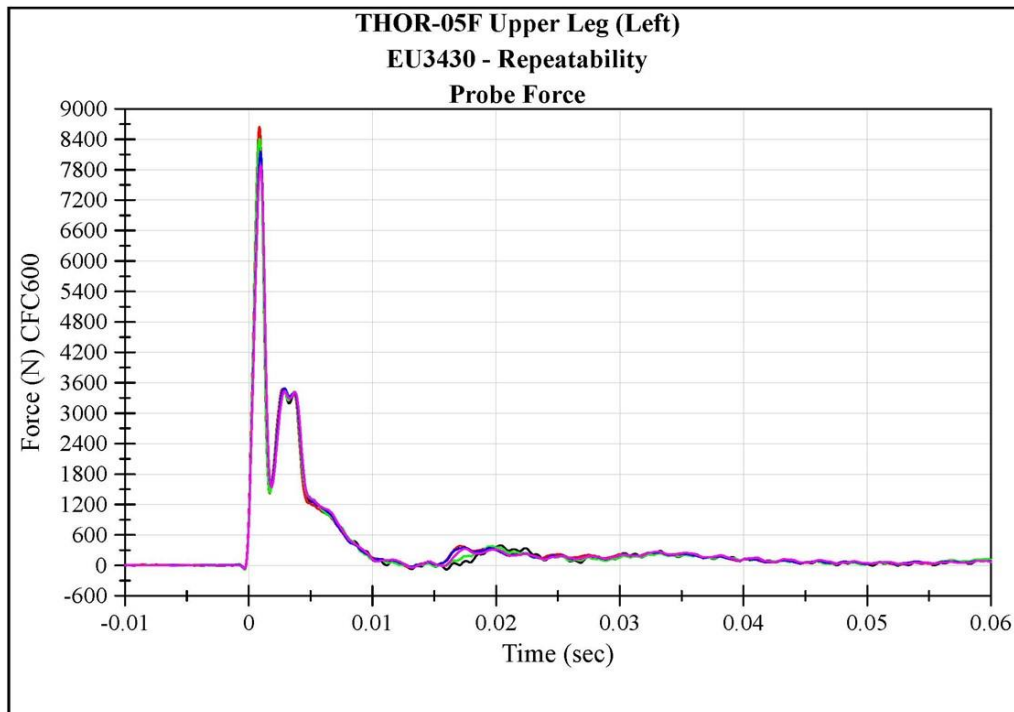


Figure 13-8. VRTC probe force for left upper leg impact repeatability tests for EU3430

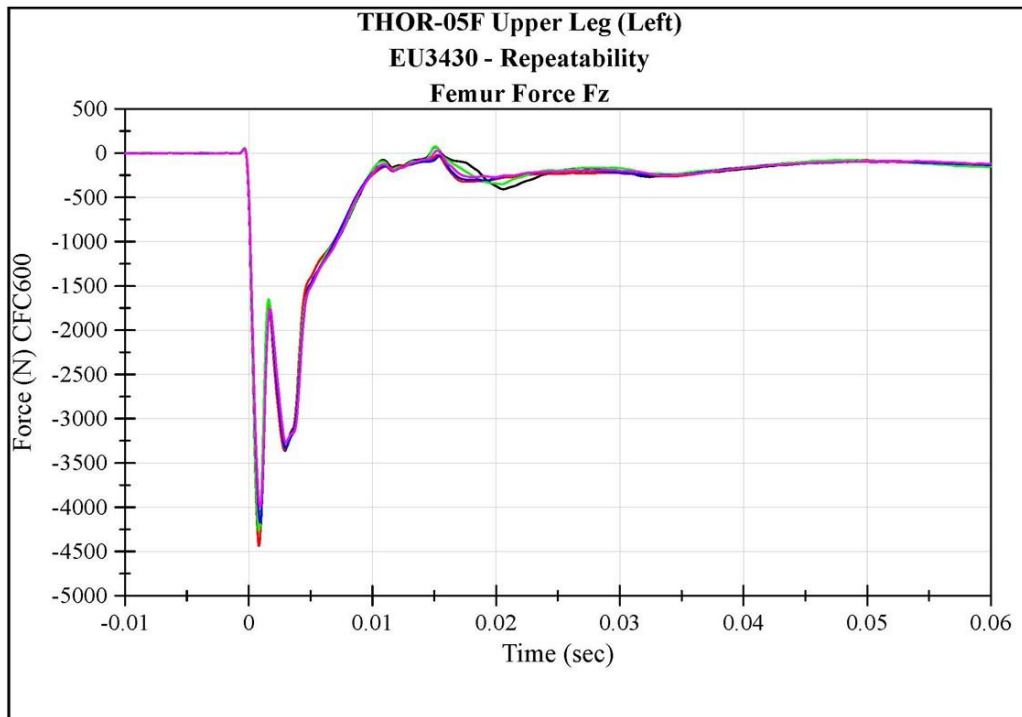


Figure 13-9. VRTC femur force Fz for left upper leg impact repeatability tests for EU3430

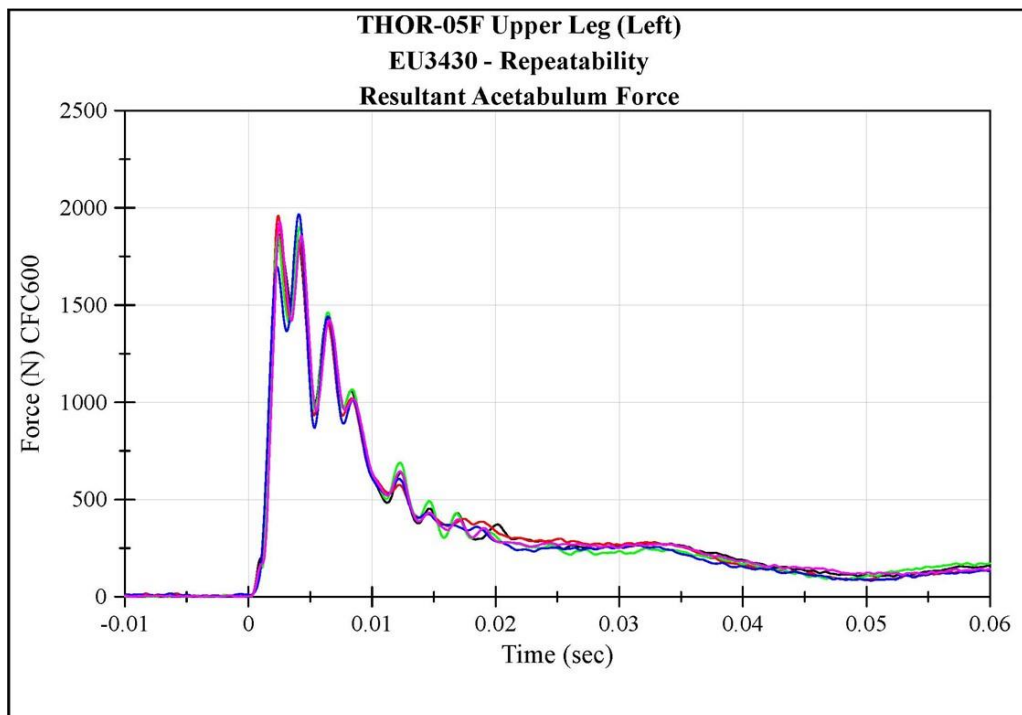


Figure 13-10. VRTC resultant acetabulum force for left upper leg impact repeatability tests for EU3430

13.2.4 THOR-05F EU3430 Right Upper Leg Testing at VRTC

Repeatability results for upper leg testing on EU3430 (right side) at VRTC yielded CV values below 5 percent (Table 13-4, Figure 13-11 through Figure 13-13).

Table 13-4. VRTC THOR-05F Right Upper Leg Repeatability Results for EU3430

Test Number	Maximum Probe Force (N)	Minimum Femur Force, F_z (N)	Maximum Resultant Acetabulum Force (N)
241120-8	7,669	-3,669	1,971
241120-11	7,893	-3,816	2,012
241120-13	7,849	-3,992	1,961
241120-15	7,750	-4,002	2,022
241120-18	7,856	-4,076	2,001
Mean	7,803	-3,911	1,993
Standard Deviation	91.6	165	26.3
CV	1.2%	4.2%	1.3%

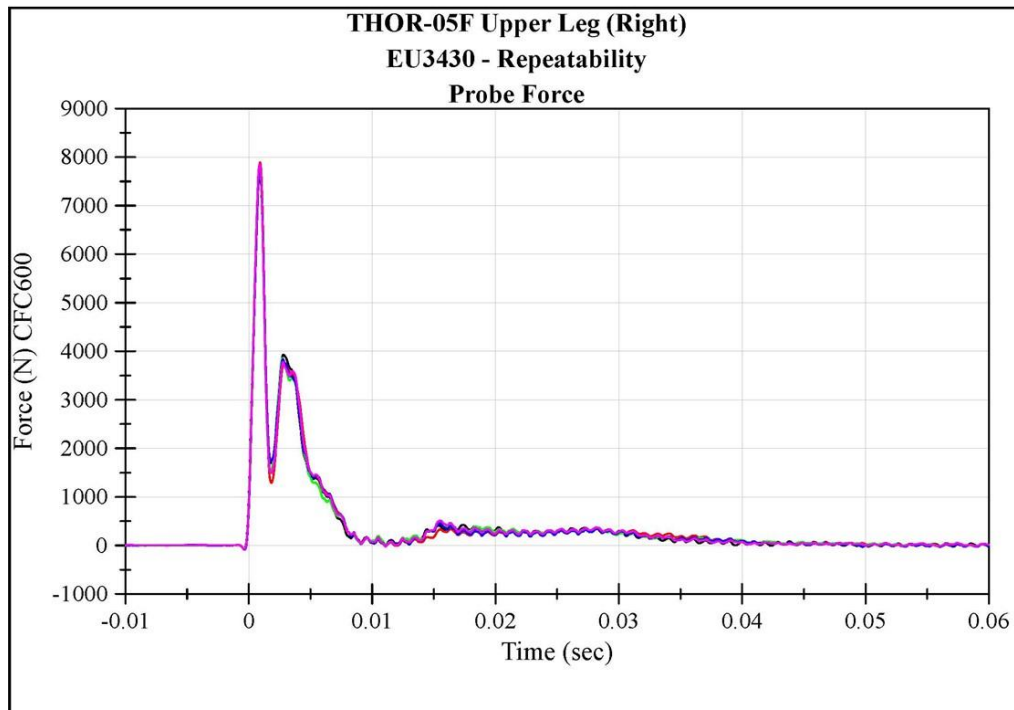


Figure 13-11. VRTC probe force for right upper leg impact repeatability tests for EU3430

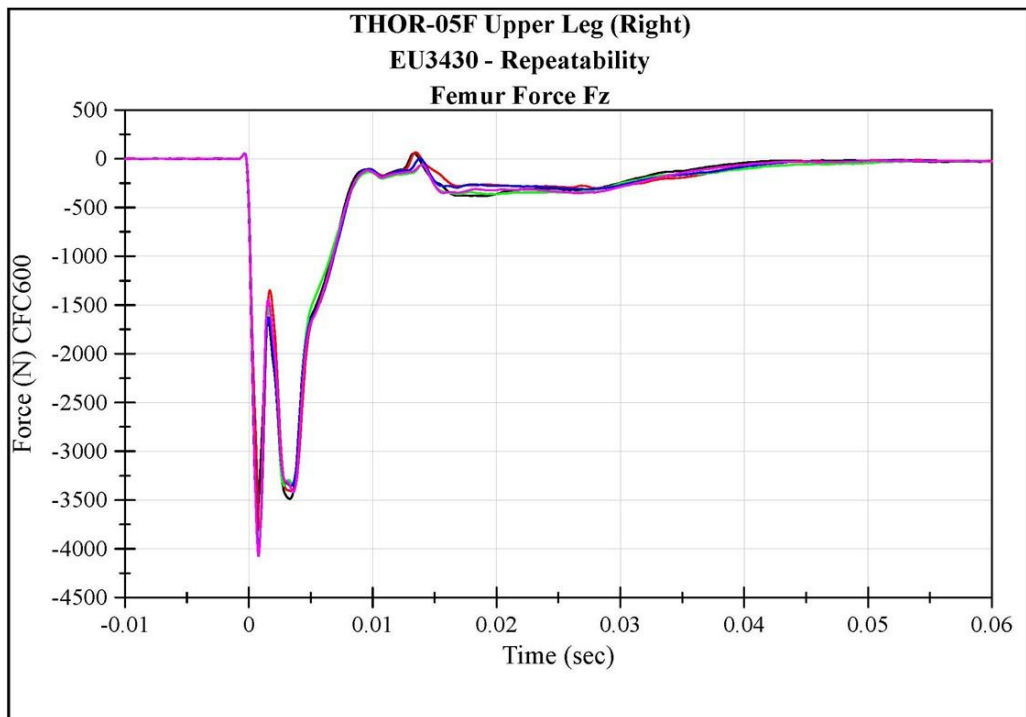


Figure 13-12. VRTC femur force Fz for right upper leg impact repeatability tests for EU3430

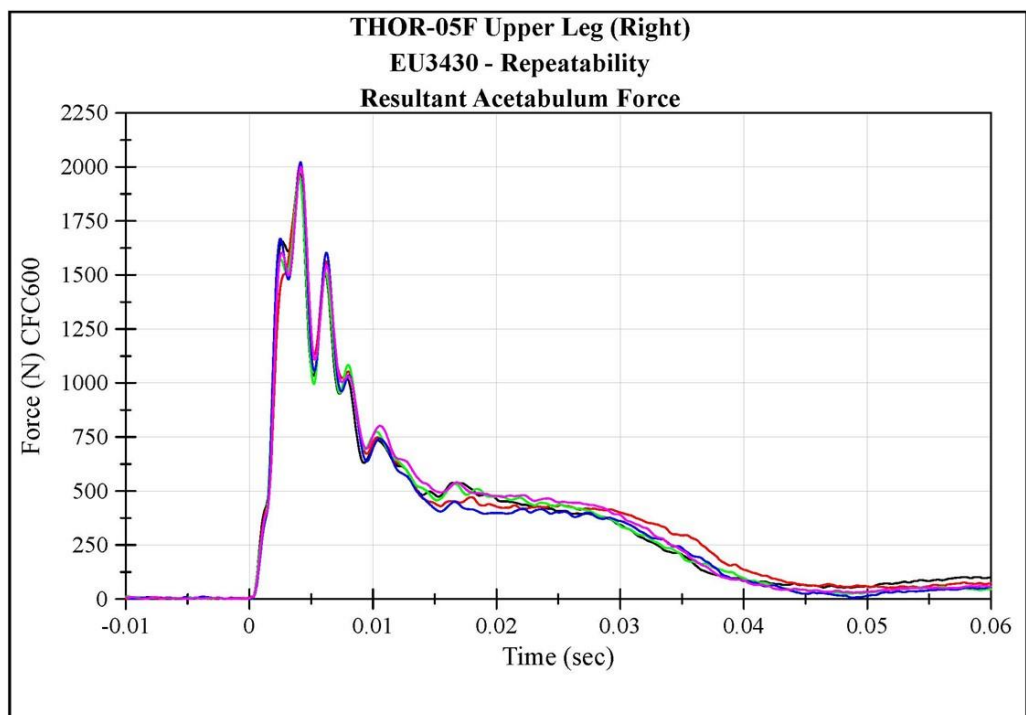


Figure 13-13. VRTC resultant acetabulum force for right upper leg impact repeatability tests for EU3430

13.2.5 THOR-05F EV4675 Left Upper Leg Testing at VRTC

Repeatability results for upper leg testing on EV4675 (left side) at VRTC yielded CV values below 5 percent (Table 13-5, Figure 13-14 through Figure 13-16).

Table 13-5. VRTC THOR-05F Left Upper Leg Repeatability Results for EV4675

Test Number	Maximum Probe Force (N)	Minimum Femur Force, F_z (N)	Maximum Resultant Acetabulum Force (N)
241004-4	7,492	-3,673	2,190
241004-5	7,570	-3,835	2,103
241004-6	7,463	-3,726	2,145
241007-1	7,671	-3,899	2,222
241007-2	7,456	-3,759	2,088
Mean	7,531	-3,778	2,150
Standard Deviation	90.6	89.4	56.6
CV	1.2%	2.4%	2.6%

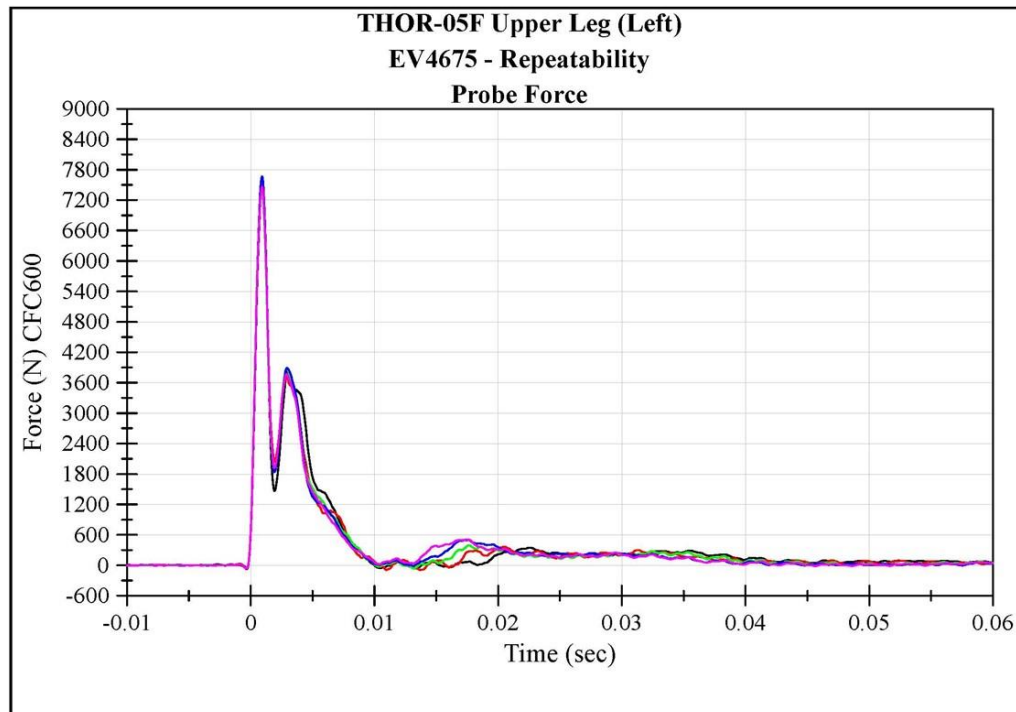


Figure 13-14. VRTC probe force for left higher energy upper leg impact repeatability tests for EV4675

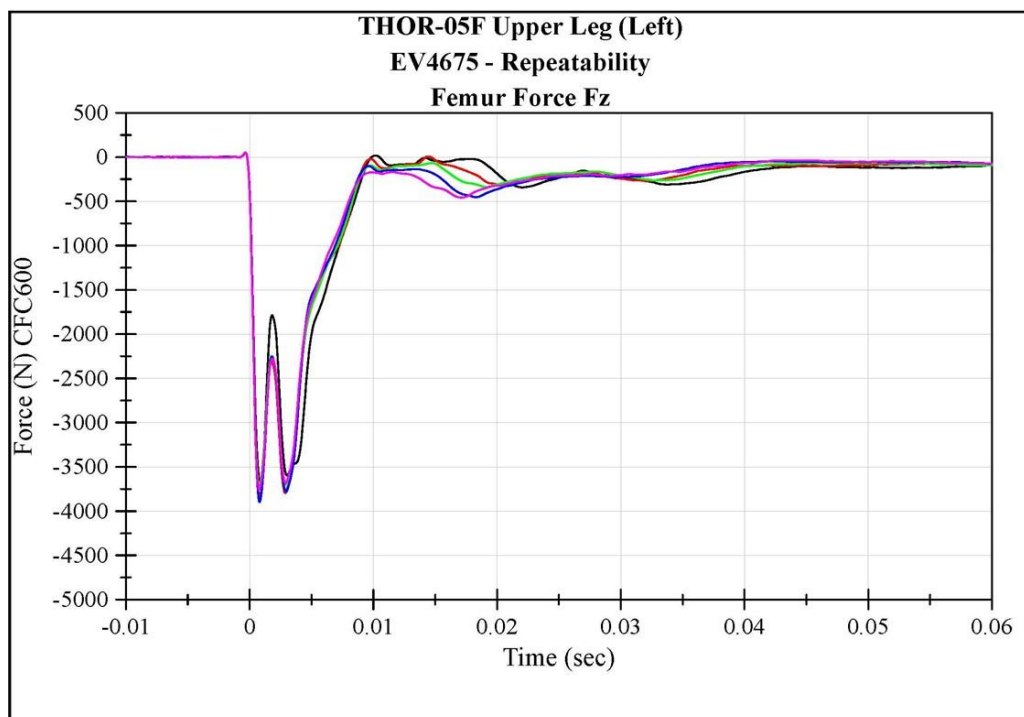


Figure 13-15. VRTC femur force Fz for left higher energy upper leg impact repeatability tests for EV4675

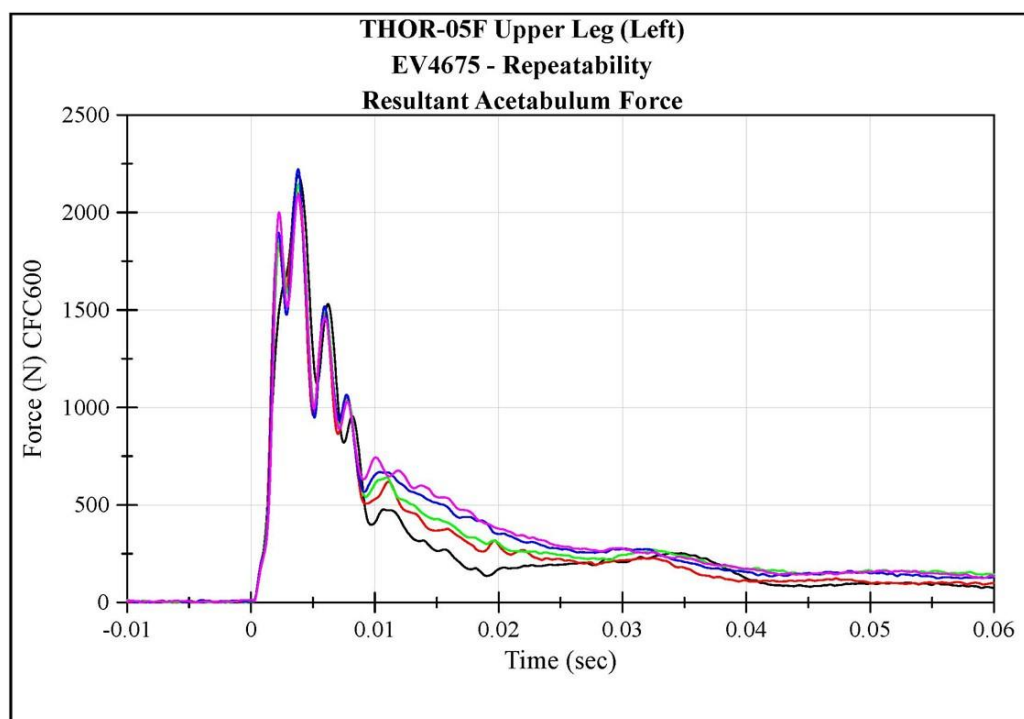


Figure 13-16. VRTC resultant acetabulum force for left higher energy upper leg impact repeatability tests for EV4675

13.2.6 THOR-05F EV4675 Right Upper Leg Testing at VRTC

Repeatability results for upper leg testing on EV4675 (right side) at VRTC yielded CV values below 5 percent (Table 13-6, Figure 13-17 through Figure 13-19).

Table 13-6. VRTC THOR-05F Right Upper Leg Repeatability Results for EV4675

Test Number	Maximum Probe Force (N)	Minimum Femur Force, F_z (N)	Maximum Resultant Acetabulum Force (N)
241004-1	7,359	-3,727	2,263
241004-2	7,303	-3,703	2,262
241004-3	7,289	-3,700	2,199
241007-3	7,608	-3,927	2,191
241007-6	7,627	-3,921	2,181
Mean	7,437	-3,796	2,219
Standard Deviation	167	118	40.1
CV	2.2%	3.1%	1.8%

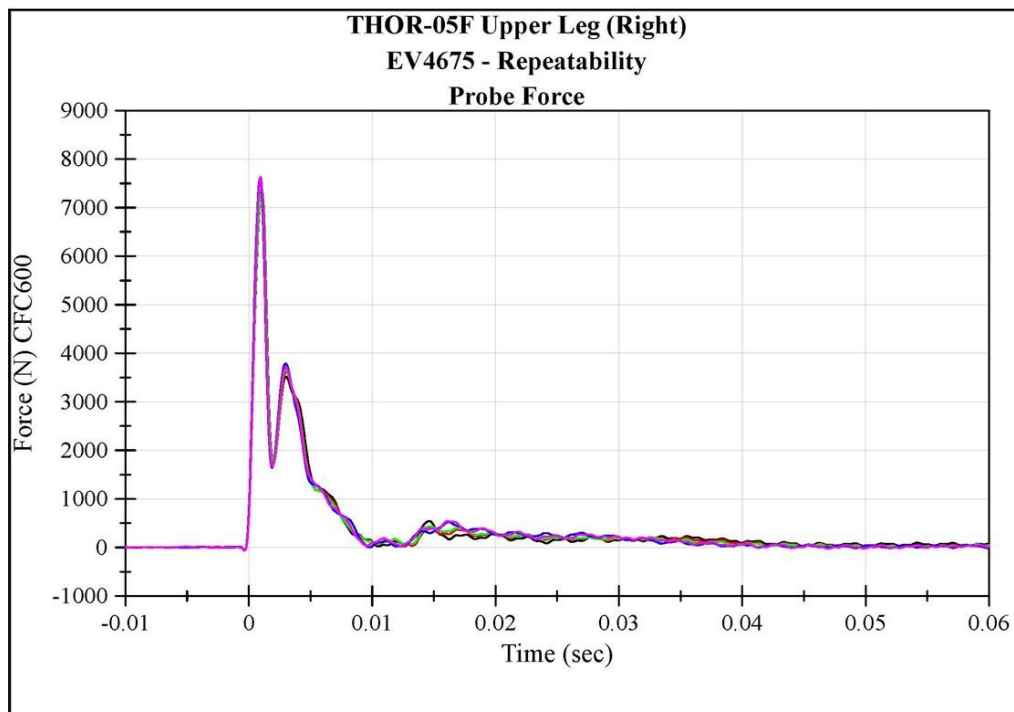


Figure 13-17. VRTC probe force for right higher energy upper leg impact repeatability tests for EV4675

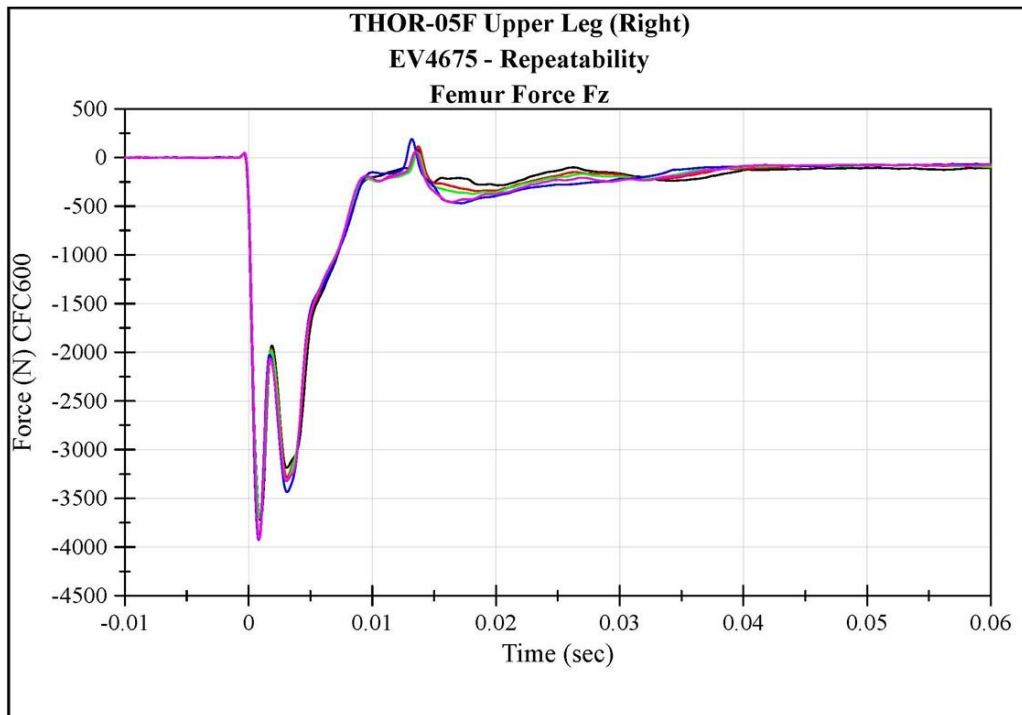


Figure 13-18. VRTC femur force Fz for right higher energy upper leg impact repeatability tests for EV4675

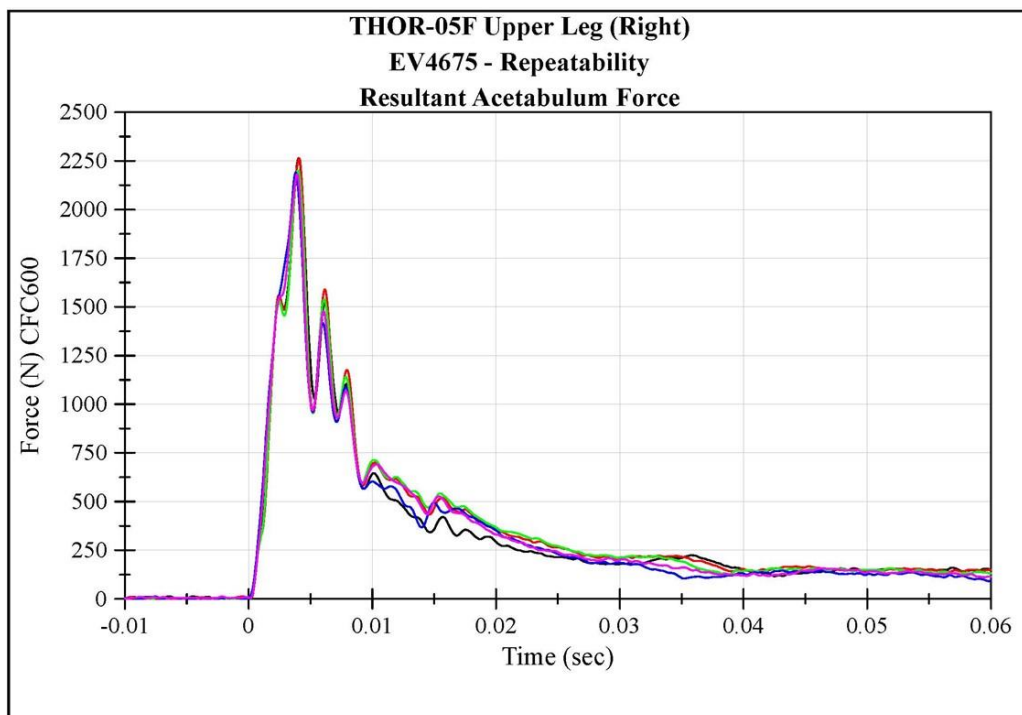


Figure 13-19. VRTC resultant acetabulum force for right higher energy upper leg impact repeatability tests for EV4675

13.2.7 THOR-05F EV4675 Left Upper Leg Testing at Humanetics

Repeatability results for upper leg testing on EV4675 (left side) at Humanetics yielded CV values below 5 percent, except for acetabulum force which was above 5 percent, but under 10 percent (Table 13-7, Figure 13-20 through Figure 13-22).

Table 13-7. Humanetics THOR-05F Left Upper Leg Repeatability Results for EV4675

Test Number	Maximum Probe Force (N)	Minimum Femur Force, F_z (N)	Maximum Resultant Acetabulum Force (N)
687692	8,559	-4,353	1,891
687683	8,410	-4,234	2,067
687713	8,275	-4,208	2,022
687720	8,305	-4,248	1,838
687704	8,351	-4,194	1,818
Mean	8,380	-4,247	1,927
Standard Deviation	112	62.6	112
CV	1.3%	1.5%	5.8%

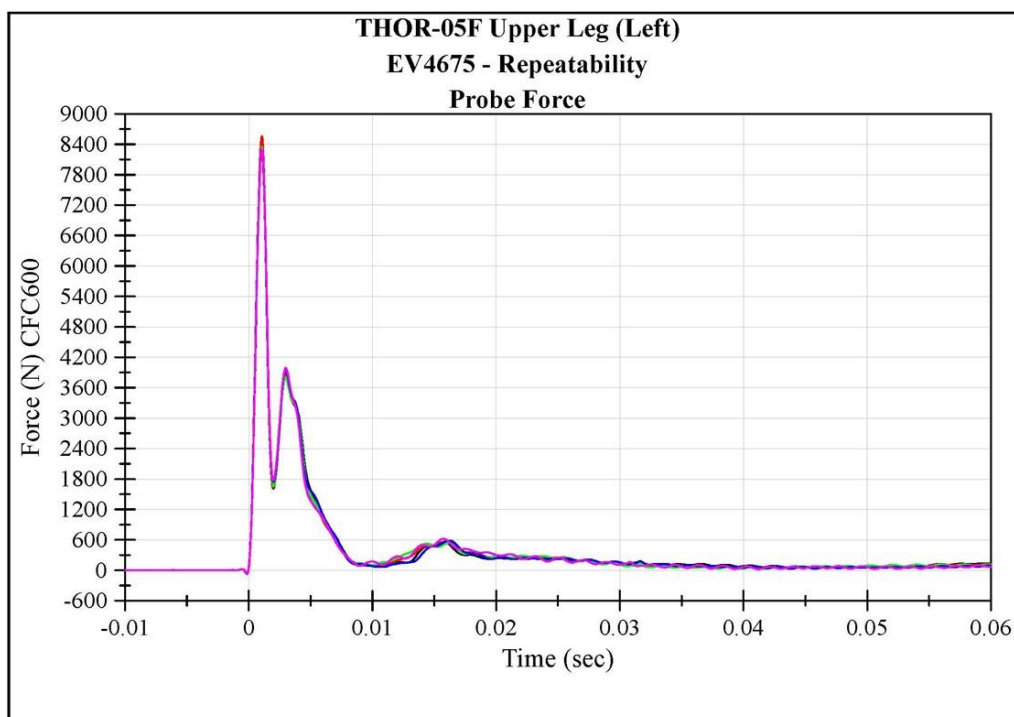


Figure 13-20. Humanetics probe force for left upper leg impact repeatability tests for EV4675

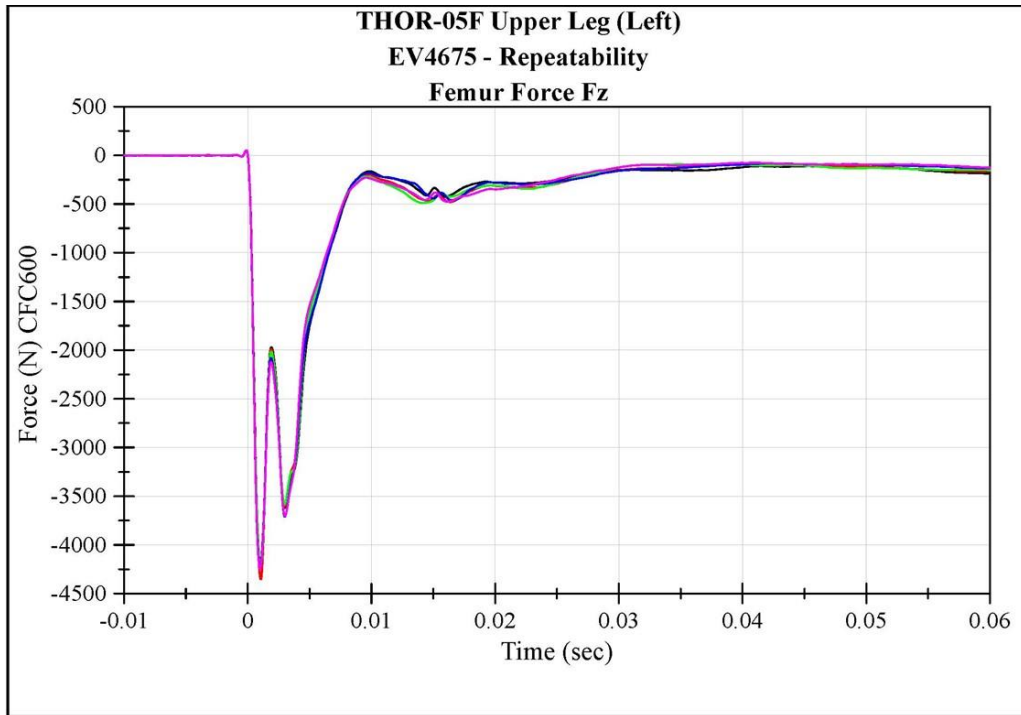


Figure 13-21. Humanetics femur force Fz for left upper leg impact repeatability tests for EV4675

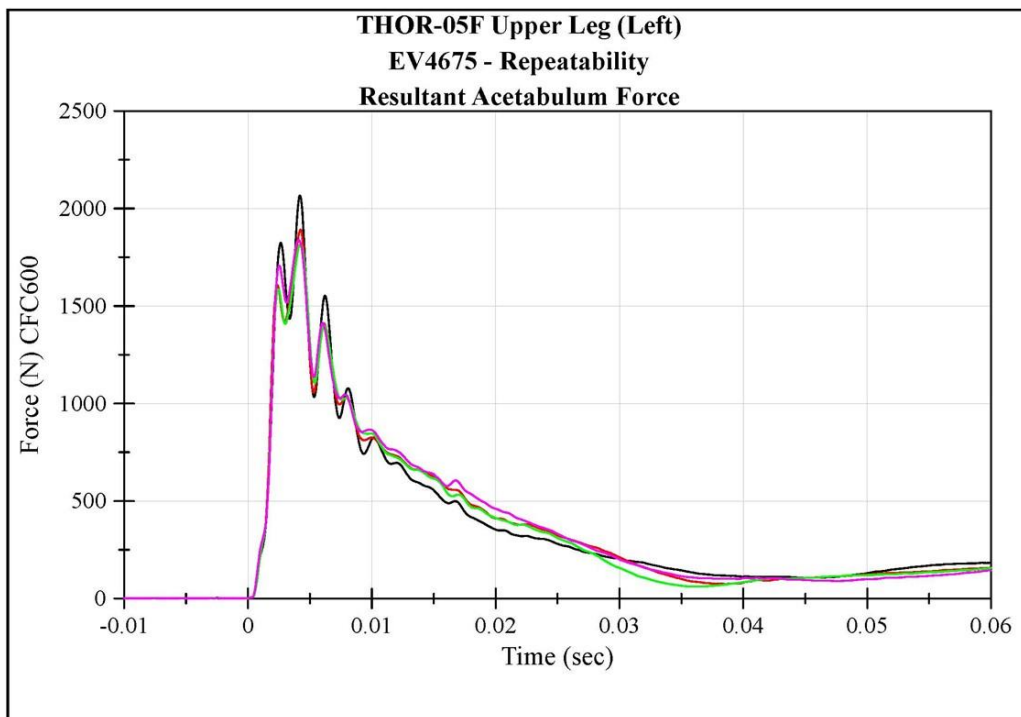


Figure 13-22. Humanetics resultant acetabulum force for left upper leg impact repeatability tests for EV4675

13.2.8 THOR-05F EV4675 Right Upper Leg Testing at Humanetics

Repeatability results for upper leg testing on EV4675 (right side) at Humanetics yielded CV values below 5 percent (Table 13-8, Figure 13-23 through Figure 13-25).

Table 13-8. Humanetics THOR-05F Right Upper Leg Repeatability Results for EV4675

Test Number	Maximum Probe Force (N)	Minimum Femur Force, F_z (N)	Maximum Resultant Acetabulum Force (N)
687455	8,332	-4,304	2,095
687435	8,420	-4,260	2,200
687444	8,375	-4,269	2,137
687409	8,354	-4,273	2,191
687423	8,545	-4,374	2,202
Mean	8,405	-4,296	2,165
Standard Deviation	84.5	46.4	47.0
CV	1.0%	1.1%	2.2%

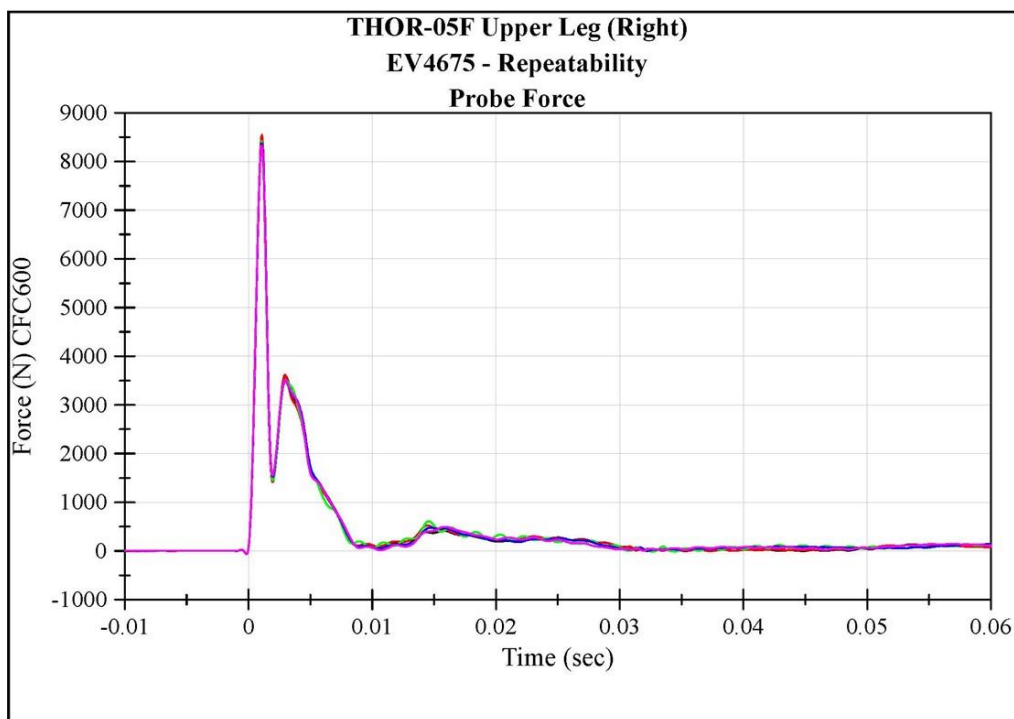


Figure 13-23. Humanetics probe force for right upper leg impact repeatability tests for EV4675

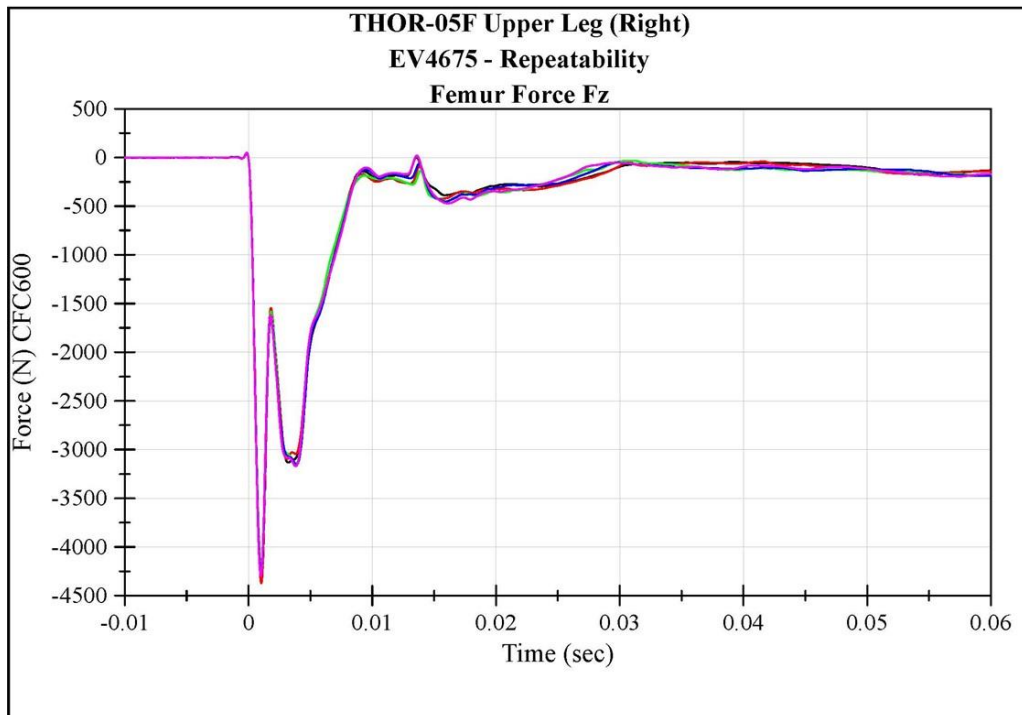


Figure 13-24. Humanetics femur force Fz for right upper leg impact repeatability tests for EV4675

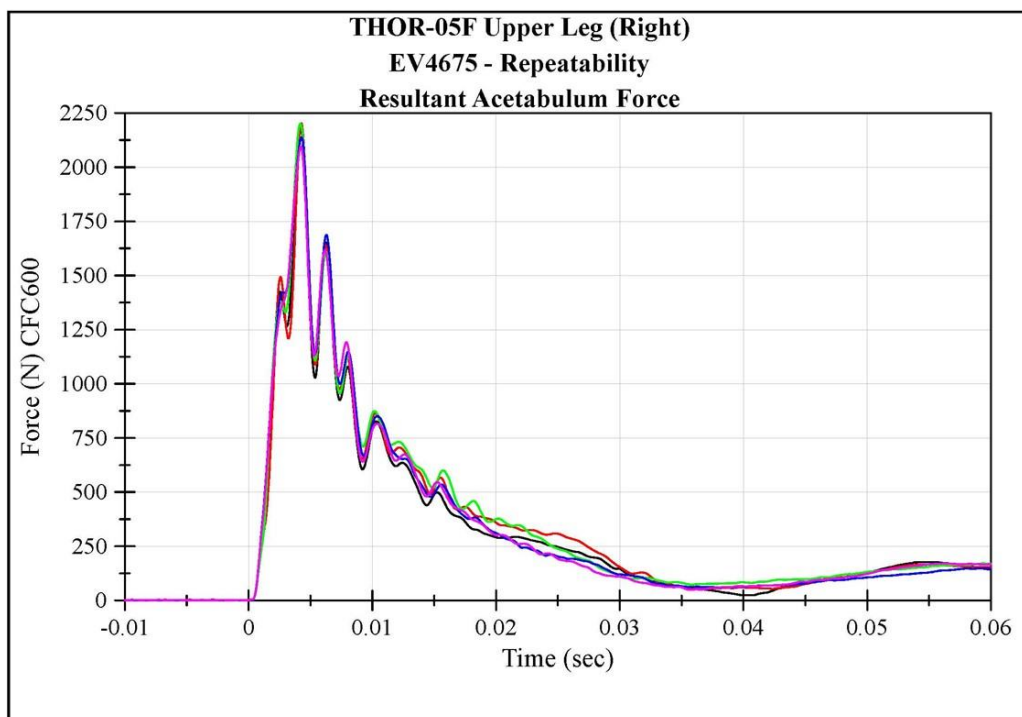


Figure 13-25. Humanetics resultant acetabulum force for right upper leg impact repeatability tests for EV4675

13.2.9 THOR-05F EV4675 Left Upper Leg Testing at Calspan

Repeatability results for upper leg testing on EV4675 (left side) at Calspan yielded CV values below 5 percent (Table 13-9, Figure 13-26 through Figure 13-28).

Table 13-9. Calspan THOR-05F Left Upper Leg Repeatability Results for EV4675

Test Number	Maximum Probe Force (N)	Minimum Femur Force, F_z (N)	Maximum Resultant Acetabulum Force (N)
2025_03_22 14_14	8,580	-4,554	1,953
2025_03_22 14_49	8,555	-4,494	1,875
2025_03_22 15_22	8,527	-4,455	1,879
2025_03_22 15_55	8,687	-4,472	1,759
2025_03_22 16_29	8,438	-4,270	1,979
Mean	8,557	-4,449	1,889
Standard Deviation	90.1	107	85.9
CV	1.1%	2.4%	4.5%

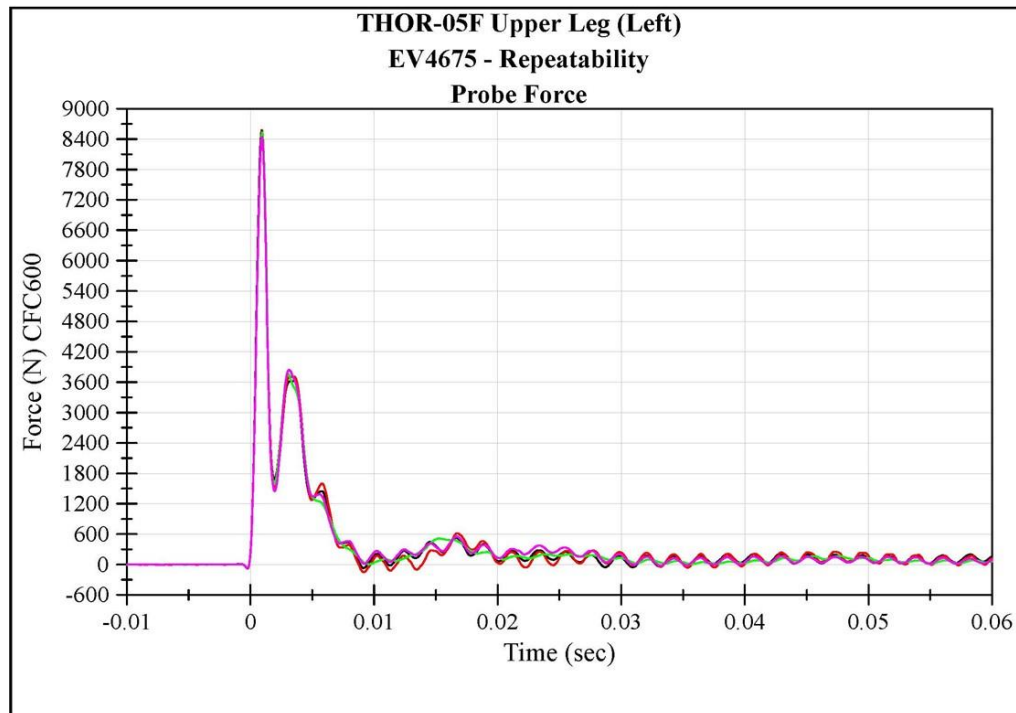


Figure 13-26. Calspan probe force for left upper leg impact repeatability tests for EV4675

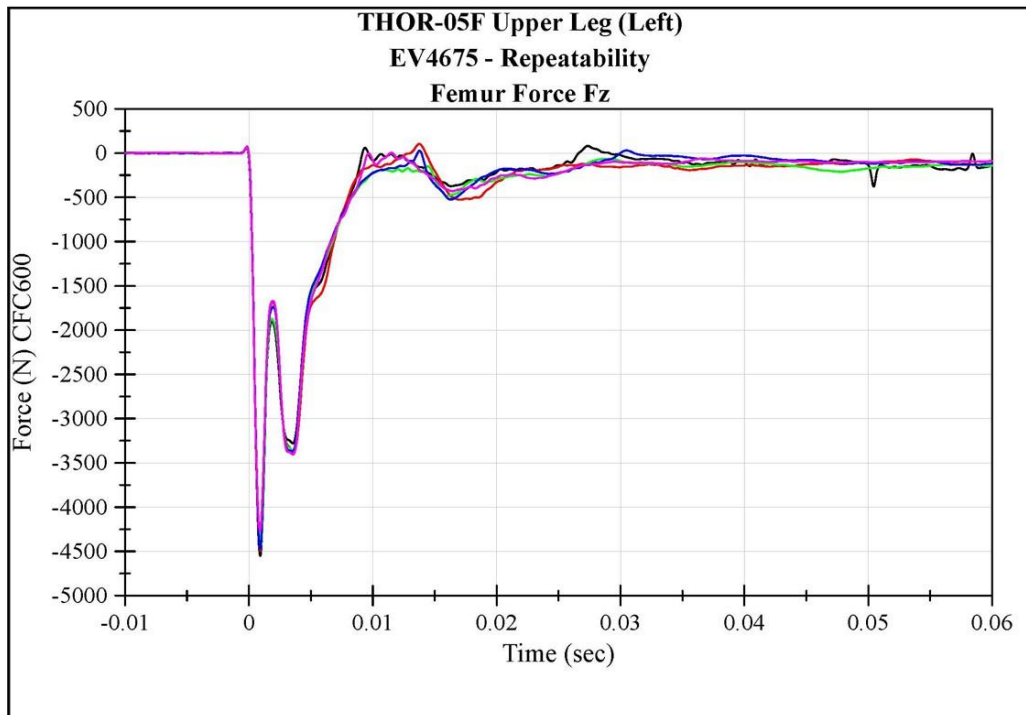


Figure 13-27. Calspan femur force Fz for left upper leg impact repeatability tests for EV4675

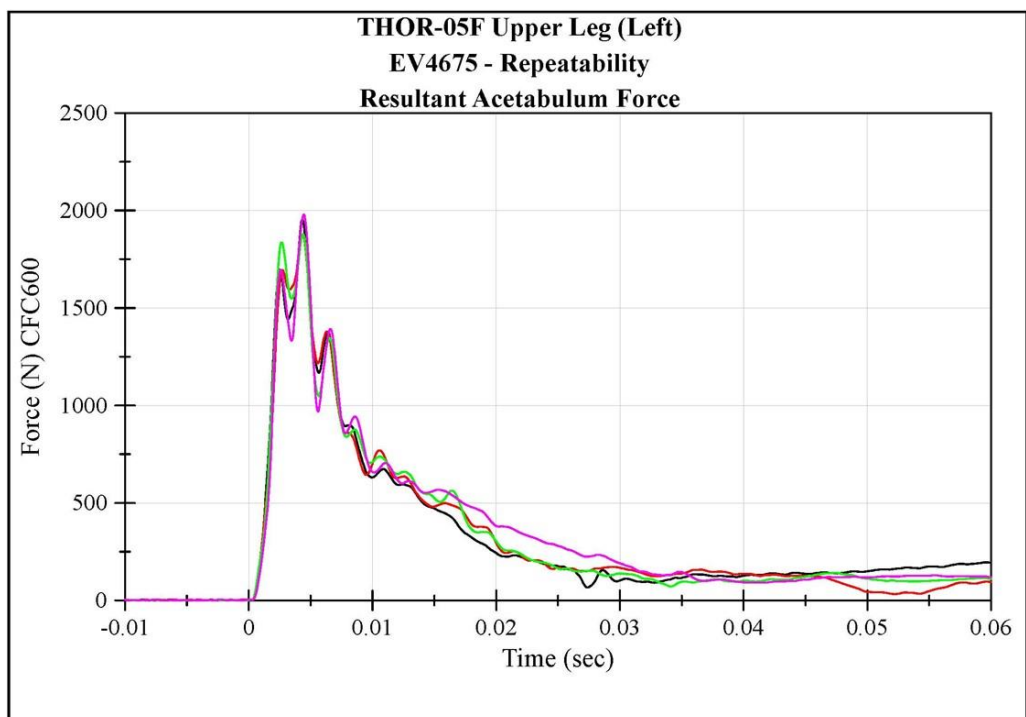


Figure 13-28. Calspan resultant acetabulum force for left upper leg impact repeatability tests for EV4675

13.2.10 THOR-05F EV4675 Right Upper Leg Testing at Calspan

Repeatability results for upper leg testing on EV4675 (right side) yielded CV values at Calspan below 5 percent (Table 13-10, Figure 13-29 through Figure 13-31).

Table 13-10. Calspan THOR-05F Right Upper Leg Repeatability Results for EV4675

Test Number	Maximum Probe Force (N)	Minimum Femur Force, F_z (N)	Maximum Resultant Acetabulum Force (N)
2025_03_22_11_22	8,176	-4,353	1,989
2025_03_22_12_04	8,012	-4,432	2,079
2025_03_22_12_41	8,025	-4,329	1,920
2025_03_22_13_19	7,969	-4,150	2,016
2025_03_22_13_52	7,916	-4,127	1,973
Mean	8,020	-4,278	1,995
Standard Deviation	97.0	133	58.4
CV	1.2%	3.1%	2.9%

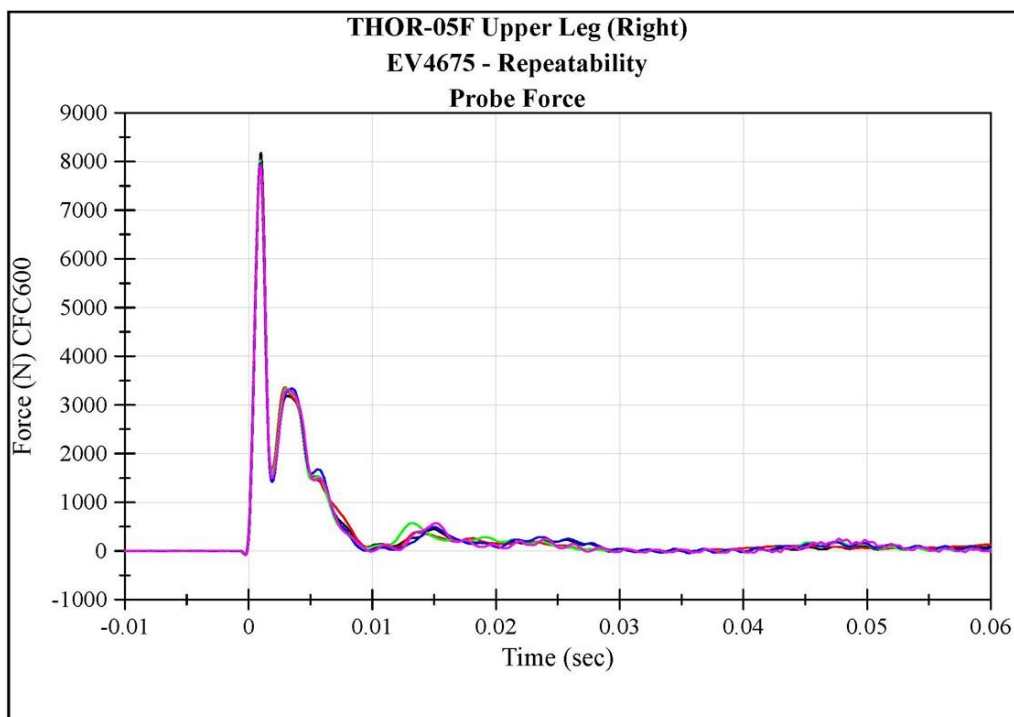


Figure 13-29. Calspan probe force for right upper leg impact repeatability tests for EV4675

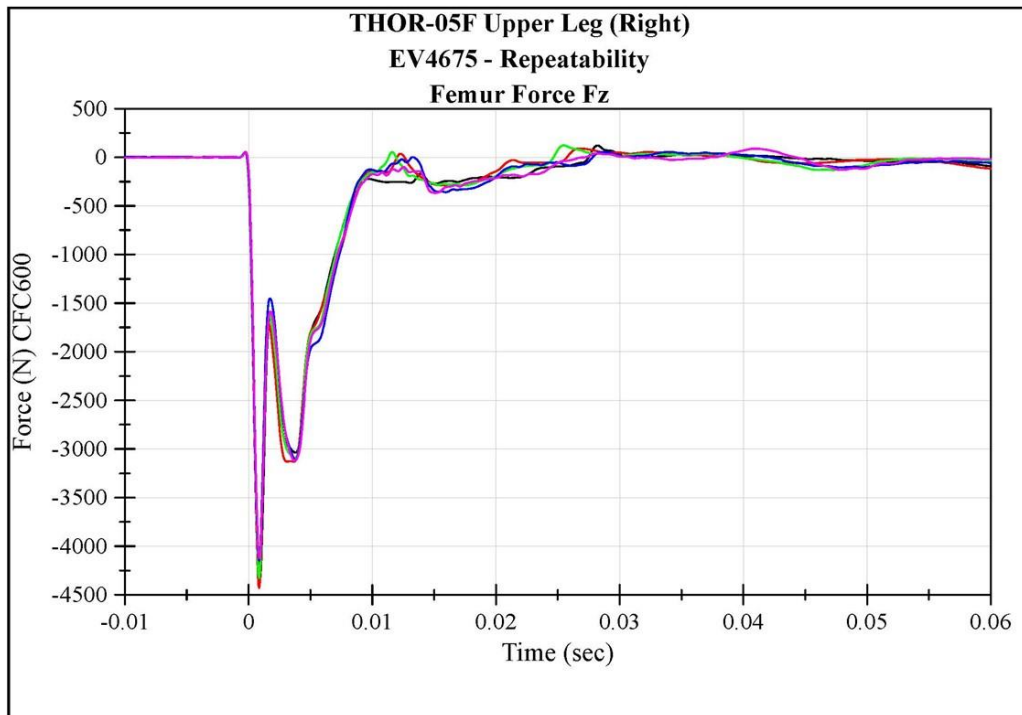


Figure 13-30. Calspan femur force Fz for right upper leg impact repeatability tests for EV4675

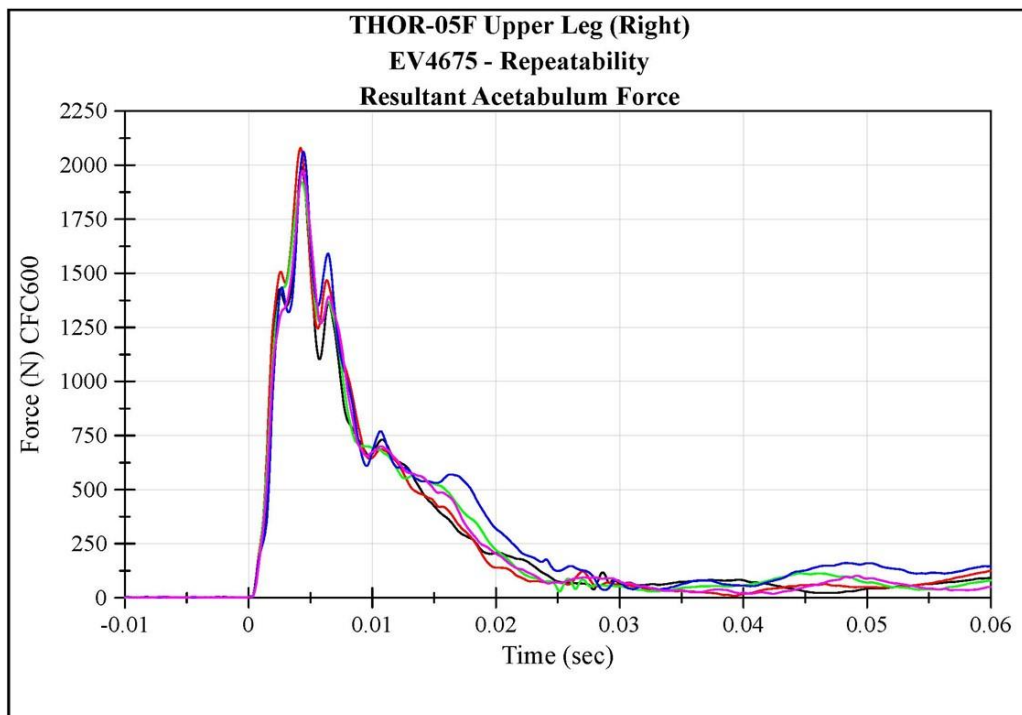


Figure 13-31. Calspan resultant acetabulum force for right upper leg impact repeatability tests for EV4675

13.2.11 THOR-05F EV4675 Left Upper Leg Testing at TRC

Repeatability results for upper leg testing on EV4675 (left side) at TRC yielded CV values below 5 percent (Table 13-11, Figure 13-32 through Figure 13-34).

Table 13-11. TRC THOR-05F Left Upper Leg Repeatability Results for EV4675

Test Number	Maximum Probe Force (N)	Minimum Femur Force, F_z (N)	Maximum Resultant Acetabulum Force (N)
2025_05_08 10_01	7,453	-4,120	2,061
2025_05_08 10_58	7,311	-3,908	2,102
2025_05_08 14_42	7,352	-4,187	2,153
2025_05_08 15_09	7,395	-4,184	2,174
2025_05_09 08_23	7,246	-4,099	2,132
Mean	7,351	-4,099	2,125
Standard Deviation	78.9	114	44.2
CV	1.1%	2.8%	2.1%

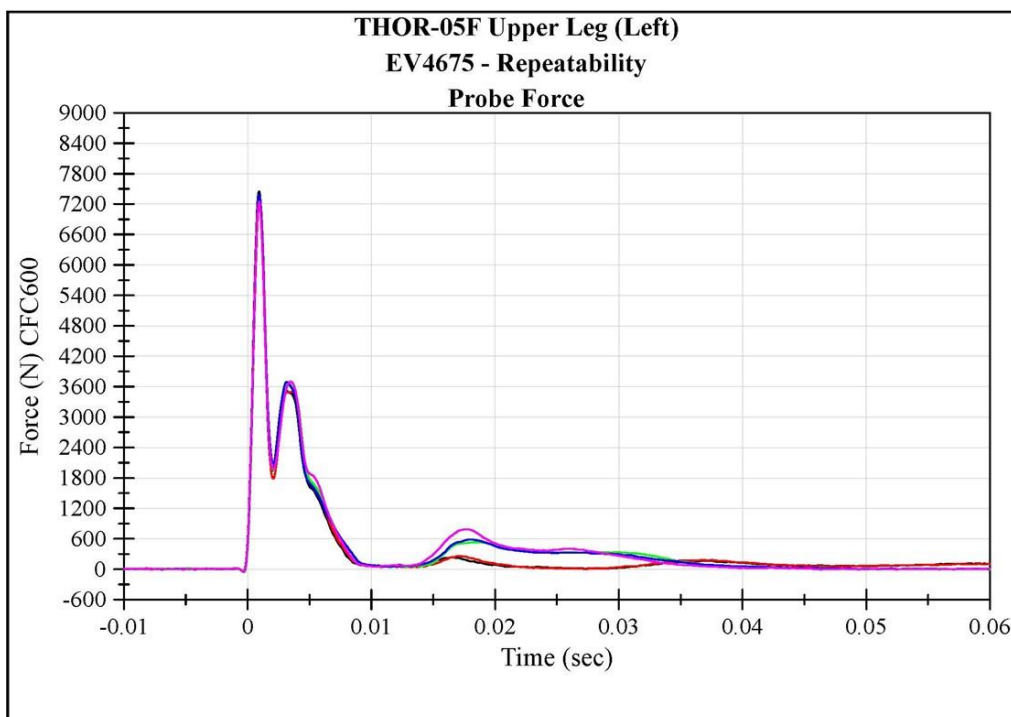


Figure 13-32. TRC probe force for left upper leg impact repeatability tests for EV4675

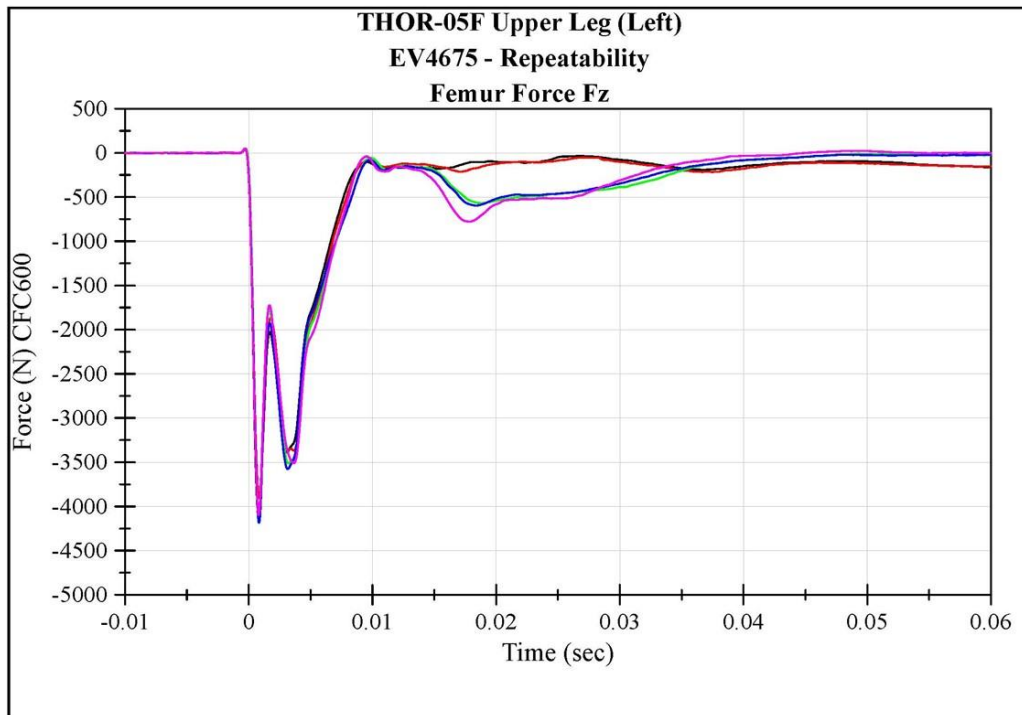


Figure 13-33. TRC femur force Fz for left upper leg impact repeatability tests for EV4675

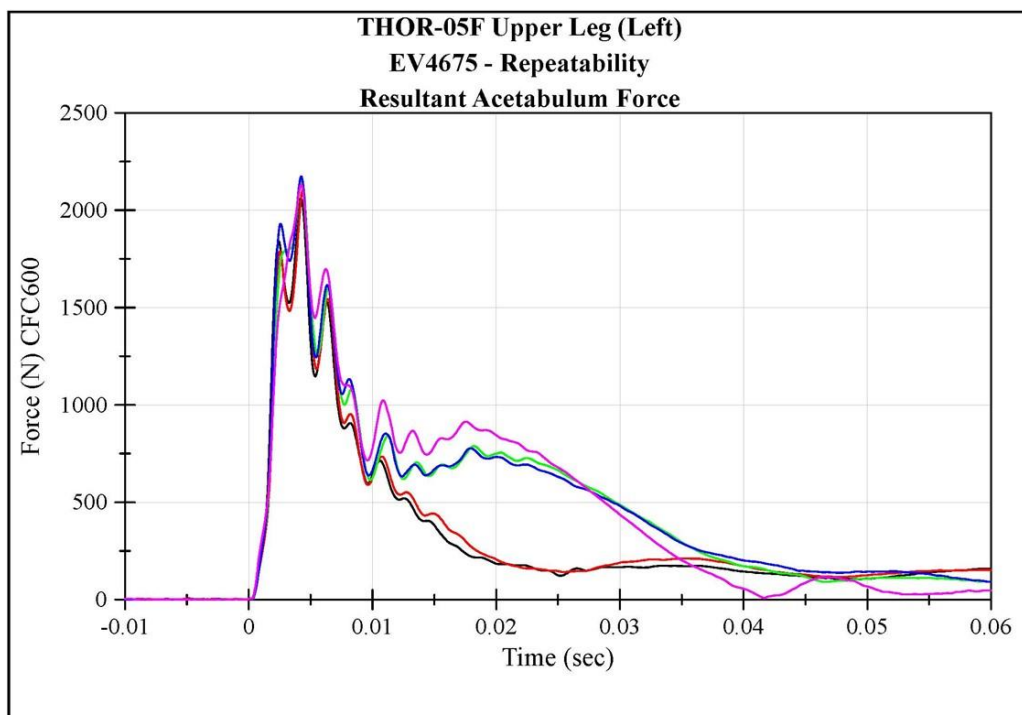


Figure 13-34. TRC resultant acetabulum force for left upper leg impact repeatability tests for EV4675

13.2.12 THOR-05F EV4675 Right Upper Leg Testing at TRC

Repeatability results for upper leg testing on EV4675 (right side) at TRC yielded CV values below 5 percent (Table 13-12, Figure 13-35 through Figure 13-37).

Table 13-12. TRC THOR-05F Right Upper Leg Repeatability Results for EV4675

Test Number	Maximum Probe Force (N)	Minimum Femur Force, F_z (N)	Maximum Resultant Acetabulum Force (N)
2025_05_08_11_23	7,402	-3,960	2,101
2025_05_08_11_49	7,369	-3,888	2,086
2025_05_08_12_55	7,349	-3,874	2,089
2025_05_08_14_02	7,273	-3,956	2,100
2025_05_08_14_10	7,193	-3,927	2,063
Mean	7,317	-3,921	2,088
Standard Deviation	83.9	38.9	15.4
CV	1.1%	1.0%	0.7%

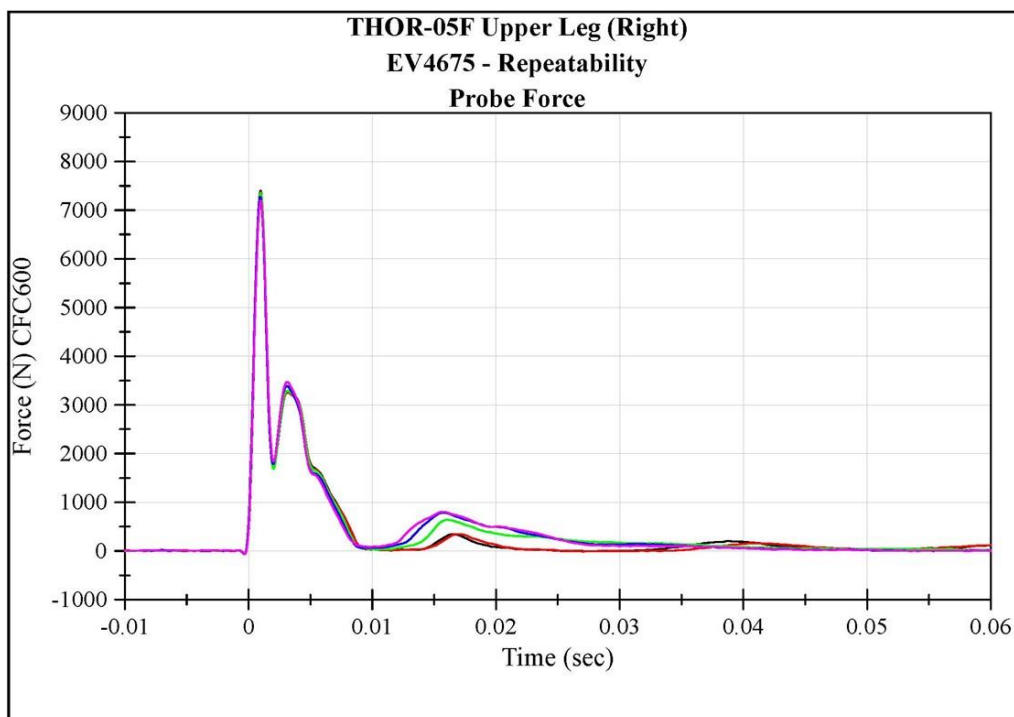


Figure 13-35. TRC probe force for right upper leg impact repeatability tests for EV4675

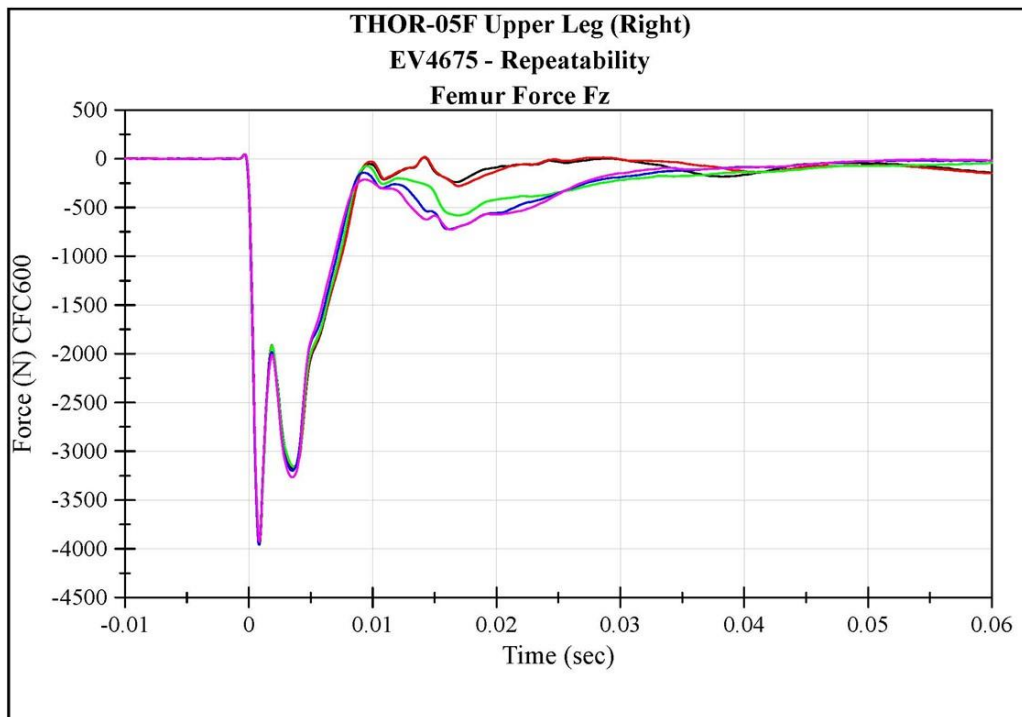


Figure 13-36. TRC femur force Fz for right upper leg impact repeatability tests for EV4675

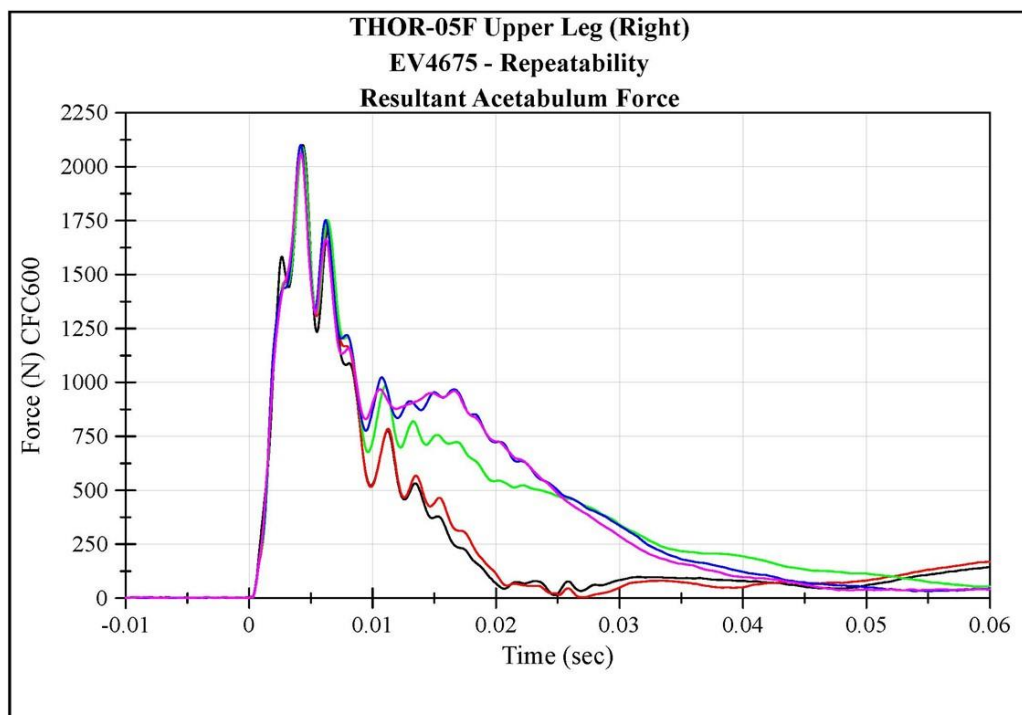


Figure 13-37. TRC resultant acetabulum force for right upper leg impact repeatability tests for EV4675

13.3 Upper Leg Dummy Reproducibility Results

Dummy Reproducibility results at VRTC for the upper leg tests yielded CV values below 5 percent for probe force and above 5 percent, but under 10 percent for femur and resultant acetabulum force (Table 13-13).

Table 13-13. THOR-05F Upper Leg Reproducibility Results

Dummy	Test Number	Maximum Probe Force (N)	Minimum Femur Force, F_z (N)	Maximum Resultant Acetabulum Force (N)
VRTC Left EU3430	241016-8	8,261	-4,274	1,861
	241016-9	8,648	-4,435	1,960
	241016-10	8,406	-4,265	1,904
	241016-11	8,158	-4,174	1,966
	241016-12	7,895	-4,001	1,928
VRTC Right EU3430	241120-8	7,669	-3,669	1,971
	241120-11	7,893	-3,816	2,012
	241120-13	7,849	-3,992	1,961
	241120-15	7,750	-4,002	2,022
	241120-18	7,856	-4,076	2,001
VRTC Left EV4675	241004-4	7,492	-3,673	2,190
	241004-5	7,570	-3,835	2,103
	241004-6	7,463	-3,726	2,145
	241007-1	7,671	-3,899	2,222
	241007-2	7,456	-3,759	2,088
VRTC Right EV4675	241004-1	7,359	-3,727	2,263
	241004-2	7,303	-3,703	2,262
	241004-3	7,289	-3,700	2,199
	241007-3	7,608	-3,927	2,191
	241007-6	7,627	-3,921	2,181
VRTC Left EV9863	241021-1	8,126	-4,644	2,000
	241021-2	8,096	-4,564	2,041
	241021-3	8,110	-4,538	1,999
	241021-4	8,121	-4,555	1,985
	241021-5	8,031	-4,475	1,974
VRTC Right EV9863	241017-11	7,712	-3,984	1,930
	241017-12	7,692	-3,939	1,898
	241017-13	7,485	-3,909	1,894
	241017-14	7,423	-3,861	1,981
	241017-15	7,482	-3,889	1,885
Mean		7,783	-4,031	2,034
Standard Deviation		344	301	120
CV		4.4%	7.5%	5.9%

13.4 Lab-to-Lab Variability

Test Reproducibility results at all four labs for the upper leg tests yielded CV values above 5 percent, but under 10 percent (Table 13-14).

Table 13-14. THOR-05F Upper Leg Reproducibility Results

Dummy	Test Number	Maximum Probe Force (N)	Minimum Femur Force, F_z (N)	Maximum Resultant Acetabulum Force (N)
VRTC Left EV4675	241004-4	7,492	-3,673	2,190
	241004-5	7,570	-3,835	2,103
	241004-6	7,463	-3,726	2,145
	241007-1	7,671	-3,899	2,222
	241007-2	7,456	-3,759	2,088
VRTC Right EV4675	241004-1	7,359	-3,727	2,263
	241004-2	7,303	-3,703	2,262
	241004-3	7,289	-3,700	2,199
	241007-3	7,608	-3,927	2,191
	241007-6	7,627	-3,921	2,181
Humanetics Left EV4675	687692	8,559	-4,353	1,891
	687683	8,410	-4,234	2,067
	687713	8,275	-4,208	2,022
	687720	8,305	-4,248	1,838
	687704	8,351	-4,194	1,818
Humanetics Right EV4675	687455	8,332	-4,304	2,095
	687435	8,420	-4,260	2,200
	687444	8,375	-4,269	2,137
	687409	8,354	-4,273	2,191
	687423	8,545	-4,374	2,202
Calspan Left EV4675	2025_03_22_14_14	8,580	-4,554	1,953
	2025_03_22_14_49	8,555	-4,494	1,875
	2025_03_22_15_22	8,527	-4,455	1,879
	2025_03_22_15_55	8,687	-4,472	1,759
	2025_03_22_16_29	8,438	-4,270	1,979
Calspan Right EV4675	2025_03_22_11_22	8,176	-4,353	1,989
	2025_03_22_12_04	8,012	-4,432	2,079
	2025_03_22_12_41	8,025	-4,329	1,920
	2025_03_22_13_19	7,969	-4,150	2,016
	2025_03_22_13_52	7,916	-4,127	1,973
TRC Left EV4675	2025_05_08_10_01	7,453	-4,120	2,061
	2025_05_08_10_58	7,311	-3,908	2,102
	2025_05_08_14_42	7,352	-4,187	2,153
	2025_05_08_15_09	7,395	-4,184	2,174
	2025_05_09_08_23	7,246	-4,099	2,132
TRC Right EV4675	2025_05_08_11_23	7,402	-3,960	2,101
	2025_05_08_11_49	7,369	-3,888	2,086
	2025_05_08_12_55	7,349	-3,874	2,089
	2025_05_08_14_02	7,273	-3,956	2,100
	2025_05_08_14_10	7,193	-3,927	2,063
Test Reproducibility EV4675				
Mean		7,875	-4,108	2,070
Standard Deviation		505	253	127
CV		6.4%	6.2%	6.1%

13.5 Corridor Development

All the data used to determine the upper leg qualification corridors is shown in Table 13-15. The qualification corridors were calculated using the mean plus or minus 10 percent of the peak for the specified measured or calculated channels (Table 13-16).

Table 13-15. THOR-05F Upper Leg Qualification Corridor Results
(Highlighted values fell outside average $\pm 10\%$.)

Dummy	Test Number	Maximum Probe Force (N)	Minimum Femur Force, F_z (N)	Maximum Resultant Acetabulum Force (N)
VRTC Left EU3430	241016-8	8,261	-4,274	1,861
	241016-9	8,648	-4,435	1,960
	241016-10	8,406	-4,265	1,904
	241016-11	8,158	-4,174	1,966
	241016-12	7,895	-4,001	1,928
VRTC Right EU3430	241120-8	7,669	-3,669	1,971
	241120-11	7,893	-3,816	2,012
	241120-13	7,849	-3,992	1,961
	241120-15	7,750	-4,002	2,022
	241120-18	7,856	-4,076	2,001
VRTC Left EV4675	241004-4	7,492	-3,673	2,190
	241004-5	7,570	-3,835	2,103
	241004-6	7,463	-3,726	2,145
	241007-1	7,671	-3,899	2,222
	241007-2	7,456	-3,759	2,088
VRTC Right EV4675	241004-1	7,359	-3,727	2,263
	241004-2	7,303	-3,703	2,262
	241004-3	7,289	-3,700	2,199
	241007-3	7,608	-3,927	2,191
	241007-6	7,627	-3,921	2,181
VRTC Left EV9863	241021-1	8,126	-4,644	2,000
	241021-2	8,096	-4,564	2,041
	241021-3	8,110	-4,538	1,999
	241021-4	8,121	-4,555	1,985
	241021-5	8,031	-4,475	1,974
VRTC Right EV9863	241017-11	7,712	-3,984	1,930
	241017-12	7,692	-3,939	1,898
	241017-13	7,485	-3,909	1,894
	241017-14	7,423	-3,861	1,981
	241017-15	7,482	-3,889	1,885
Humanetics Left EV4675	687692	8,559	-4,353	1,891
	687683	8,410	-4,234	2,067
	687713	8,275	-4,208	2,022
	687720	8,305	-4,248	1,838
	687704	8,351	-4,194	1,818
Humanetics Right EV4675	687455	8,332	-4,304	2,095
	687435	8,420	-4,260	2,200
	687444	8,375	-4,269	2,137
	687409	8,354	-4,273	2,191
	687423	8,545	-4,374	2,202

Calspan Left EV4675	2025_03_22 14_14	8,580	-4,554	1,953
	2025_03_22 14_49	8,555	-4,494	1,875
	2025_03_22 15_22	8,527	-4,455	1,879
	2025_03_22 15_55	8,687	-4,472	1,759
	2025_03_22 16_29	8,438	-4,270	1,979
Calspan Right EV4675	2025_03_22 11_22	8,176	-4,353	1,989
	2025_03_22 12_04	8,012	-4,432	2,079
	2025_03_22 12_41	8,025	-4,329	1,920
	2025_03_22 13_19	7,969	-4,150	2,016
	2025_03_22 13_52	7,916	-4,127	1,973
TRC Left EV4675	2025_05_08 10_01	7,453	-4,120	2,061
	2025_05_08 10_58	7,311	-3,908	2,102
	2025_05_08 14_42	7,352	-4,187	2,153
	2025_05_08 15_09	7,395	-4,184	2,174
	2025_05_09 08_23	7,246	-4,099	2,132
TRC Right EV4675	2025_05_08 11_23	7,402	-3,960	2,101
	2025_05_08 11_49	7,369	-3,888	2,086
	2025_05_08 12_55	7,349	-3,874	2,089
	2025_05_08 14_02	7,273	-3,956	2,100
	2025_05_08 14_10	7,193	-3,927	2,063
Mean		7,894	-4,123	2,033
Standard Deviation		449	266	119
CV		5.7%	6.4%	5.9%

Table 13-16. Upper Leg Qualification Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Impact Velocity	m/s	3.60	3.70	3.65	
Maximum Probe Force	N	7,105	8,684	7,894	10%
Minimum Femur Force, F_z	N	-4,535	-3,711	-4,123	10%
Maximum Resultant Acetabulum Force	N	1,829	2,236	2,033	10%

Discussion. Highlighted cells in Table 13-15 indicate test values that did not meet the respective target response $\pm 10\%$ in Table 13-16. All CV values were greater than 5 percent, but under 10 percent. Most of the non-conformities occurred in VRTC tests for the Z-axis femur force specification, but there were also missed corridors for acetabulum force and one for probe force.

Repeatability CV values were all below 5 percent, with the exception for acetabulum force on the left leg of EV4675 at Humanetics. Considering the degree of consistency, there were no apparent differences between left and right leg values.

Dummy Reproducibility was below 5 percent for maximum probe force, which was the most consistent measurement among the three specifications. Femur force and acetabulum force CV values were both above 5 percent, but under 10 percent. As stated in the corridor discussion above, most of the non-conformities were from VRTC tests where the femur force was out of range in approximately 27% of the tests.

The *Test Reproducibility* CV results were all near 6 percent, even for maximum probe force, which was below 5 percent for *Dummy Reproducibility*. Three of the five VRTC tests, and two of the five Calspan tests on the left leg EV4675 were non-conforming due to out of range femur force and/or acetabulum force.

14 KNEE

14.1 Methodology

Knee repeatability and reproducibility tests followed the qualification procedures described in the *THOR-05F Qualification Procedures and Requirements*. This test examines the response of the anterior-posterior translation of the tibia with respect to the femur at the knee joint. A 7.26 ± 0.09 kg impactor with a 76.2 ± 0.3 mm diameter rigid disk impact surface, impacts a load distribution bracket attached at the knee joint; the test velocity is 2.15 ± 0.05 m/s (Figure 14-1). During these tests, the femur Z-axis force and knee deflection at maximum femur force were measured.

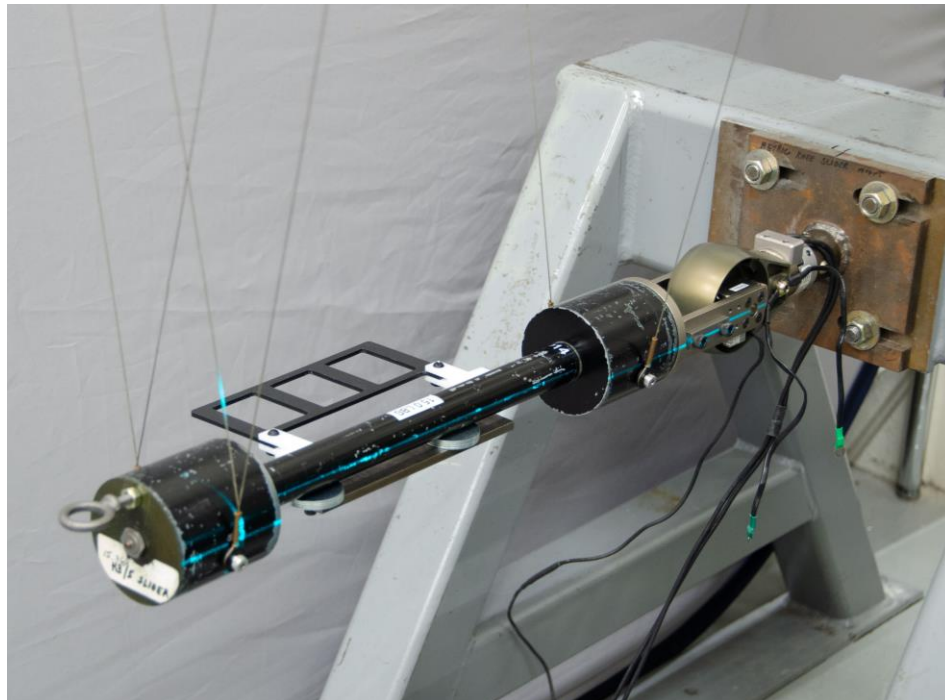


Figure 14-1. Knee impact test setup

14.2 Knee Repeatability Results

Sections 14.2.1 through 14.2.7 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 four labs. The design of the knee does not differ from left to right and testing was performed on 4 knee assemblies. 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-05F Knee FB2720 Testing at VRTC

Repeatability results for knee testing on knee FB2720 (removed from ATD EU9863 right leg) at VRTC yielded CV values below 5 percent for knee deflection at minimum femur force and above 5 percent, but under 10 percent for minimum femur force (Table 14-1, Figure 14-2 through Figure 14-3).

Table 14-1. VRTC THOR-05F Knee Repeatability Results for FB2720

Test Number	Minimum Femur Force, F_z (N)	Knee Deflection at Minimum F_z (mm)
240926-6	-3,242	-13.8
240926-7	-3,666	-13.9
240926-8	-3,690	-14.0
240926-9	-3,819	-14.0
240926-10	-3,591	-14.0
Mean	-3,602	-13.9
Standard Deviation	217	0.1
CV	6.0%	0.6%

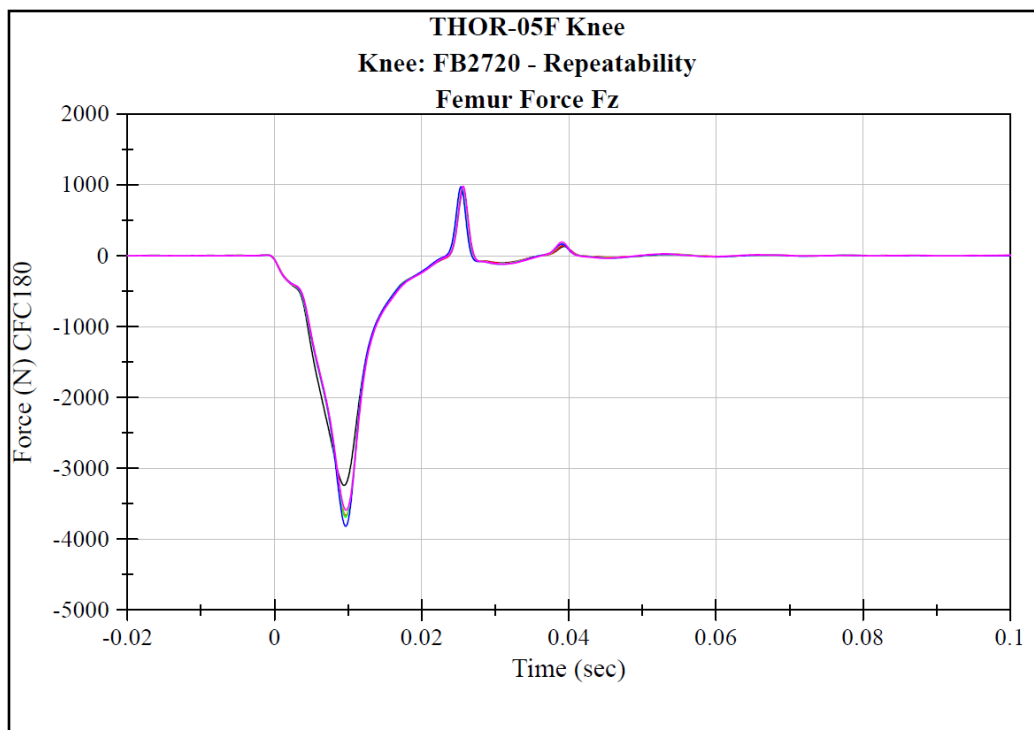


Figure 14-2. VRTC femur force for knee impact repeatability tests for FB2720

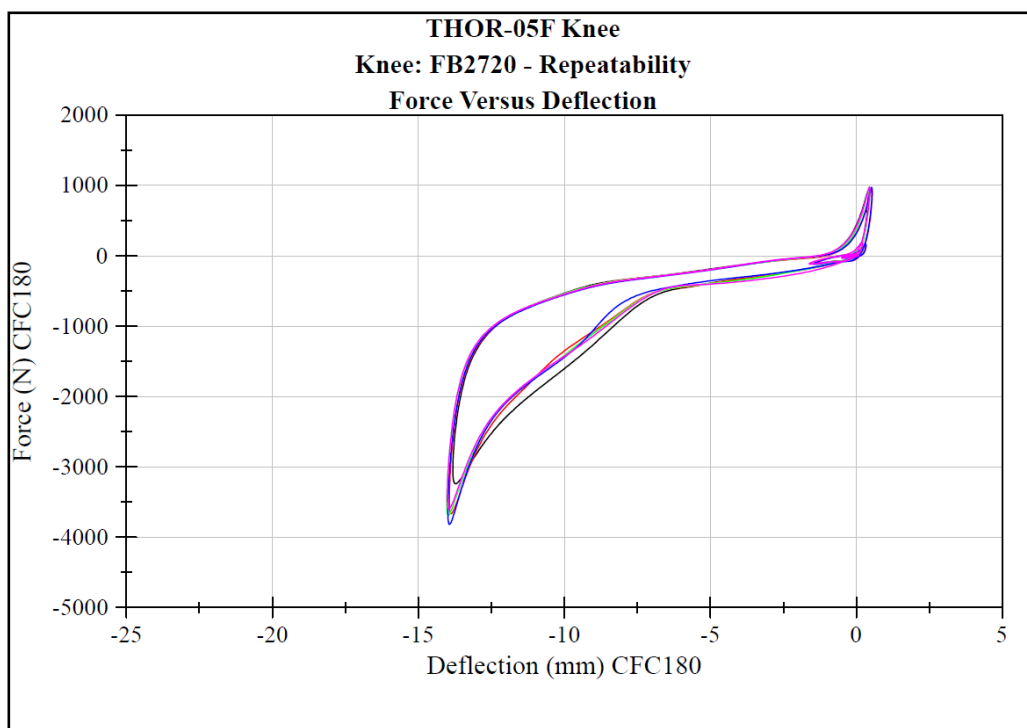


Figure 14-3. VRTC femur force vs. knee deflection for knee impact repeatability tests for FB2720

14.2.2 THOR-05F Knee FB5409 Testing at VRTC

Repeatability results for knee testing on knee FB5409 (removed from ATD EU3430 left leg) at VRTC yielded CV values below 5 percent for knee deflection at minimum femur force and above 5 percent, but under 10 percent for minimum femur force (Table 14-2, Figure 14-4 through Figure 14-5).

Table 14-2. VRTC THOR-05F Knee Repeatability Results for FB5409

Test Number	Minimum Femur Force, F_z (N)	Knee Deflection at Minimum F_z (mm)
250507-6	-3,625	-13.7
250507-8	-4,126	-13.8
250507-9	-4,132	-13.8
250507-10	-4,178	-13.9
250507-11	-4,217	-13.9
Mean	-4,055	-13.8
Standard Deviation	244	0.1
CV	6.0%	0.6%

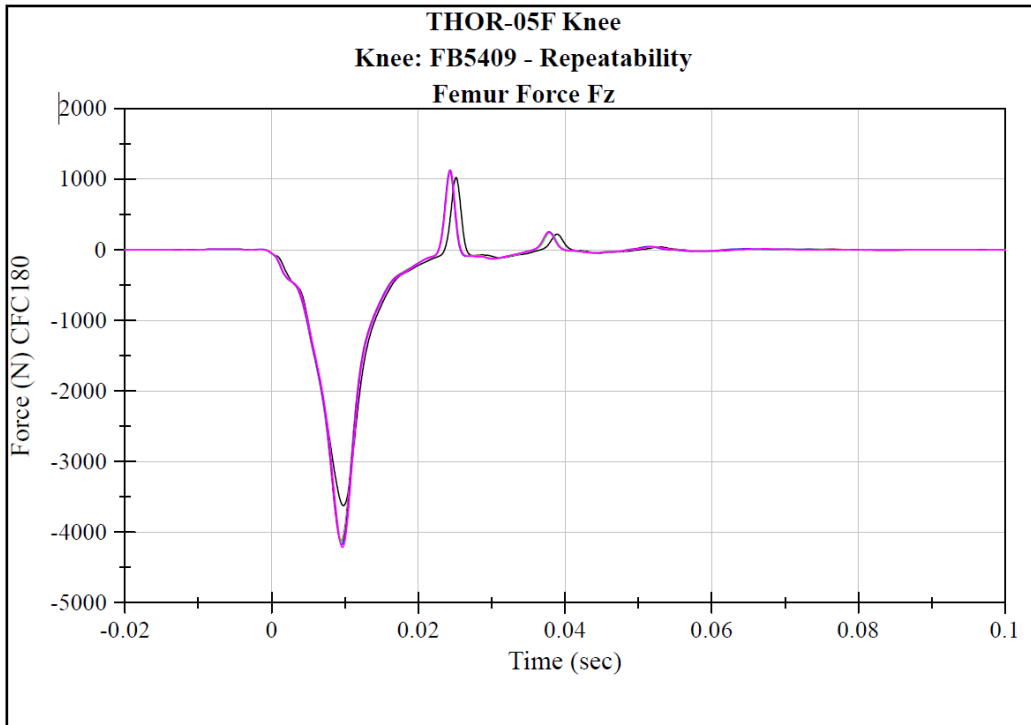


Figure 14-4. VRTC femur force for knee impact repeatability tests for FB5409

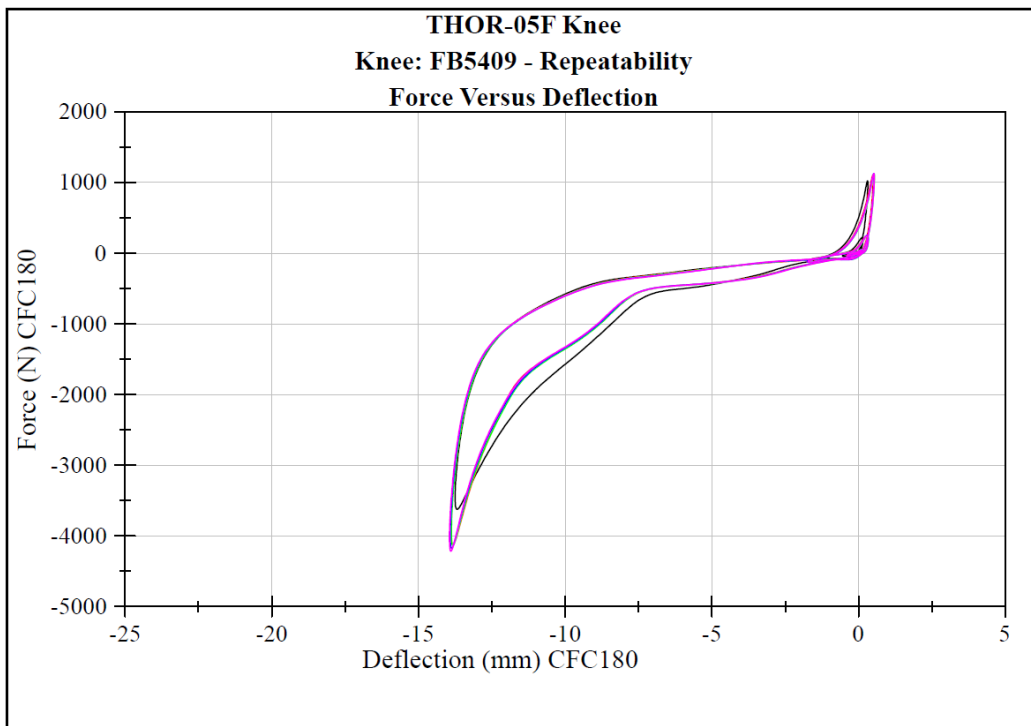


Figure 14-5. VRTC femur force vs. knee deflection for knee impact repeatability tests for FB5409

14.2.3 THOR-05F Knee FB5410 Testing at VRTC

Repeatability results for knee testing on knee FB5410 (removed from ATD EU3430 right leg) at VRTC yielded CV values below 5 percent for knee deflection at minimum femur force and above 5 percent, but under 10 percent for minimum femur force (Table 14-3, Figure 14-6 through Figure 14-7).

Table 14-3. VRTC THOR-05F Knee Repeatability Results for FB5410

Test Number	Minimum Femur Force, F_z (N)	Knee Deflection at Minimum F_z (mm)
250508-1	-3,600	-13.4
250508-2	-3,940	-13.8
250508-3	-4,068	-13.9
250508-4	-4,150	-14.0
250508-5	-4,131	-14.0
Mean	-3,978	-13.8
Standard Deviation	227	0.2
CV	5.7%	1.6%

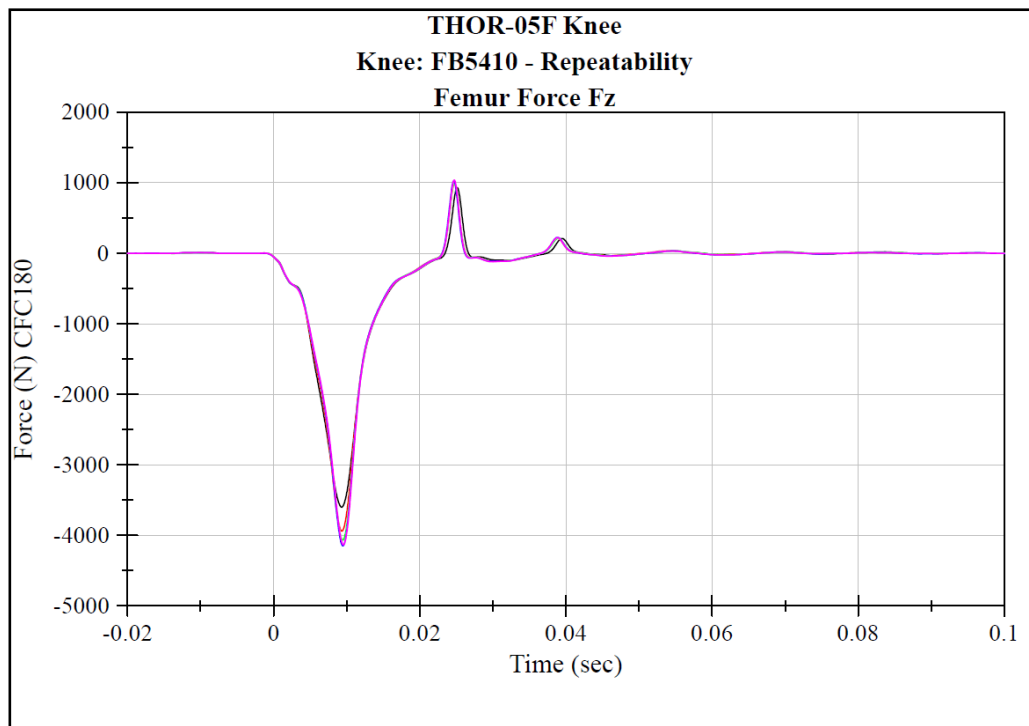


Figure 14-6. VRTC femur force for knee impact repeatability tests for FB5410

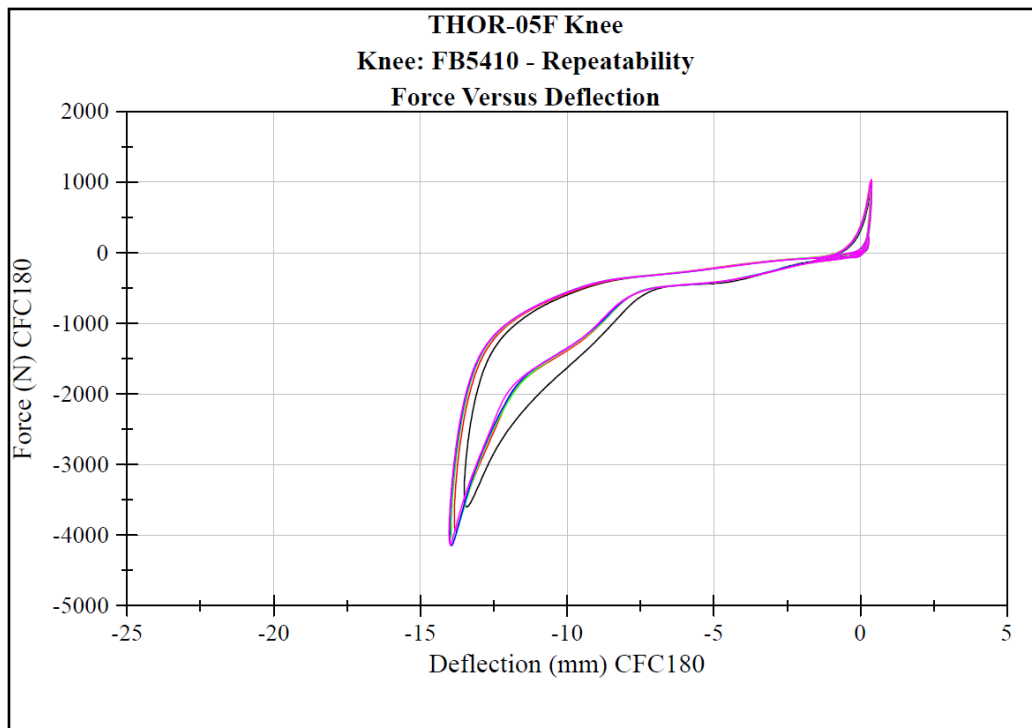


Figure 14-7. VRTC femur force vs. knee deflection for knee impact repeatability tests for FB5410

14.2.4 THOR-05F Knee FB5964 Testing at VRTC

Repeatability results for knee testing on knee FB5964 (removed from ATD EU9863 left leg) at VRTC tests yielded CV values below 5 percent (Table 14-4, Figure 14-8 through Figure 14-9).

Table 14-4. VRTC THOR-05F Knee Repeatability Results for FB5964

Test Number	Minimum Femur Force, F_z (N)	Knee Deflection at Minimum F_z (mm)
240926-1	-3,467	-13.8
240926-2	-3,765	-13.9
240926-3	-3,414	-13.9
240926-4	-3,733	-13.8
240926-5	-3,644	-13.8
Mean	-3,604	-13.8
Standard Deviation	157	0.1
CV	4.4%	0.4%

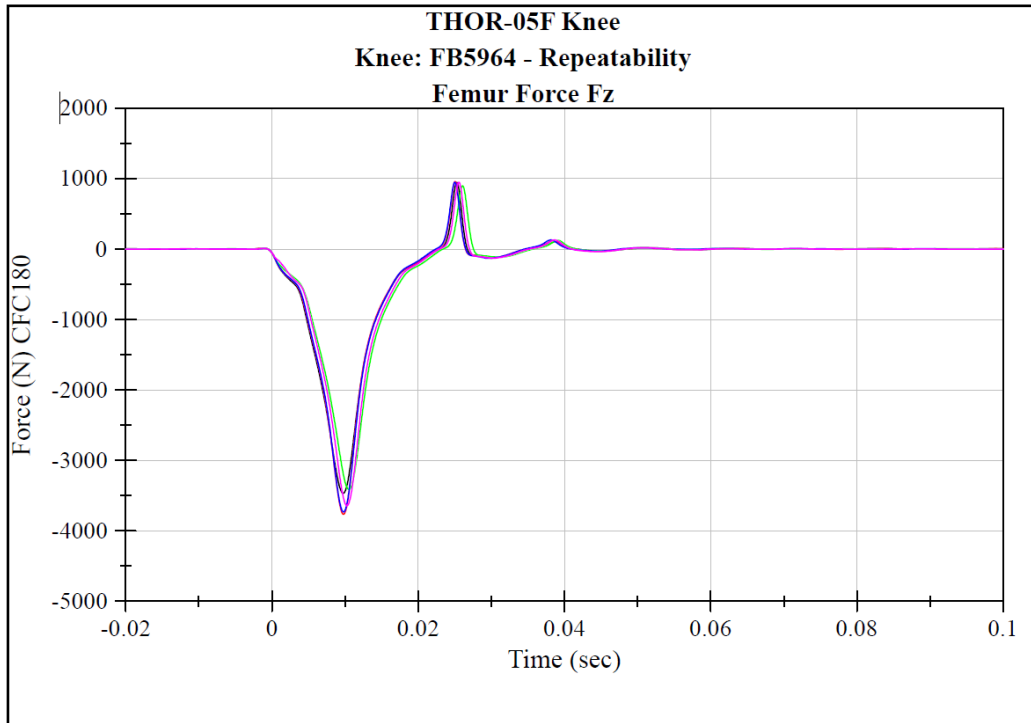


Figure 14-8. VRTC femur force for knee impact repeatability tests for FB5964

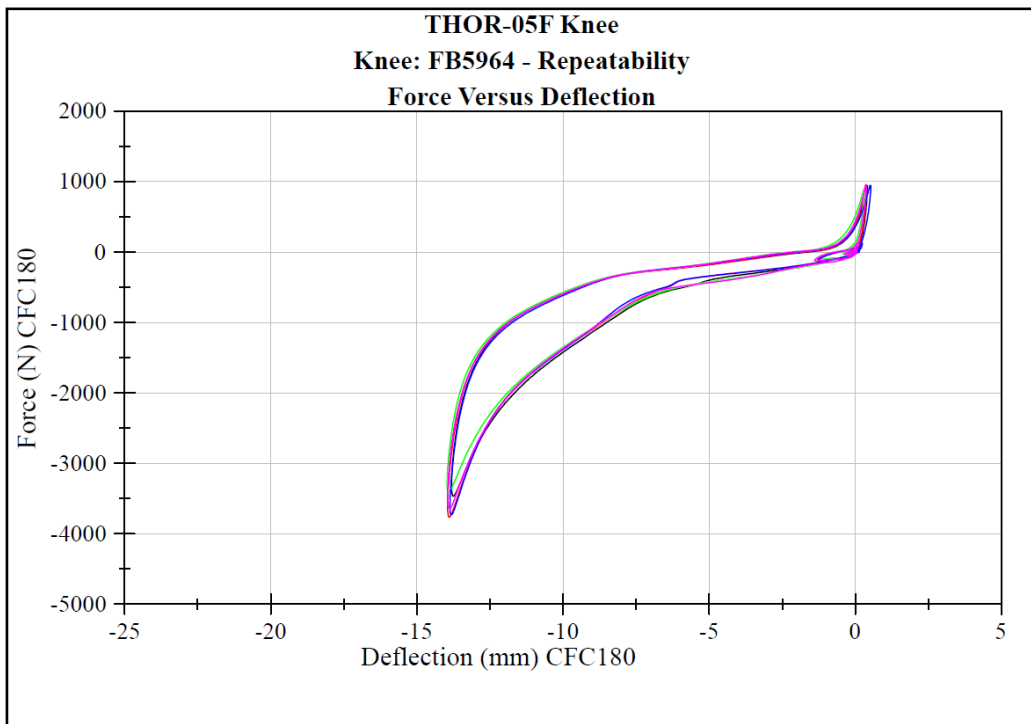


Figure 14-9. VRTC femur force vs. knee deflection for knee impact repeatability tests for FB5964

14.2.5 THOR-05F Knee FB5964 Testing at Humanetics

Repeatability results for knee testing on knee FB5964 (removed from ATD EU9863 left leg) at Humanetics yielded CV values below 5 percent (Table 14-5, Figure 14-10 through Figure 14-11).

Table 14-5. Humanetics THOR-05F Knee Repeatability Results for FB5964

Test Number	Minimum Femur Force, F_z (N)	Knee Deflection at Minimum F_z (mm)
685270	-3,661	-14.2
685237	-3,549	-14.4
685277	-3,703	-14.2
685256	-3,645	-14.2
685133	-3,639	-14.2
Mean	-3,639	-14.2
Standard Deviation	56	0.1
CV	1.5%	0.6%

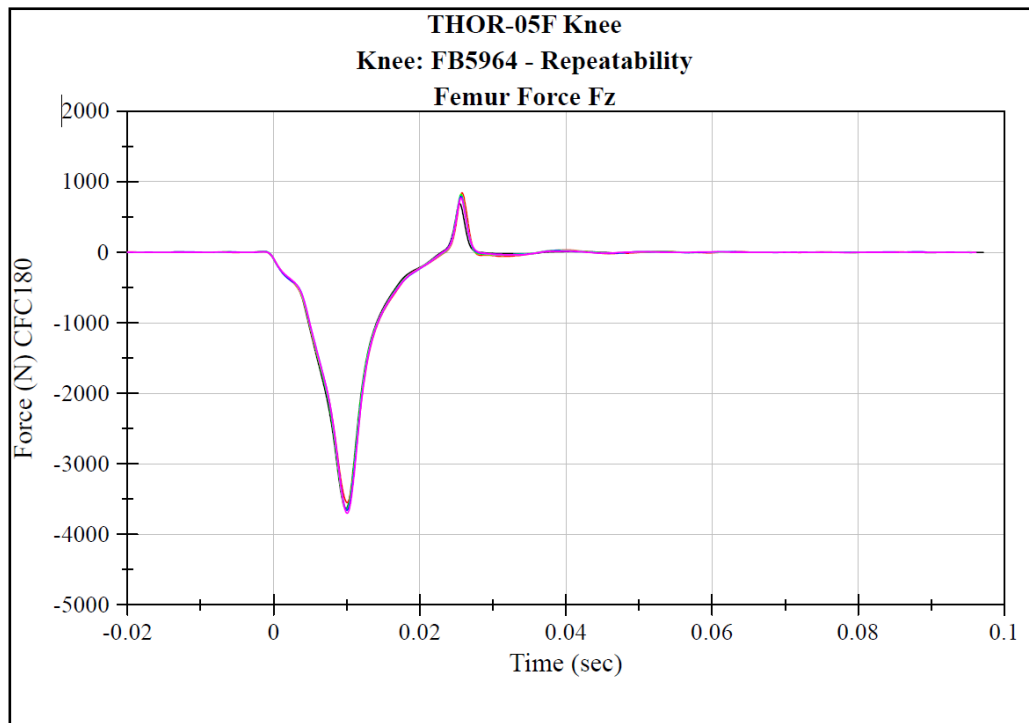


Figure 14-10. Humanetics femur force for knee impact repeatability tests for FB5964

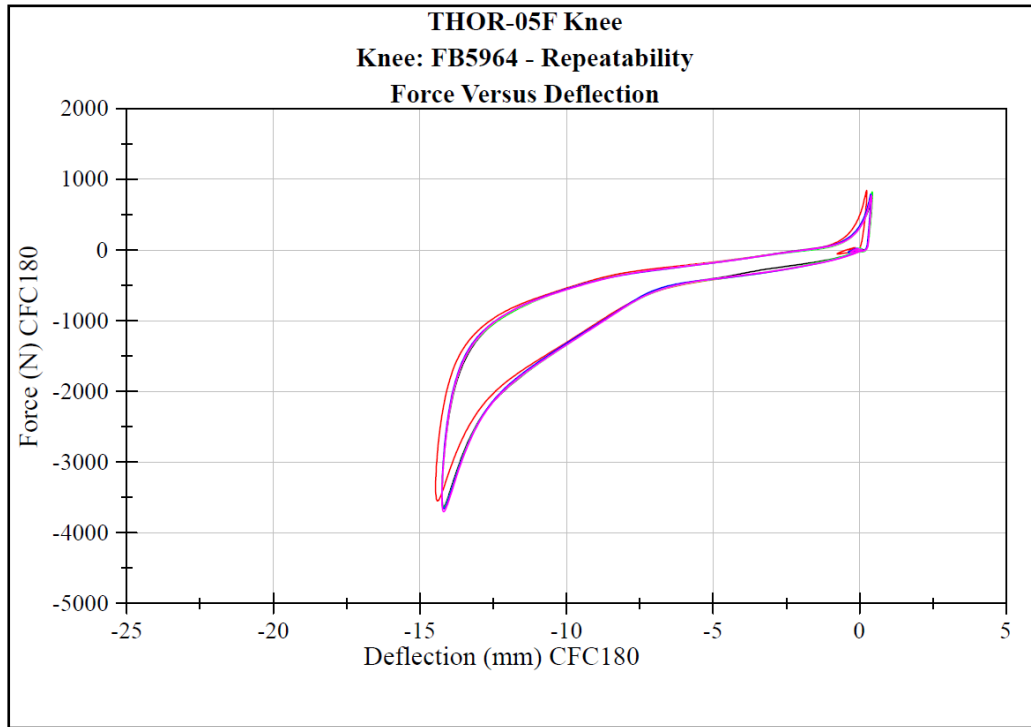


Figure 14-11. Humanetics femur force vs. knee deflection for knee impact repeatability tests for FB5964

14.2.6 THOR-05F Knee FB5964 Testing at Calspan

Repeatability results for knee testing on Knee FB5964 (removed from ATD EU9863 left leg) at Calspan yielded CV values below 5 percent (Table 14-6, Figure 14-12 through Figure 14-13).

Table 14-6. Calspan THOR-05F Knee Repeatability Results for FB5964 Left

Test Number	Minimum Femur Force, F_z (N)	Knee Deflection at Minimum F_z (mm)
2025_06_13 09_24	-3,472	-13.4
2025_06_13 10_03	-3,729	-13.4
2025_06_13 10_40	-3,850	-13.4
2025_06_13 11_19	-3,924	-13.5
2025_06_13 12_01	-3,857	-13.5
Mean	-3,766	-13
Standard Deviation	179	0.1
CV	4.7%	0.4%

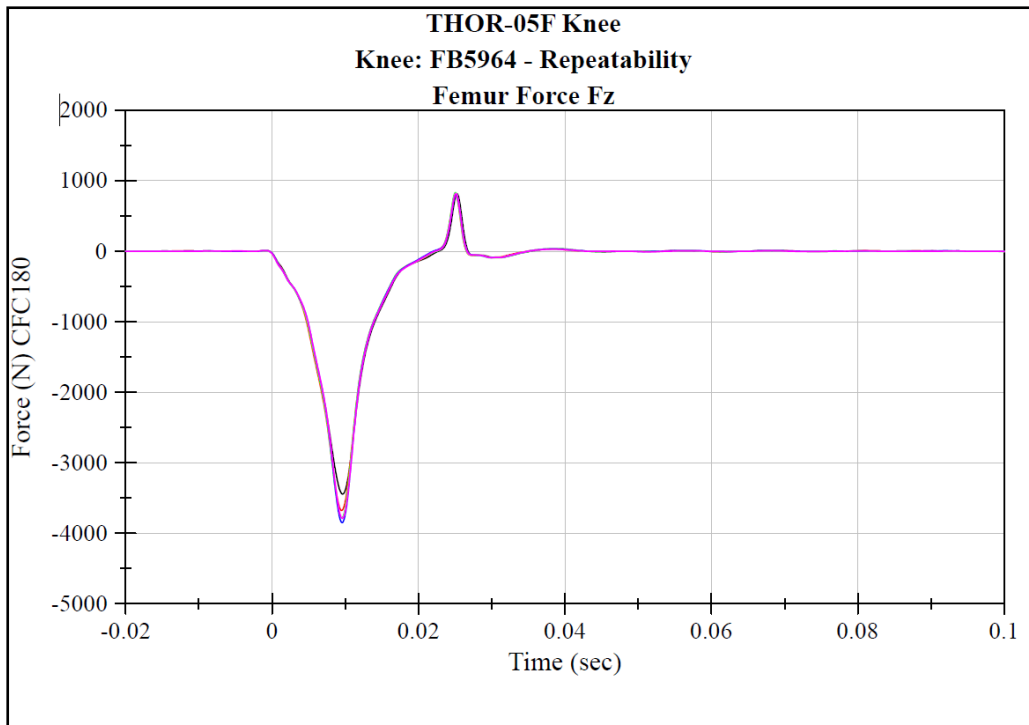


Figure 14-12. Calspan femur force for knee impact repeatability tests for FB5964

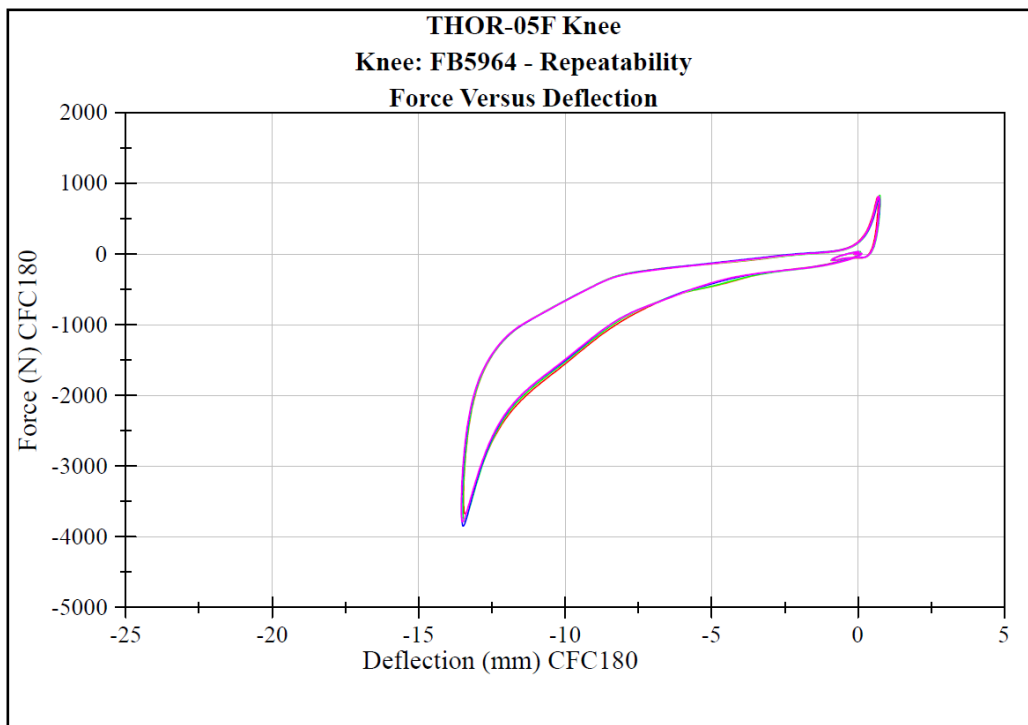


Figure 14-13. Calspan femur force vs. knee deflection for knee impact repeatability tests for FB5964

14.2.7 THOR-05F Knee FB5964 Testing at TRC

Repeatability results for knee testing on Knee FB5964 (removed from ATD EU9863) at TRC yielded CV values below 5 percent (Table 14-7, Figure 14-14 and Figure 14-15).

Table 14-7. TRC THOR-05F Knee Repeatability Results for FB5964 Left

Test Number	Minimum Femur Force, F_z (N)	Knee Deflection at Minimum F_z (mm)
2025_05_06_14_50	-3,899	-13.4
2025_05_06_15_42	-4,060	-13.5
2025_05_06_16_14	-4,091	-13.5
2025_05_07_08_10	-4,039	-13.5
2025_05_07_08_23	-4,127	-13.6
Mean	-4,043	-13.5
Standard Deviation	87	0.1
CV	2.2%	0.5%

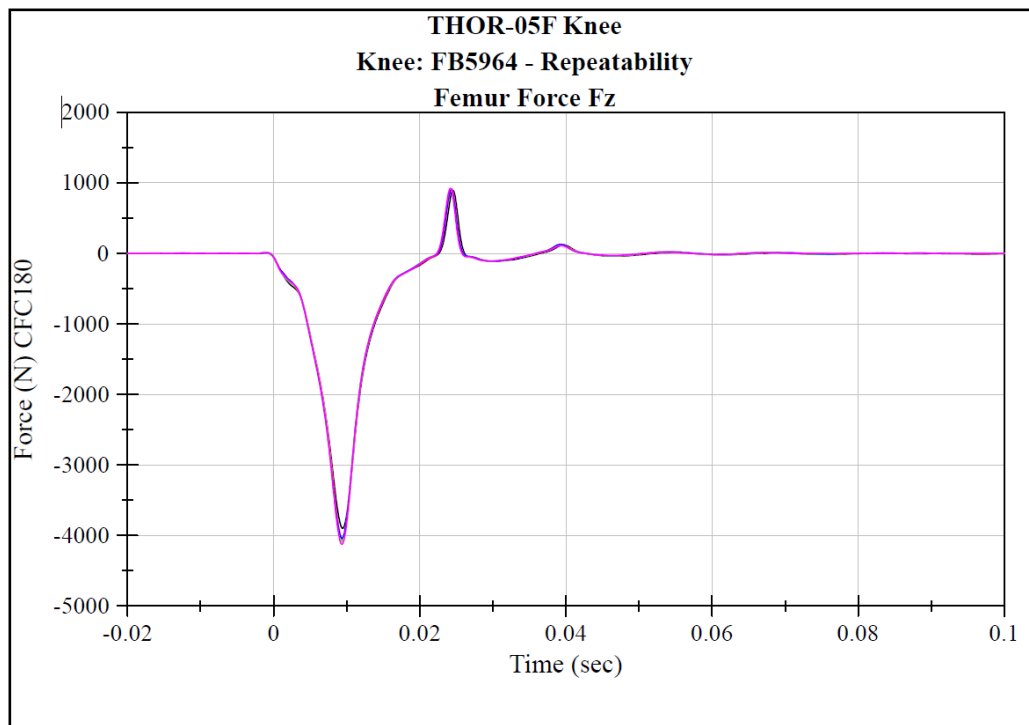


Figure 14-14. TRC femur force for knee impact repeatability tests for FB5964

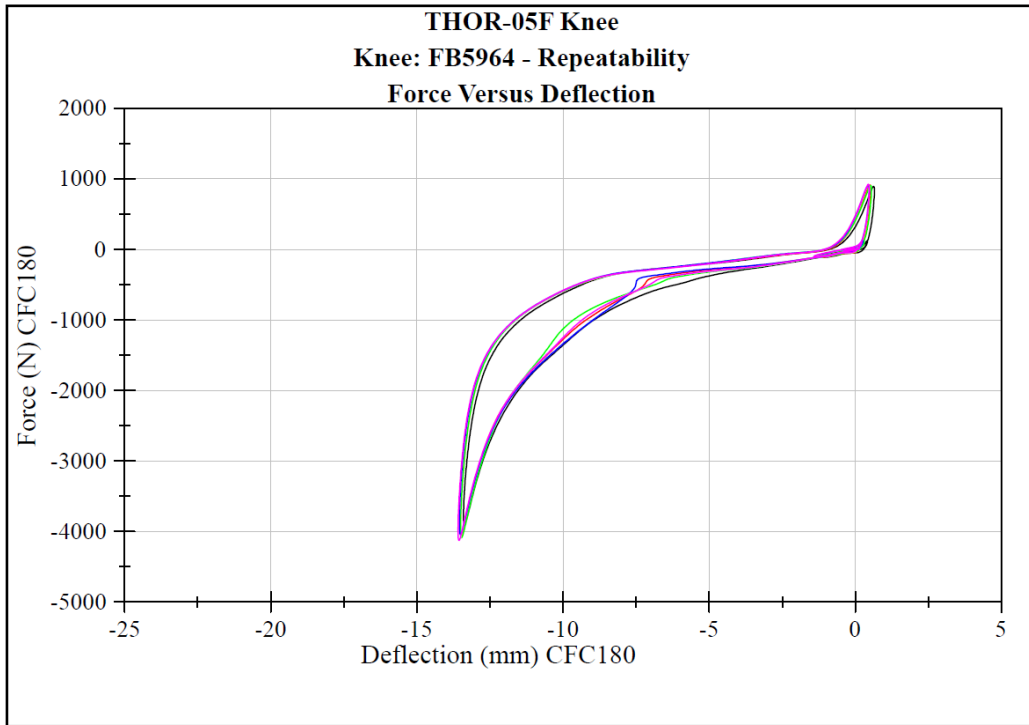


Figure 14-15. TRC femur force vs. knee deflection for knee impact repeatability tests for FB5964

14.3 Knee Impact Dummy Reproducibility Results

Dummy Reproducibility results at VRTC for the knee impact qualification tests displayed CV values below 5 percent for knee deflection at minimum femur force and above 5 percent, but under 10 percent for minimum femur force (Table 14-8). Data from four knees were included in the dummy reproducibility analysis, rather than the three samples used in several other qualification tests. The additional knee was included because its data were available and contributed to more robust corridor development.

Table 14-8. THOR-05F Knee Reproducibility Results

Knee Number	Test Number	Minimum Femur Force, F_z (N)	Knee Deflection at Minimum F_z (mm)
VRTC EU9863 Knee FB2720	240926-6	-3,242	-13.8
	240926-7	-3,666	-13.9
	240926-8	-3,690	-14.0
	240926-9	-3,819	-14.0
	240926-10	-3,591	-14.0
VRTC EU3430 Knee FB5409	250507-6	-3,625	-13.7
	250507-8	-4,126	-13.8
	250507-9	-4,132	-13.8
	250507-10	-4,178	-13.9
	250507-11	-4,217	-13.9
VRTC EU3430 Knee FB5410	250508-1	-3,600	-13.4
	250508-2	-3,940	-13.8
	250508-3	-4,068	-13.9
	250508-4	-4,150	-14.0
	250508-5	-4,131	-14.0
VRTC EU9863 Knee FB5964	240926-1	-3,467	-13.8
	240926-2	-3,765	-13.9
	240926-3	-3,414	-13.9
	240926-4	-3,733	-13.8
	240926-5	-3,644	-13.8
Mean		-3,810	-13.9
Standard Deviation		290	0.1
CV		7.6%	1.0%

14.4 Lab-to-Lab Variability

Test Reproducibility results at all four labs for knee impacts yielded CV values below 5 percent for knee deflection at minimum femur force and above 5 percent, but under 10 percent for minimum Z-axis femur force (Table 14-9).

Table 14-9. THOR-05F Knee Qualification Reproducibility Results

Knee Number	Test Number	Minimum Femur Force, F_z (N)	Knee Deflection at Minimum F_z (mm)
VRTC EU9863 Knee FB5964	240926-1	-3,467	-13.8
	240926-2	-3,765	-13.9
	240926-3	-3,414	-13.9
	240926-4	-3,733	-13.8
	240926-5	-3,644	-13.8
Humanetics EU9863 Knee FB5964	685270	-3,661	-14.2
	685237	-3,549	-14.4
	685277	-3,703	-14.2
	685256	-3,645	-14.2
	685133	-3,639	-14.2
Calspan EU9863 Knee FB5964	2025_06_13 09_24	-3,472	-13.4
	2025_06_13 10_03	-3,729	-13.4
	2025_06_13 10_40	-3,850	-13.4
	2025_06_13 11_19	-3,924	-13.5
	2025_06_13 12_01	-3,857	-13.5
TRC EU9863 Knee FB5964	2025_05_06 14_50	-3,899	-13.4
	2025_05_06 15_42	-4,060	-13.5
	2025_05_06 16_14	-4,091	-13.5
	2025_05_07 08_10	-4,039	-13.5
	2025_05_07 08_23	-4,127	-13.6
Test Reproducibility Knee FB5964			
Mean		-3,763	-13.7
Standard Deviation		220	0.3
CV		5.8%	2.2%

14.5 Corridor Development

All the data used to determine the knee qualification corridors is shown in Figure 14-10. The qualification corridors were calculated using the mean plus or minus 10 percent of the peak for the specified measured or calculated channels (Table 14-11).

Table 14-10. THOR-05F Knee Qualification Corridor Results
(Highlighted values fell outside average $\pm 10\%$.)

Knee Number	Test Number	Minimum Femur Force, F_z (N)	Knee Deflection at Minimum F_z (mm)
VRTC EU9863 Knee FB2720	240926-6	-3,242	-13.8
	240926-7	-3,666	-13.9
	240926-8	-3,690	-14.0
	240926-9	-3,819	-14.0
	240926-10	-3,591	-14.0
VRTC EU3430 Knee FB5409	250507-6	-3,625	-13.7
	250507-8	-4,126	-13.8
	250507-9	-4,132	-13.8
	250507-10	-4,178	-13.9
	250507-11	-4,217	-13.9
VRTC EU3430 Knee FB5410	250508-1	-3,600	-13.4
	250508-2	-3,940	-13.8
	250508-3	-4,068	-13.9
	250508-4	-4,150	-14.0
	250508-5	-4,131	-14.0
VRTC EU9863 Knee FB5964	240926-1	-3,467	-13.8
	240926-2	-3,765	-13.9
	240926-3	-3,414	-13.9
	240926-4	-3,733	-13.8
	240926-5	-3,644	-13.8
Humanetics EU9863 Knee FB5964	685270	-3,661	-14.2
	685237	-3,549	-14.4
	685277	-3,703	-14.2
	685256	-3,645	-14.2
	685133	-3,639	-14.2
Calspan EU9863 Knee FB5964	2025_06_13 09_24	-3,472	-13.4
	2025_06_13 10_03	-3,729	-13.4
	2025_06_13 10_40	-3,850	-13.4
	2025_06_13 11_19	-3,924	-13.5
	2025_06_13 12_01	-3,857	-13.5
TRC EU9863 Knee FB5964	2025_05_06 14_50	-3,899	-13.4
	2025_05_06 15_42	-4,060	-13.5
	2025_05_06 16_14	-4,091	-13.5
	2025_05_07 08_10	-4,039	-13.5
	2025_05_07 08_23	-4,127	-13.6
Mean		-3,813	-13.8
Standard Deviation		254	0.3
CV		6.7%	2.0%

Table 14-11. Knee Qualification Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Impact Velocity	m/s	2.10	2.20	2.15	
Minimum Femur Z-axis Force	N	-4,194	-3,431	-3,813	10%
Knee Deflection at Min Femur Force	mm	-15.2	-12.4	-13.8	10%

Discussion. Highlighted cells in Table 14-10 indicate trial values that did not meet the respective target response $\pm 10\%$ in Table 14-11. Three tests, one each from three different knees tested at VRTC, had a non-conforming femur force.

Repeatability CV values were below 5 percent for knee deflection in all tests. CV values for Z-axis femur force were only below 5 percent for all tests with knee FB5964. The Z-axis femur forces for the other knees (all tested only at VRTC) all displayed CV values above 5 percent. In all but two of the test series, the first trial had a femur force between 300 N to 500 N lower than subsequent testing; this may indicate that a “break-in” test may need to be considered prior to conducting a qualification test. For tests with the two knees where the first tests were not significantly lower (Humanetics FB964 and TRC FB5964), the labs may have conducted a test prior to what was reported. For example, if velocity was not within specification for a first, unreported run; then, the first test reported would not actually have been the first time the knee was exercised in the test series, masking the “break-in” issue seen in the other tests.

Dummy Reproducibility results showed CV values for knee deflections below 5 percent, while Z-axis femur force was above 5 percent, but under 10 percent (Table 14-8). All tests that explored *Dummy Reproducibility* were included in the “break-in” issue for the first test described in the *Repeatability* discussion above. This was also the cause of the higher CV values for *Dummy Reproducibility*.

Lab-to-lab variability results showed that *Test Reproducibility* CV values were below 5 percent for knee deflections and above 5 percent, but under 10 percent for Z-axis femur force (Table 14-9). Since three tests showed non-conformance for this parameter in the series of tests conducted at VRTC, the CV value was higher than 5 percent.

15 ANKLE INVERSION

15.1 Methodology

Repeatability and reproducibility tests were performed using the ankle inversion qualification procedures described in the *THOR-05F Qualification Procedures and Requirements*. The ankle inversion qualification consists of impact to an inversion/eversion bracket (TH-1603-0675) which is temporarily attached to the bottom of the ankle assembly in place of the molded shoe (Figure 15-1). The impact surface of the bracket is covered with PTFE 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 lower tibia load cell 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-9000-007, TLX-9000-006), as described in *THOR-05F Drawing Package*, with an effective mass of 3.00 ± 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 force (F_z) and X-axis rotation were measured; the ankle resistive moment about the X-axis was calculated from F_y and M_x .

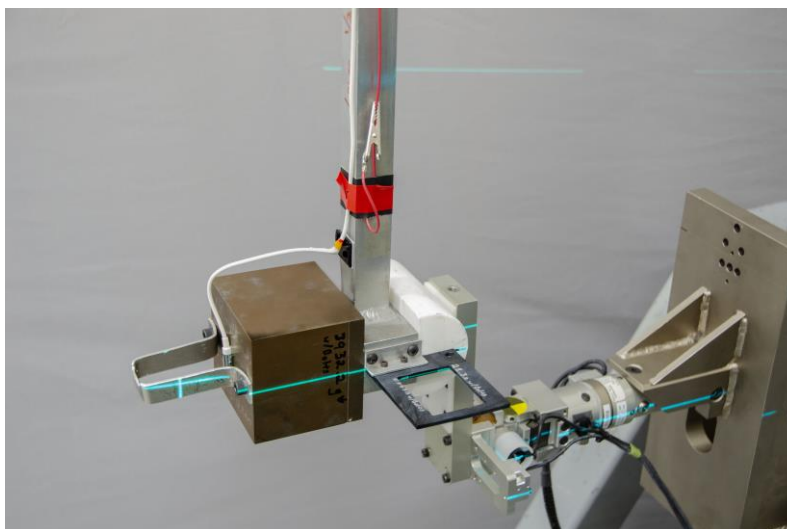


Figure 15-1. Ankle Inversion Test

15.2 Ankle Inversion Repeatability Results

Sections 15.2.1 through 15.2.6 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 four labs. Since this is a component-level test and the left and right side designs are symmetric, only the left ankle was tested. 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-05F Left Ankle EV4180 Inversion Testing at VRTC

Repeatability results for ankle inversion testing on Ankle EV4180 (removed from ATD EV0668, left side) at VRTC yielded CV values below 5 percent (Table 15-1, Figure 15-2 through Figure 15-4).

Table 15-1. VRTC THOR-05F Left Ankle Inversion Repeatability Results for Ankle EV4180

Test Number	Minimum Lower Tibia Fz (N)	Minimum Ankle M _x (Nm)	Minimum Ankle θ_x (deg)
240523-5	-312	-28.2	-27.5
240523-6	-306	-28.5	-27.5
240523-13	-311	-28.5	-27.5
240523-14	-309	-28.5	-27.5
240523-16	-308	-28.7	-27.5
Mean	-309	-28.5	-27.5
Standard Deviation	2.3	0.2	0.0
CV	0.7%	0.7%	0.1%

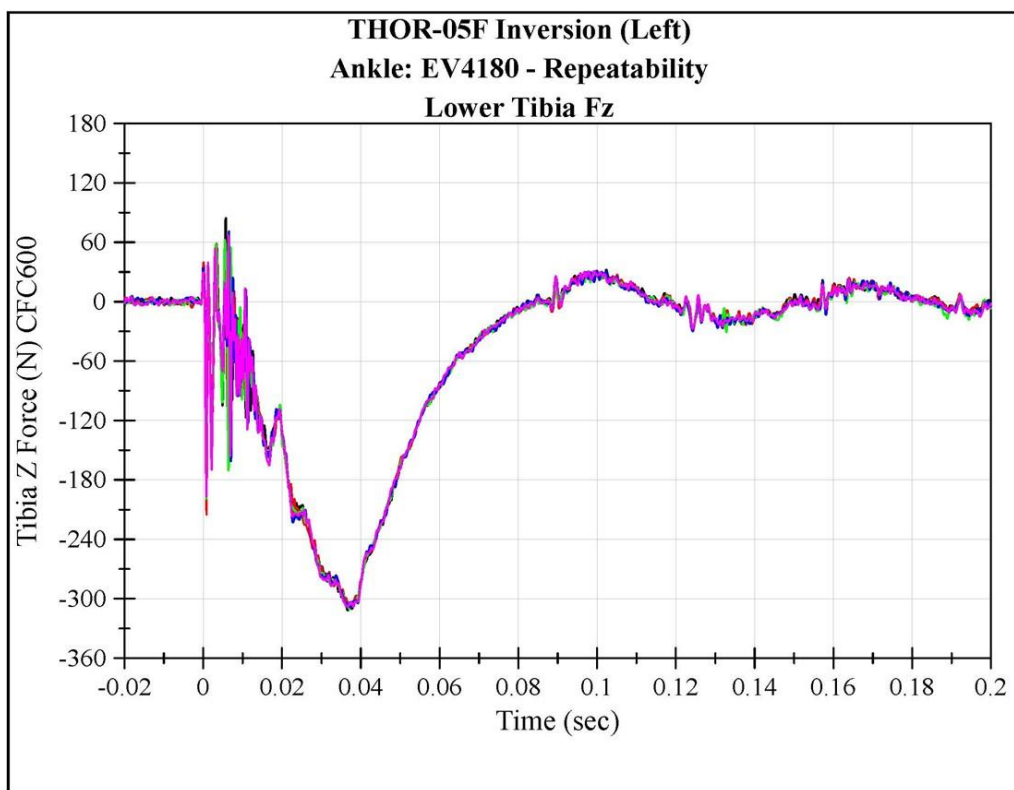


Figure 15-2. VRTC lower tibia force Fz for ankle inversion repeatability tests for Ankle EV4180

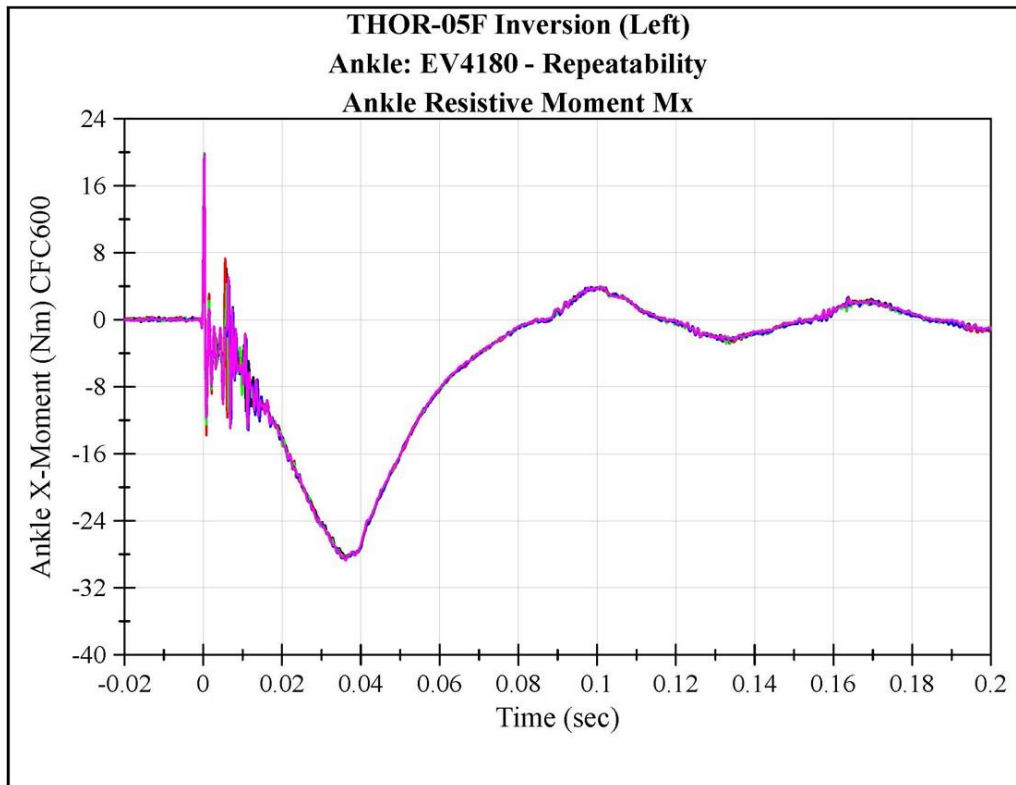


Figure 15-3. VRTC ankle resistive moment Mx for ankle inversion repeatability tests for Ankle EV4180

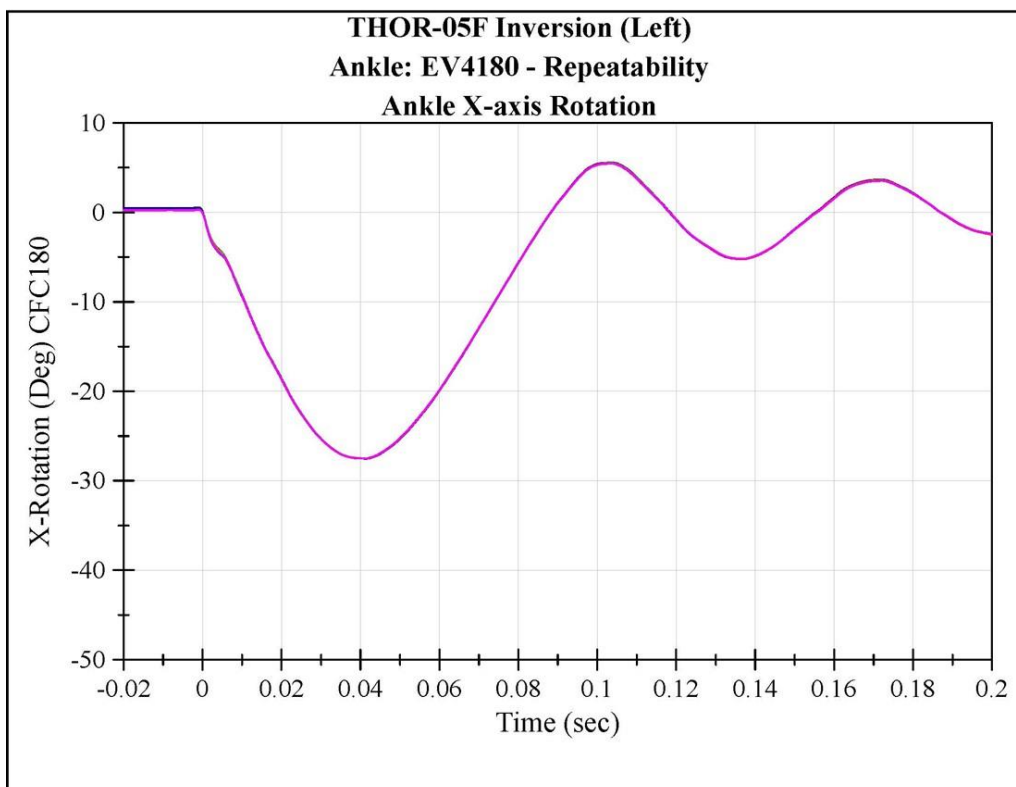


Figure 15-4. VRTC ankle X axis rotation for ankle inversion repeatability tests for Ankle EV4180

15.2.2 THOR-05F Left Ankle EV1130 Inversion Testing at VRTC

Repeatability results for ankle inversion testing on Ankle EV1130 (removed from ATD EV0674, left side) at VRTC yielded CV values below 5 percent (Table 15-2, Figure 15-5 through Figure 15-7).

Table 15-2. VRTC THOR-05F Left Ankle Inversion Repeatability Results for Ankle EV1130

Test Number	Minimum Lower Tibia Fz (N)	Minimum Ankle M _x (Nm)	Minimum Ankle θ_x (deg)
240604-8	-320	-28.3	-27.6
240604-9	-328	-28.7	-27.8
240604-10	-325	-28.3	-27.8
240605-1	-317	-27.9	-27.6
240605-12	-318	-28.0	-27.7
Mean	-322	-28.2	-28.2
Standard Deviation	4.6	0.3	0.3
CV	1.4%	1.1%	0.4%

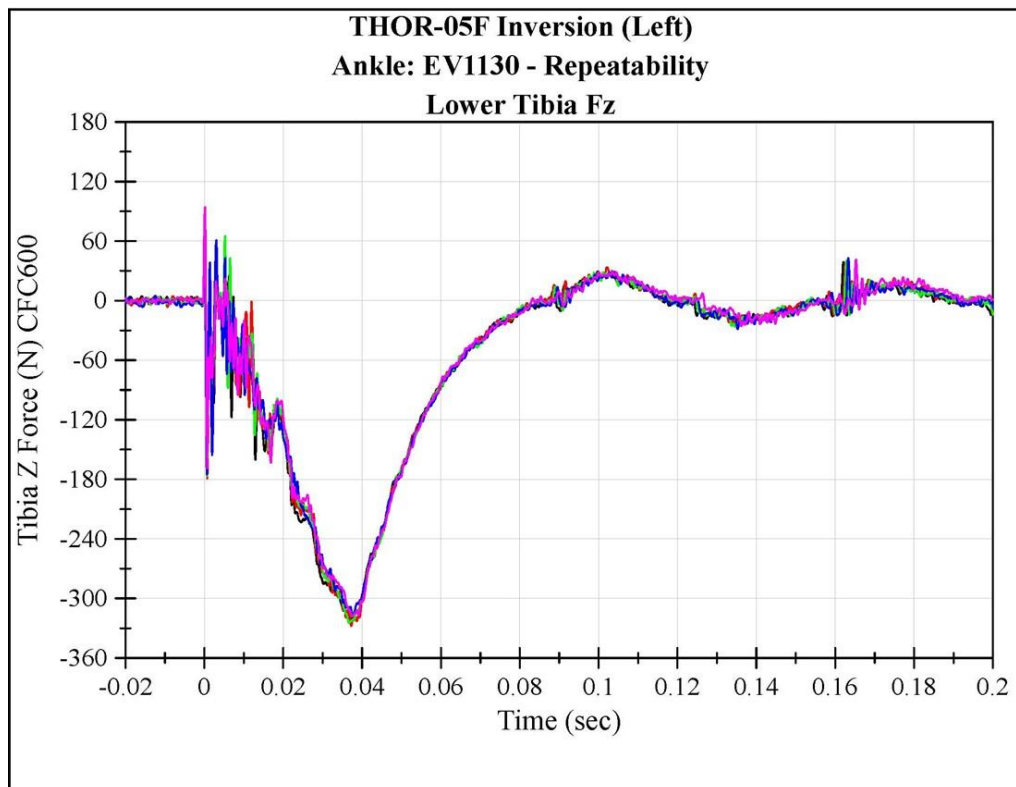


Figure 15-5. VRTC lower tibia force Fz for ankle inversion repeatability tests for Ankle EV1130

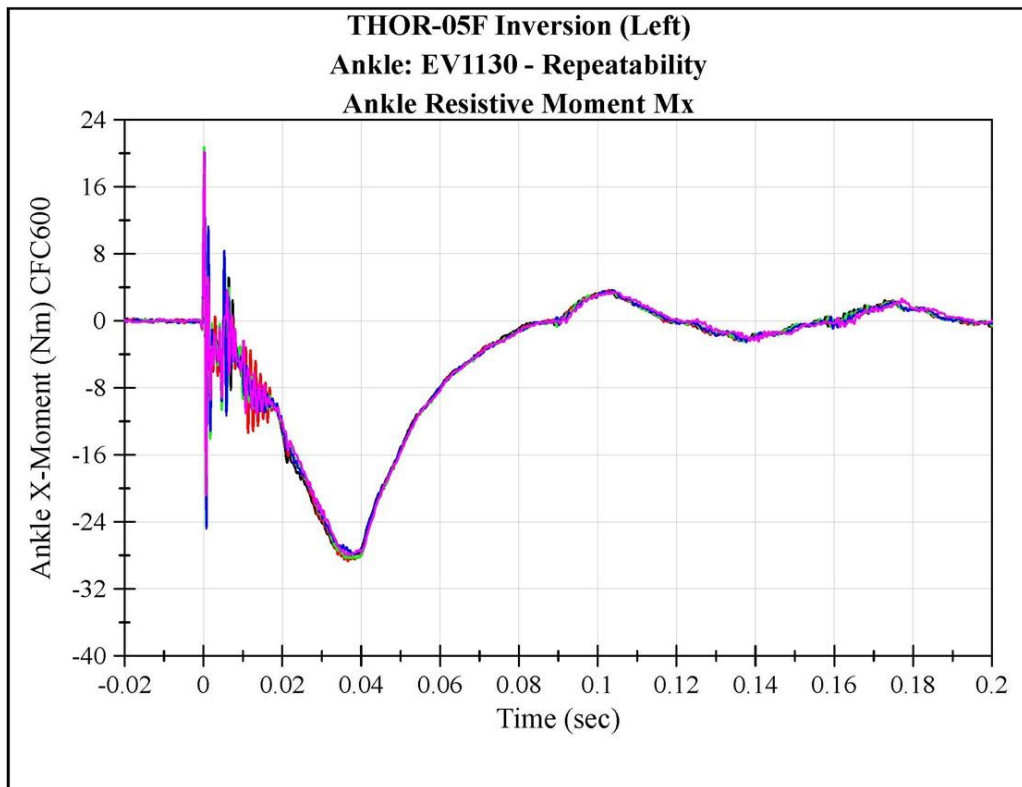


Figure 15-6. VRTC ankle resistive moment M_x for ankle inversion repeatability tests for Ankle EV1130

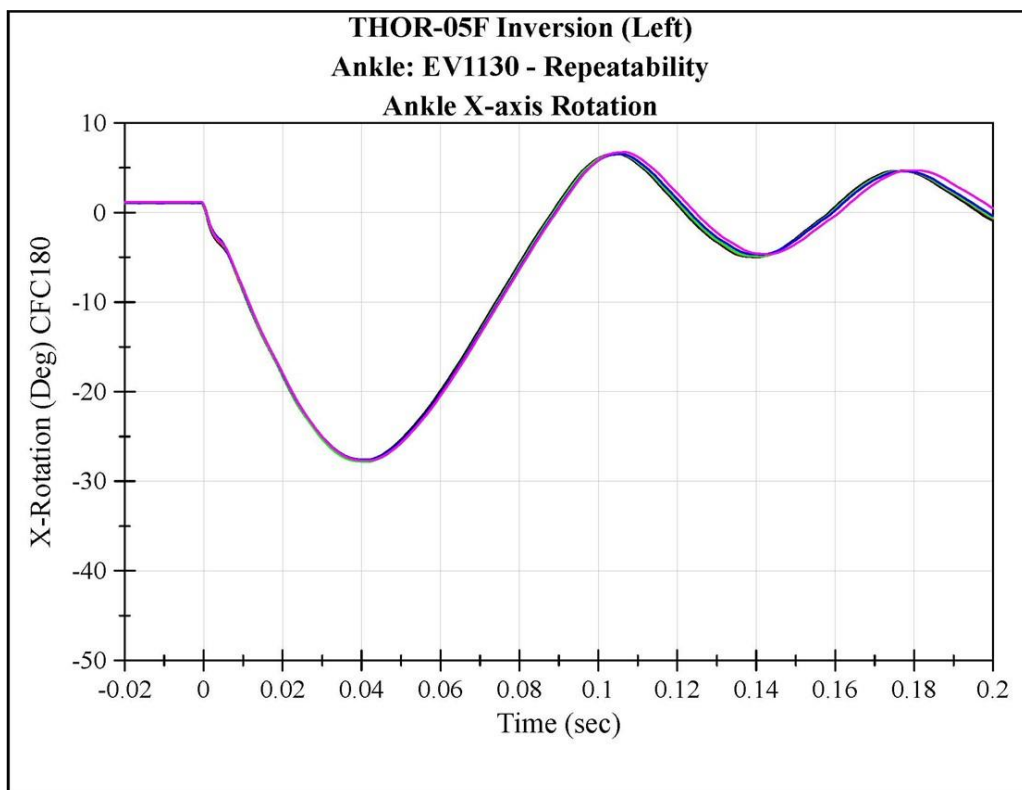


Figure 15-7. VRTC ankle X axis rotation for ankle inversion repeatability tests for Ankle EV1130

15.2.3 THOR-05F Left Ankle EV2720 Inversion Testing at VRTC

Repeatability results for ankle inversion testing on Ankle EV2720 (removed from ATD EV4675, left side) at VRTC yielded CV values below 5 percent (Table 15-3, Figure 15-8 through Figure 15-10).

Table 15-3. VRTC THOR-05F Left Ankle Inversion Repeatability Results for Ankle EV2720

Test Number	Minimum Lower Tibia Fz (N)	Minimum Ankle M _x (Nm)	Minimum Ankle θ_x (deg)
240910-9	-282	-27.4	-28.0
240910-12	-285	-27.7	-28.2
240910-13	-295	-28.3	-28.5
240910-14	-296	-28.3	-28.5
240910-15	-295	-28.6	-28.6
Mean	-290	-28.1	-28.4
Standard Deviation	6.8	0.5	0.3
CV	2.3%	1.8%	0.9%

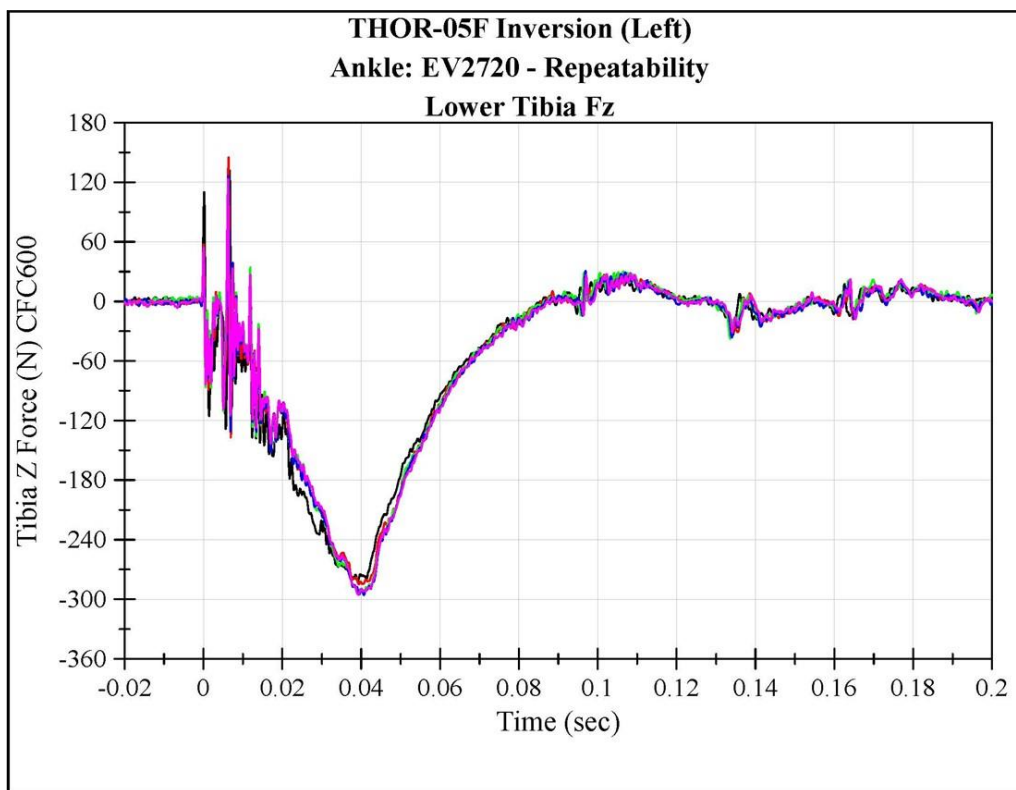


Figure 15-8. VRTC lower tibia force Fz for ankle inversion repeatability tests for Ankle EV2720

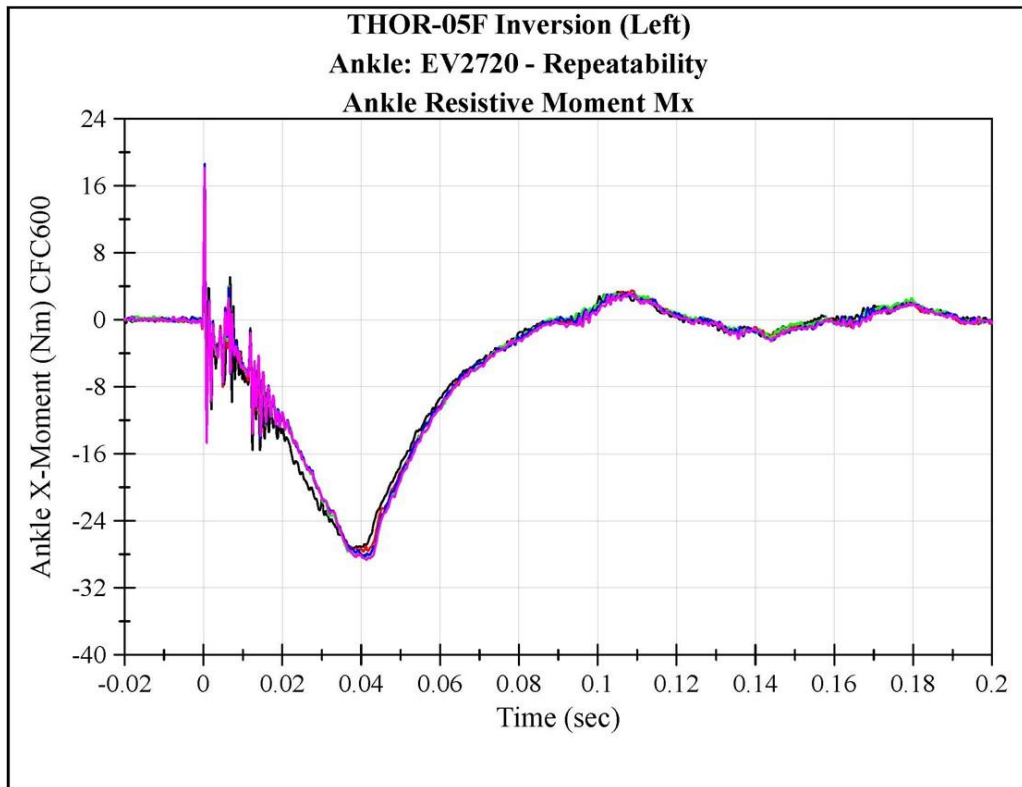


Figure 15-9. VRTC ankle resistive moment Mx for ankle inversion repeatability tests for Ankle EV2720

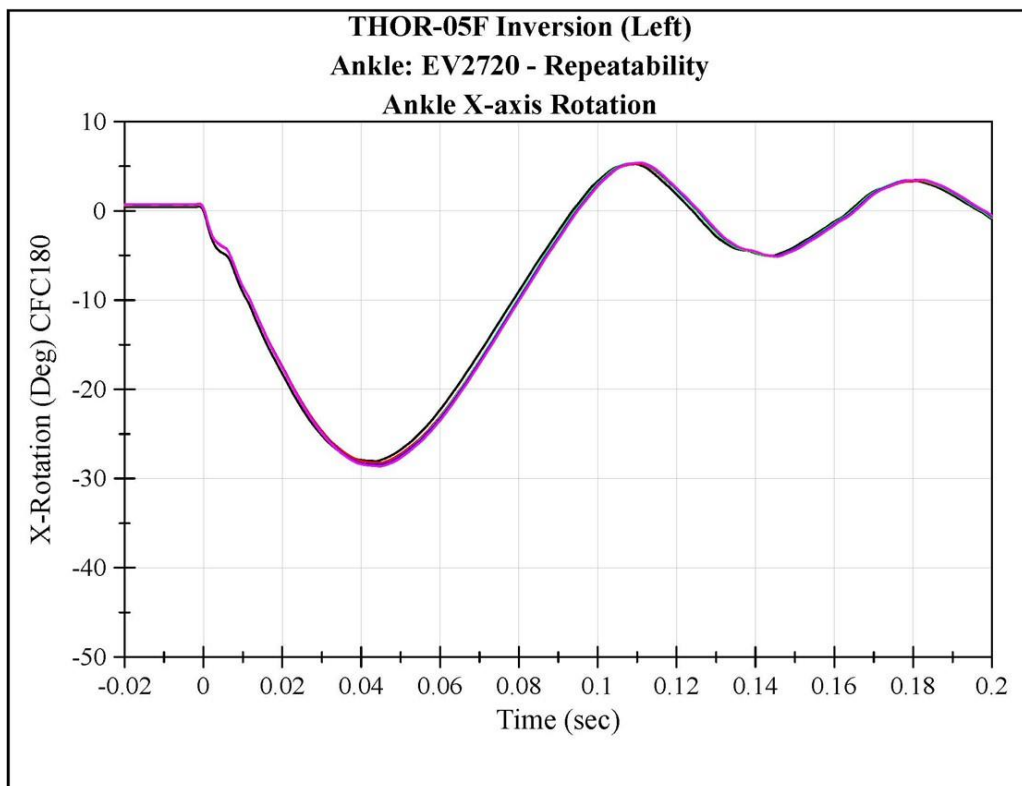


Figure 15-10. VRTC ankle X axis rotation for ankle inversion repeatability tests for Ankle EV2720

15.2.4 THOR-05F Left Ankle EV2720 Inversion Testing at Humanetics

Repeatability results for ankle inversion testing on Ankle EV2720 (removed from ATD EV4675, left side) at Humanetics yielded CV values below 5 percent (Table 15-4, Figure 15-11 through Figure 15-13). Ankle data was not collected past 0.12 s at Humanetics, but this difference did not affect the R&R analysis.

Table 15-4. Humanetics THOR-05F Left Ankle Inversion Repeatability Results for Ankle EV2720

Test Number	Minimum Lower Tibia Fz (N)	Minimum Ankle M _x (Nm)	Minimum Ankle θ_x (deg)
686064	-313	-28.9	-28.5
686071	-315	-28.8	-28.5
686056	-316	-29.2	-28.5
686049	-314	-29.1	-28.4
686018	-318	-29.3	-28.6
Mean	-315	-29.1	-28.5
Standard Deviation	2.0	0.2	0.1
CV	0.6%	0.7%	0.2%

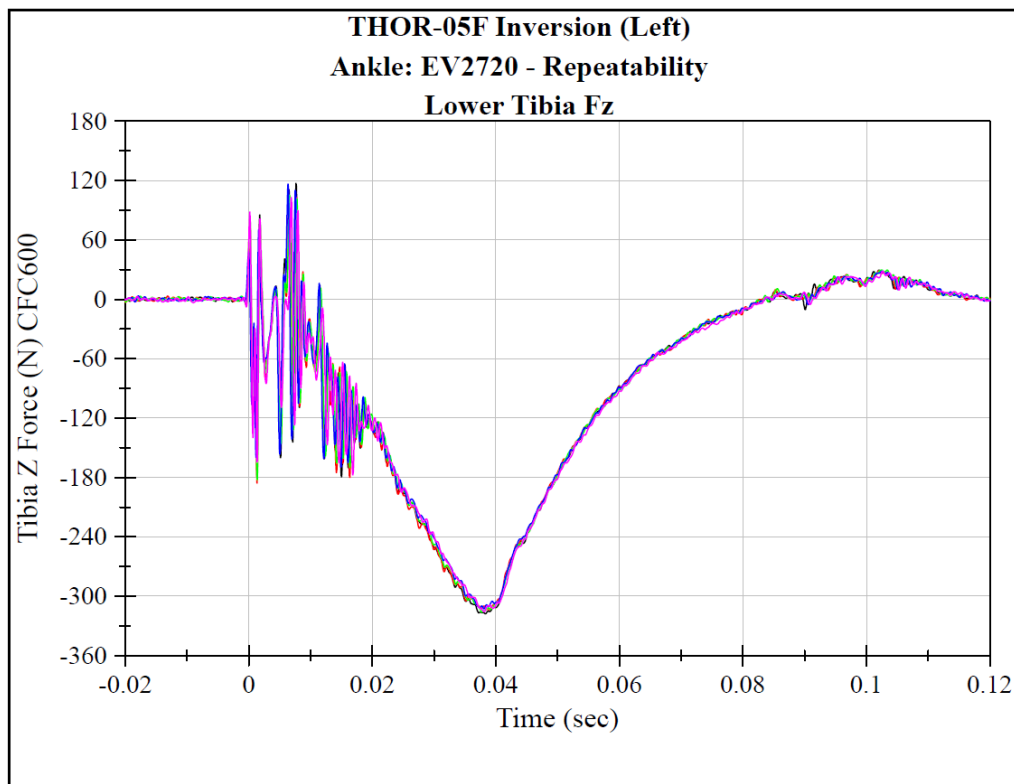


Figure 15-11. Humanetics lower tibia force Fz for ankle inversion repeatability tests for Ankle EV2720

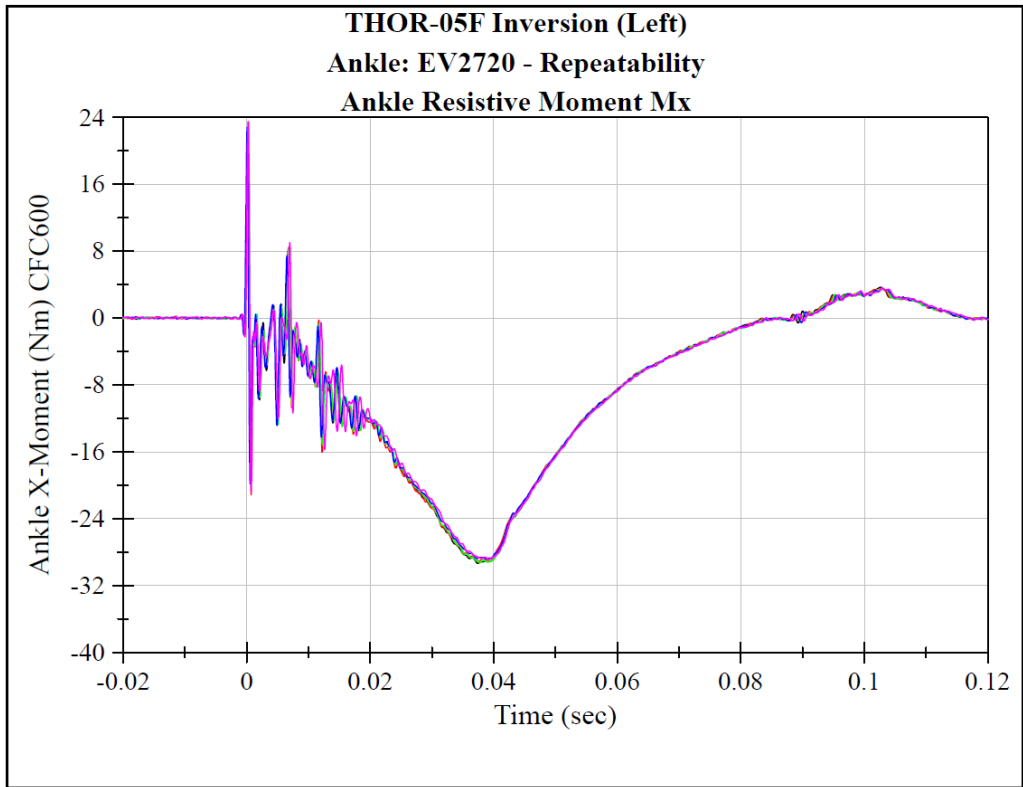


Figure 15-12. Humanetics ankle resistive moment Mx for ankle inversion repeatability tests for Ankle EV2720

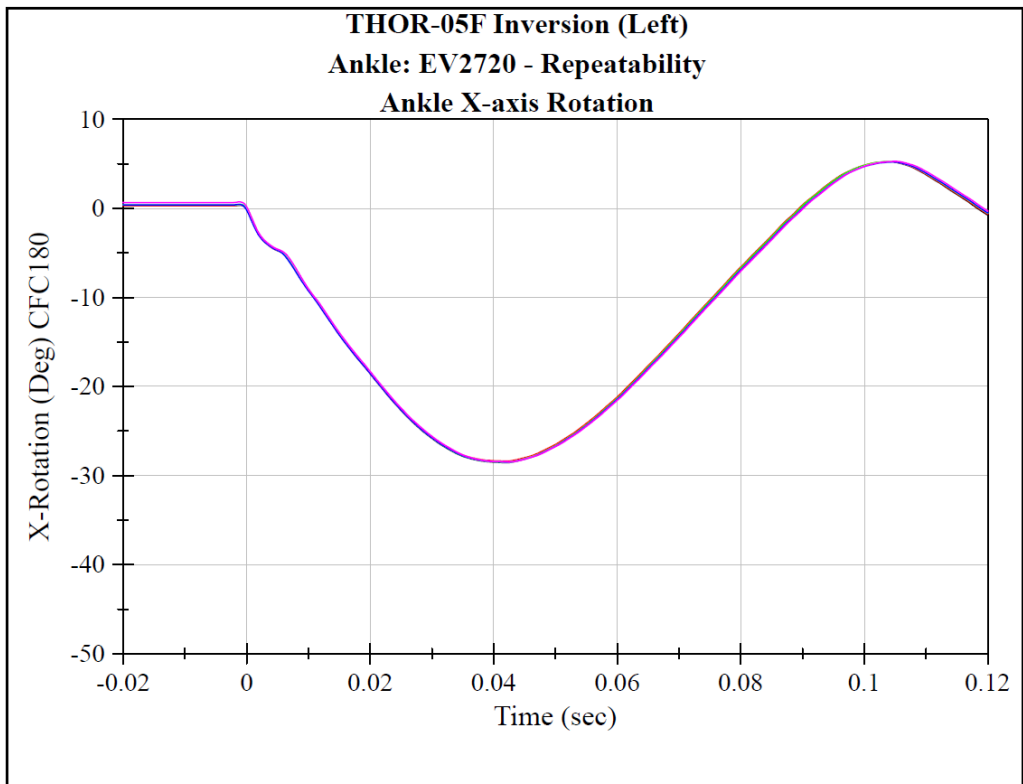


Figure 15-13. Humanetics ankle X axis rotation for ankle inversion repeatability tests for Ankle EV2720

15.2.5 THOR-05F Left Ankle EV2720 Inversion Testing at Calspan

Repeatability results for ankle inversion testing on Ankle EV2720 (removed from ATD EV4675, left side) at Calspan yielded CV values below 5 percent (Table 15-5, Figure 15-14 through Figure 15-16).

Table 15-5. Calspan THOR-05F Left Ankle Inversion Repeatability Results for Ankle EV2720

Test Number	Minimum Lower Tibia Fz (N)	Minimum Ankle M _x (Nm)	Minimum Ankle θ_x (deg)
2025_03_28_18_44	-350	-27.1	-25.7
2025_03_28_19_16	-351	-28.3	-26.0
2025_03_28_19_48	-356	-28.0	-26.2
2025_03_28_20_20	-351	-27.7	-26.4
2025_03_28_20_56	-363	-28.1	-26.4
Mean	-354	-27.8	-26.1
Standard Deviation	5.6	0.5	0.3
CV	1.6%	1.7%	1.1%

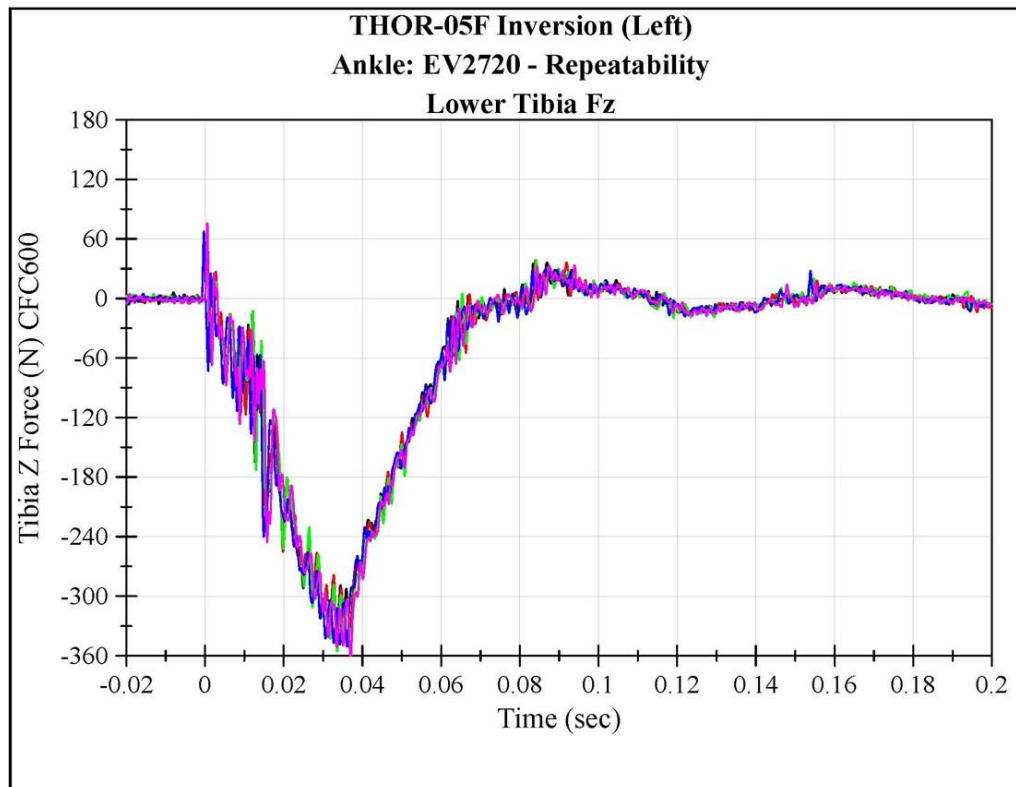


Figure 15-14. Calspan lower tibia force Fz for ankle inversion repeatability tests for Ankle EV2720

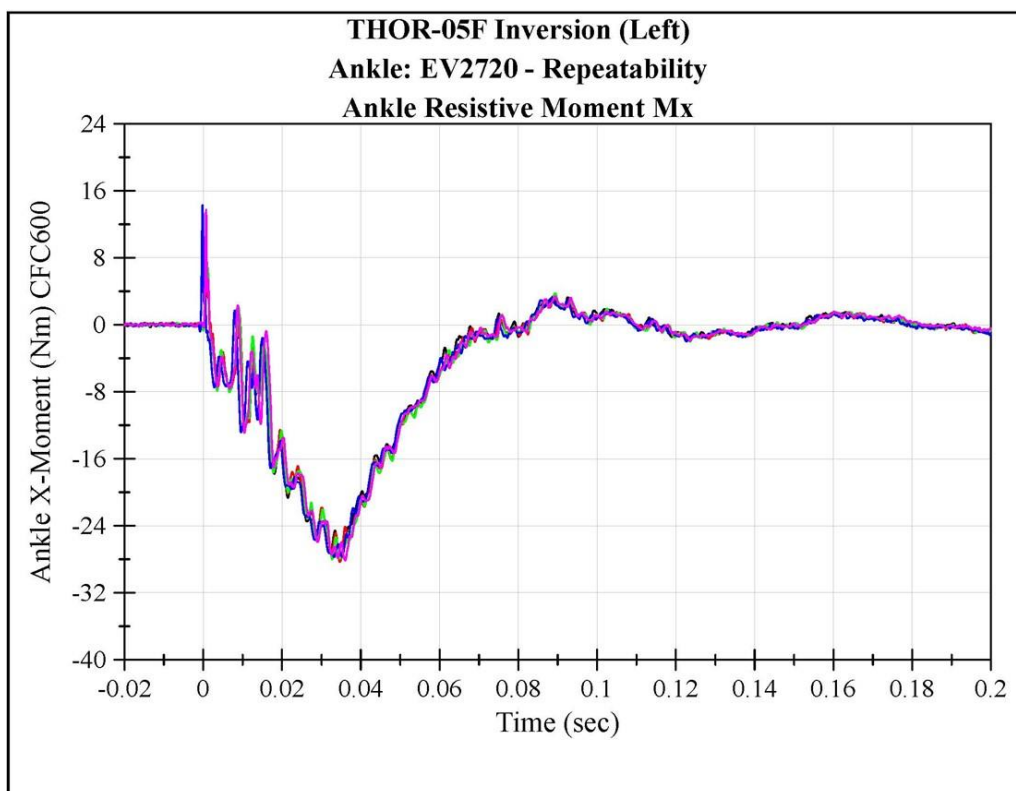


Figure 15-15. Calspan ankle resistive moment Mx for ankle inversion repeatability tests for Ankle EV2720

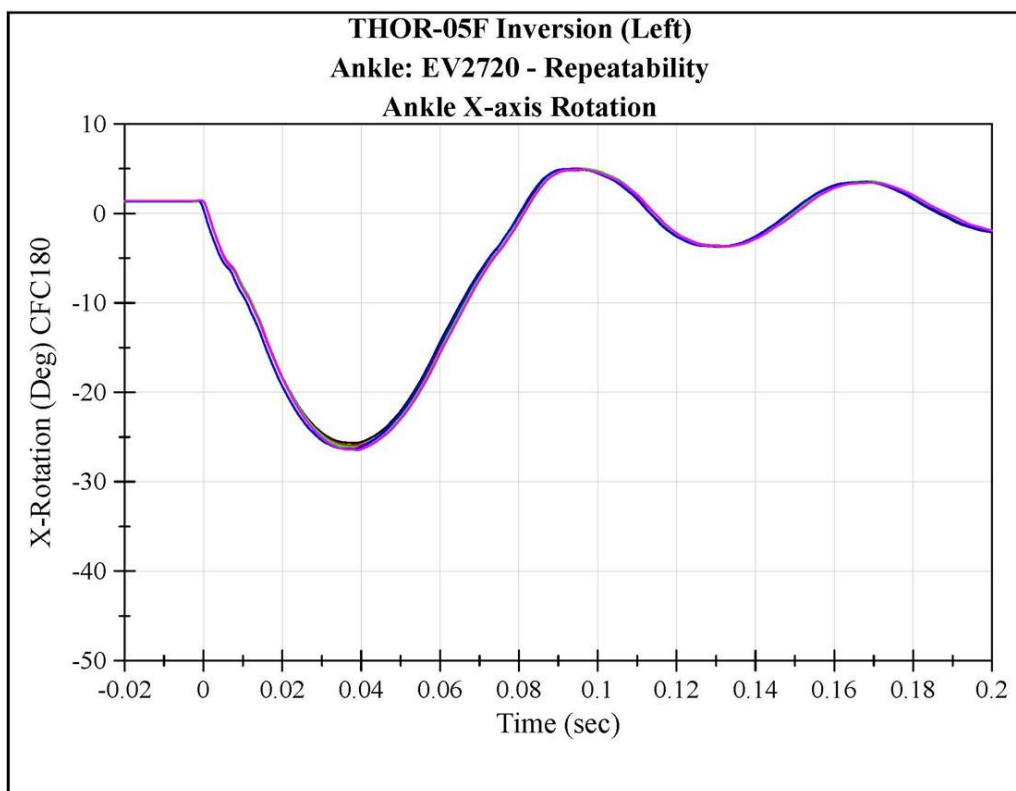


Figure 15-16. Calspan ankle X axis rotation for ankle inversion repeatability tests for Ankle EV2720

15.2.6 THOR-05F Left Ankle EV2720 Inversion Testing at TRC

Repeatability results for ankle inversion testing on Ankle EV2720 (removed from ATD EV4675, left side) at TRC yielded CV values below 5 percent (Table 15-6, Figure 15-17 through Figure 15-19).

Table 15-6. TRC THOR-05F Left Ankle Inversion Repeatability Results for Ankle EV2720

Test Number	Minimum Lower Tibia Fz (N)	Minimum Ankle M _x (Nm)	Minimum Ankle θ_x (deg)
2025_05_01 08_08	-307	-28.7	-28.3
2025_05_01 08_54	-316	-29.8	-28.8
2025_05_01 09_29	-322	-30.3	-28.9
2025_05_01 10_03	-322	-30.3	-29.0
2025_05_01 10_38	-316	-30.0	-28.9
Mean	-316	-29.8	-28.8
Standard Deviation	6.1	0.6	0.3
CV	1.9%	2.1%	0.9%

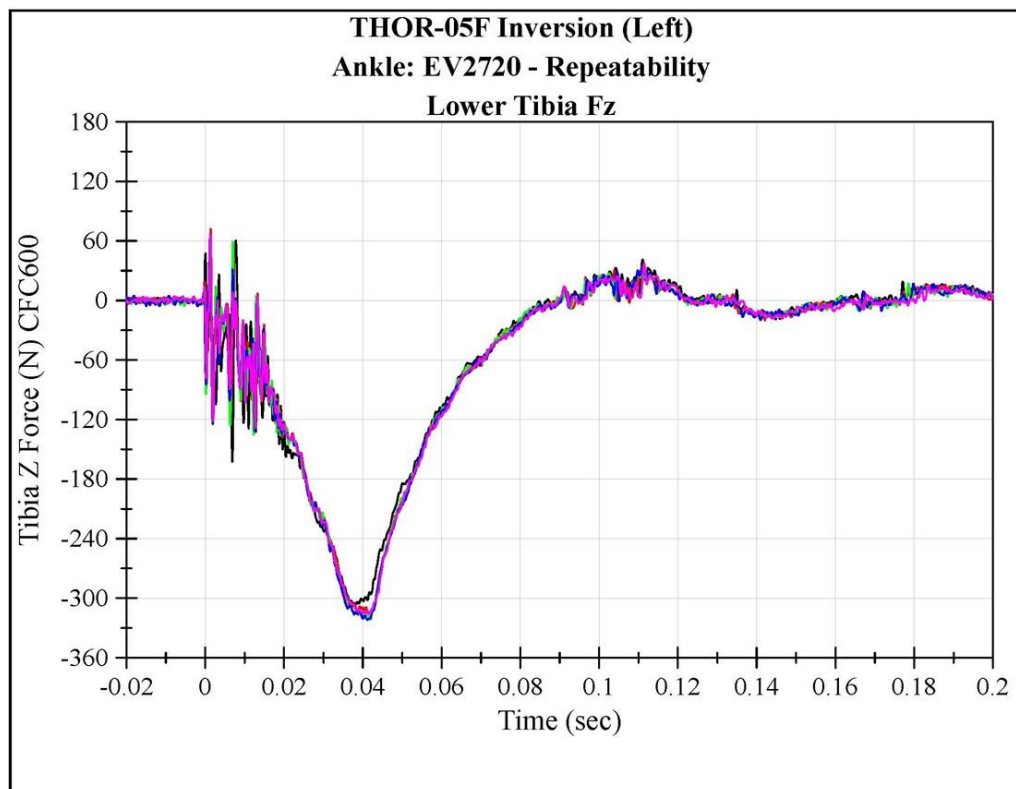


Figure 15-17. TRC lower tibia force Fz for ankle inversion repeatability tests for Ankle EV2720

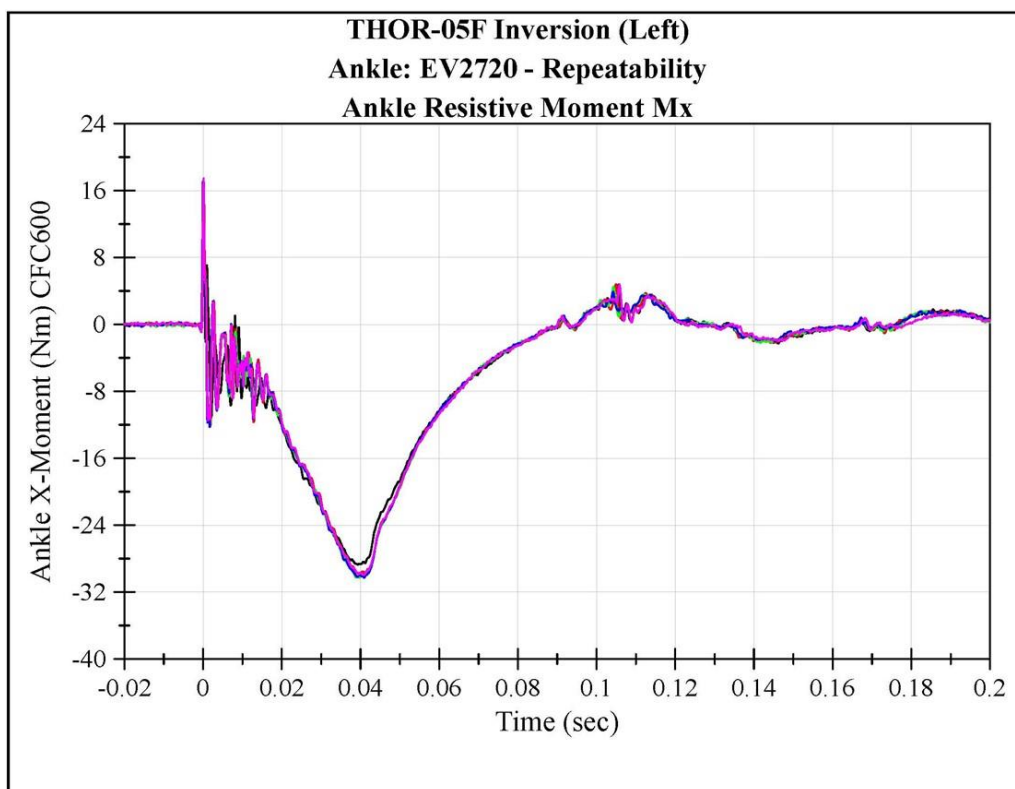


Figure 15-18. TRC ankle resistive moment M_x for ankle inversion repeatability tests for Ankle EV2720

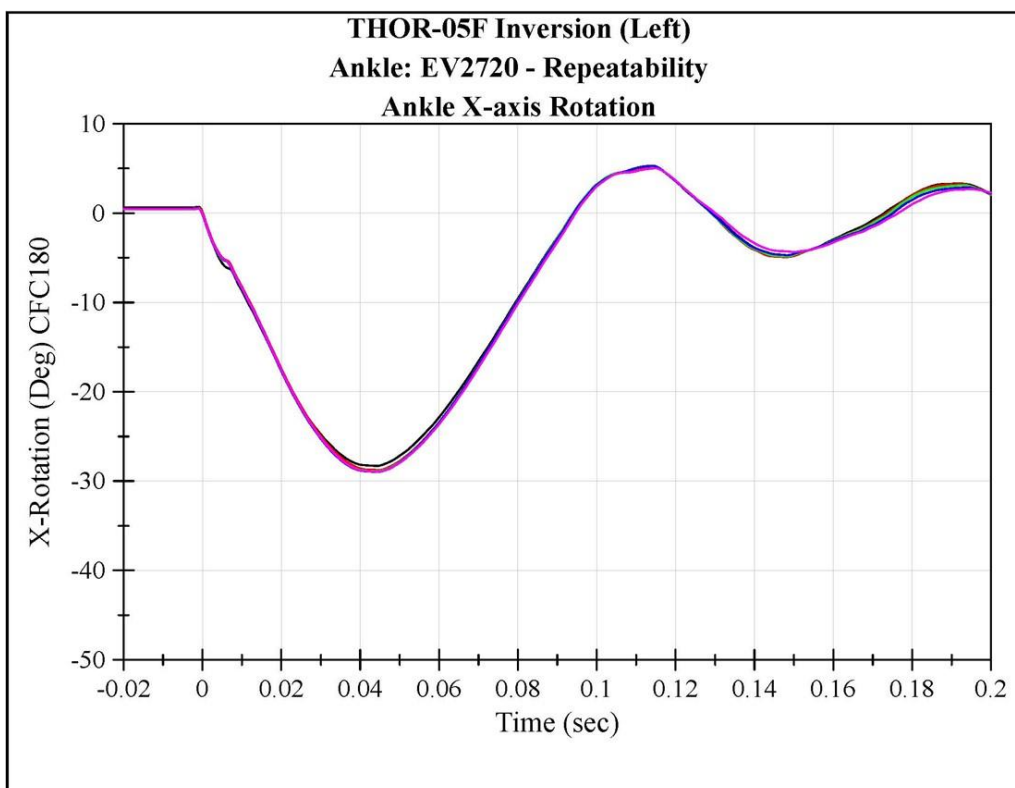


Figure 15-19. TRC ankle X axis rotation for ankle inversion repeatability tests for Ankle EV2720

15.3 Ankle Inversion Dummy Reproducibility Results

Dummy Reproducibility results at VRTC for the ankle inversion qualification tests displayed CV values all below 5 percent (Table 15-7).

Table 15-7. THOR-05F Ankle Inversion Qualification Reproducibility Results

Ankle Number	Test Number	Minimum Lower Tibia Fz (N)	Minimum Ankle M_x (Nm)	Minimum Ankle θ_x (deg)
VRTC EV4180	240523-5	-312	-28.2	-27.5
	240523-6	-306	-28.5	-27.5
	240523-13	-311	-28.5	-27.5
	240523-14	-309	-28.5	-27.5
	240523-16	-308	-28.7	-27.5
VRTC EV1130	240604-8	-320	-28.3	-27.6
	240604-9	-328	-28.7	-27.8
	240604-10	-325	-28.3	-27.8
	240605-1	-317	-27.9	-27.6
	240605-12	-318	-28.0	-27.7
VRTC EV2720	240910-9	-282	-27.4	-28.0
	240910-12	-285	-27.7	-28.2
	240910-13	-295	-28.3	-28.5
	240910-14	-296	-28.3	-28.5
	240910-15	-295	-28.6	-28.6
Mean		-307	-28.3	-27.9
Standard Deviation		14.0	0.4	0.4
CV		4.6%	1.3%	1.4%

15.4 Lab-to-Lab Variability

Test Reproducibility results for ankle inversion tests at all four labs yielded CV values below 5 percent, except for minimum lower tibia force, which was above 5 percent, but under 10 percent (Table 15-8).

Table 15-8. THOR-05F Ankle Inversion Qualification Reproducibility Results

Ankle Number	Test Number	Minimum Lower Tibia Fz (N)	Minimum Ankle M_x (Nm)	Minimum Ankle θ_x (deg)
VRTC EV2720	240910-9	-282	-27.4	-28.0
	240910-12	-285	-27.7	-28.2
	240910-13	-295	-28.3	-28.5
	240910-14	-296	-28.3	-28.5
	240910-15	-295	-28.6	-28.6
Humanetics EV2720	686064	-313	-28.9	-28.5
	686071	-315	-28.8	-28.5
	686056	-316	-29.2	-28.5
	686049	-314	-29.1	-28.4
	686018	-318	-29.3	-28.6
Calspan EV2720	2025_03_28 18_44	-350	-27.1	-25.7
	2025_03_28 19_16	-351	-28.3	-26.0
	2025_03_28 19_48	-356	-28.0	-26.2
	2025_03_28 20_20	-351	-27.7	-26.4
	2025_03_28 20_56	-363	-28.1	-26.4
TRC EV2720	2025_05_01 08_08	-307	-28.7	-28.3
	2025_05_01 08_54	-316	-29.8	-28.8
	2025_05_01 09_29	-322	-30.3	-28.9
	2025_05_01 10_03	-322	-30.3	-29.0
	2025_05_01 10_38	-316	-30.0	-28.9
Test Reproducibility EV2720				
Mean		-319	-28.7	-27.9
Standard Deviation		23.8	0.9	1.1
CV		7.5%	3.2%	3.9%

15.5 Corridor Development

All the data used to determine the ankle inversion qualification corridors is shown in Figure 15-9. The qualification corridors were calculated using the mean plus or minus 10 percent of the peak for the specified measured or calculated channels (Table 15-10 through Table 15-11).

Table 15-9. THOR-05F Ankle Inversion Qualification Corridor Results
(Highlighted values fell outside average $\pm 10\%$.)

Ankle Number	Test Number	Minimum Lower Tibia F _z (N)	Minimum Ankle M _x (Nm)	Minimum Ankle θ_x (deg)
VRTC EV4180	240523-5	-312	-28.2	-27.5
	240523-6	-306	-28.5	-27.5
	240523-13	-311	-28.5	-27.5
	240523-14	-309	-28.5	-27.5
	240523-16	-308	-28.7	-27.5
VRTC EV1130	240604-8	-320	-28.3	-27.6
	240604-9	-328	-28.7	-27.8
	240604-10	-325	-28.3	-27.8
	240605-1	-317	-27.9	-27.6
	240605-12	-318	-28.0	-27.7
VRTC EV2720	240910-9	-282	-27.4	-28.0
	240910-12	-285	-27.7	-28.2
	240910-13	-295	-28.3	-28.5
	240910-14	-296	-28.3	-28.5
	240910-15	-295	-28.6	-28.6
Humanetics EV2720	686064	-313	-28.9	-28.5
	686071	-315	-28.8	-28.5
	686056	-316	-29.2	-28.5
	686049	-314	-29.1	-28.4
	686018	-318	-29.3	-28.6
Calspan EV2720	2025_03_28 18_44	-350	-27.1	-25.7
	2025_03_28 19_16	-351	-28.3	-26.0
	2025_03_28 19_48	-356	-28.0	-26.2
	2025_03_28 20_20	-351	-27.7	-26.4
	2025_03_28 20_56	-363	-28.1	-26.4
TRC EV2720	2025_05_01 08_08	-307	-28.7	-28.3
	2025_05_01 08_54	-316	-29.8	-28.8
	2025_05_01 09_29	-322	-30.3	-28.9
	2025_05_01 10_03	-322	-30.3	-29.0
	2025_05_01 10_38	-316	-30.0	-28.9
Mean		-318	-28.6	-27.8
Standard Deviation		19.8	0.8	0.9
CV		6.2%	2.7%	3.3%

Table 15-10. Left Ankle Inversion Qualification Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Impact Velocity	m/s	1.95	2.05	2.00	
Minimum Lower Tibia F_z	N	-349	-286	-318	10%
Minimum Ankle Moment, M_x	Nm	-31.4	-25.7	-28.6	10%
Minimum Ankle Rotation, θ_x	deg	-30.6	-25.0	-27.8	10%

Table 15-11. Right Ankle Inversion Qualification Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Impact Velocity	m/s	1.95	2.05	2.00	
Minimum Lower Tibia F_z	N	-349	-286	-318	10%
Maximum Ankle Moment, M_x	Nm	25.7	31.4	28.6	10%
Maximum Ankle Rotation, θ_x	deg	25.0	30.6	27.8	10%

Discussion. Highlighted cells in Table 15-7 indicate test values that did not meet the respective target response $\pm 10\%$ in Table 15-10 and Table 15-11. Tibia force was non-conforming for all tests at Calspan (ankle EV2720), and two tests at VRTC for ankle EV2720; for those tests, the results were slightly below the lower corridors at both labs.

Repeatability results showed all CV values below 5 percent.

Dummy Reproducibility CV values were all below 5 percent.

In the case of *Test Reproducibility*, both X-axis resistive moment and X-axis rotation were below 5 percent. Minimum lower tibia force was above 5 percent, but below 10 percent, because all test at Calspan, and two tests at VRTC, were slightly outside of the corridor.

16 ANKLE EVERSION

16.1 Methodology

Repeatability and reproducibility tests were performed using the ankle eversion qualification procedures described in the *THOR-05F Qualification Procedures and Requirements*. The ankle eversion qualification consists of impact to an inversion/eversion bracket (TH-1603-0675) which is temporarily attached to the bottom of the ankle assembly in place of the molded shoe (Figure 16-1). The impact surface of the bracket is covered with PTFE 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 lower tibia load cell 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-9000-007, TLX-9000-006), as described in *THOR-05F Drawing Package*, with an effective mass of 3.00 ± 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 force (F_z) and X-axis rotation were measured; the ankle resistive moment about the X-axis was calculated from F_y and M_x .

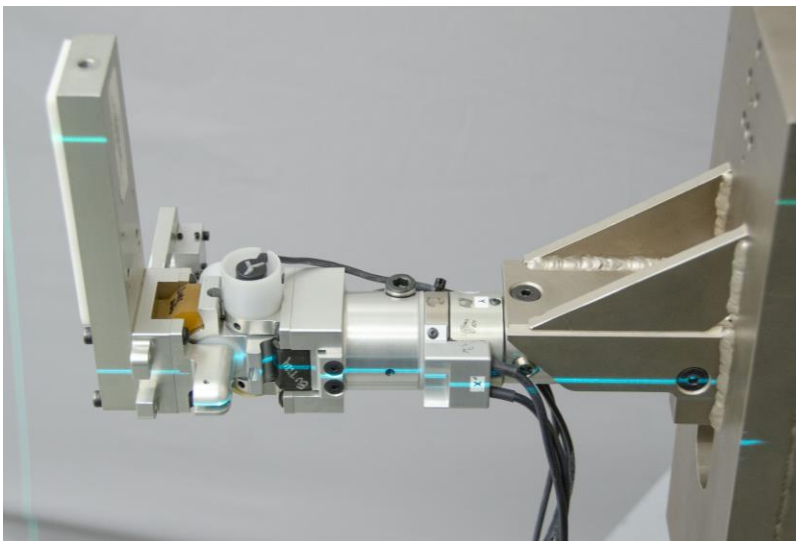


Figure 16-1. Ankle Eversion Test

16.2 Ankle Eversion Repeatability Results

Sections 16.2.1 through 16.2.6 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 four labs. Since this is a component-level test and the left and right side designs are symmetric, only the left ankle was tested. 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-05F Left Ankle EV4180 Eversion Testing at VRTC

Repeatability results for ankle eversion testing on Ankle EV4180 (removed from ATD EV0668, left side) at VRTC yielded CV values below 5 percent (Table 16-1, Figure 16-2 through Figure 16-4).

Table 16-1. VRTC THOR-05F Left Ankle Eversion Repeatability Results for EV4180

Test Number	Minimum Lower Tibia Fz (N)	Maximum Ankle M _x (Nm)	Maximum Ankle θ_x (deg)
240523-21	-297	28.3	26.5
240523-22	-307	29.3	26.8
240523-27	-306	29.2	26.9
240528-4	-298	28.5	26.6
240528-5	-319	28.7	27.0
Mean	-305	28.3	28.0
Standard Deviation	9.0	0.5	0.2
CV	2.9%	1.5%	0.7%

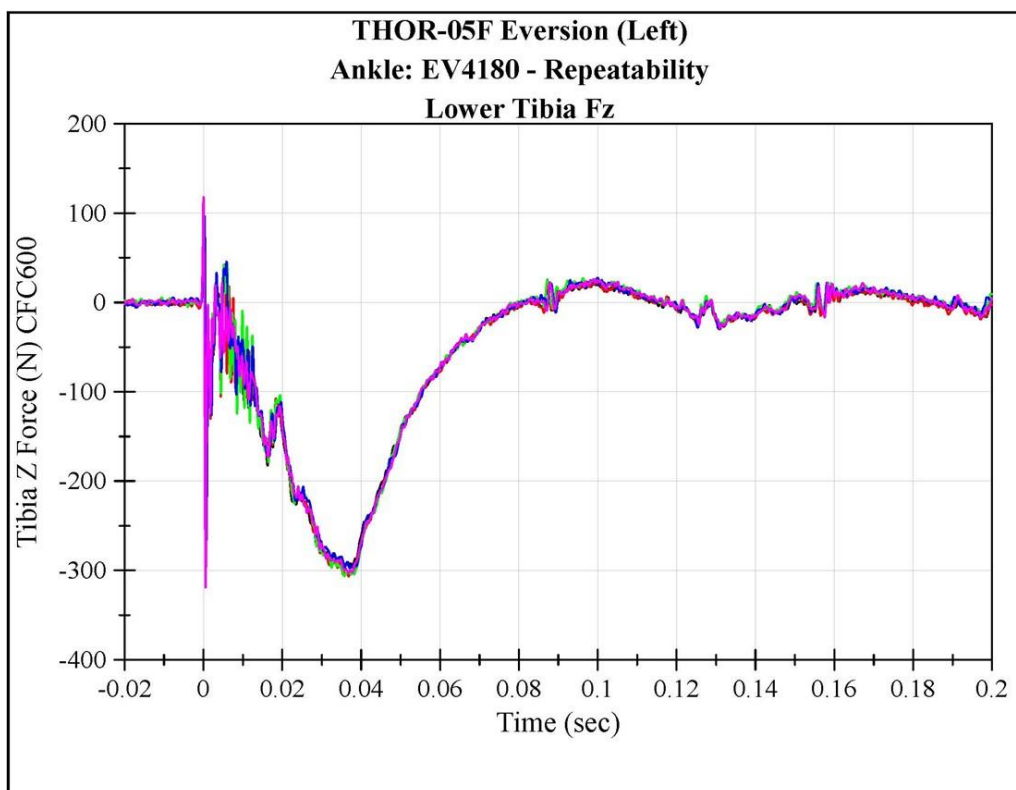


Figure 16-2. VRTC lower tibia force Fz for ankle eversion repeatability tests for EV4180

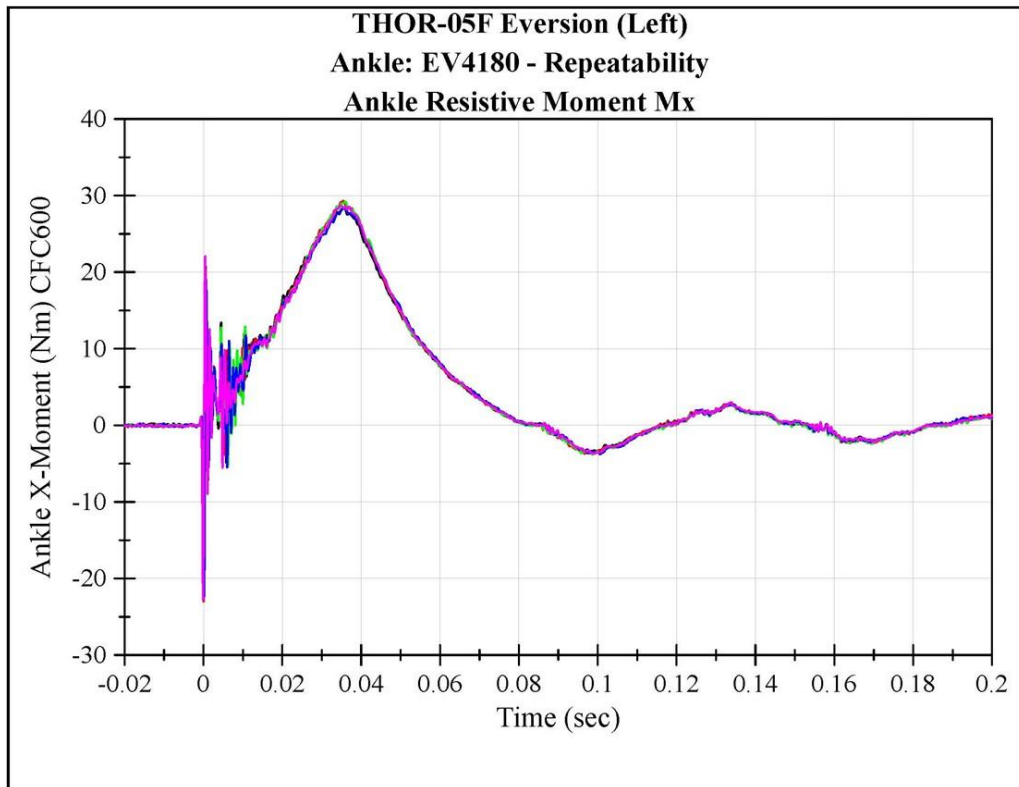


Figure 16-3. VRTC ankle resistive moment Mx for ankle eversion repeatability tests for EV4180

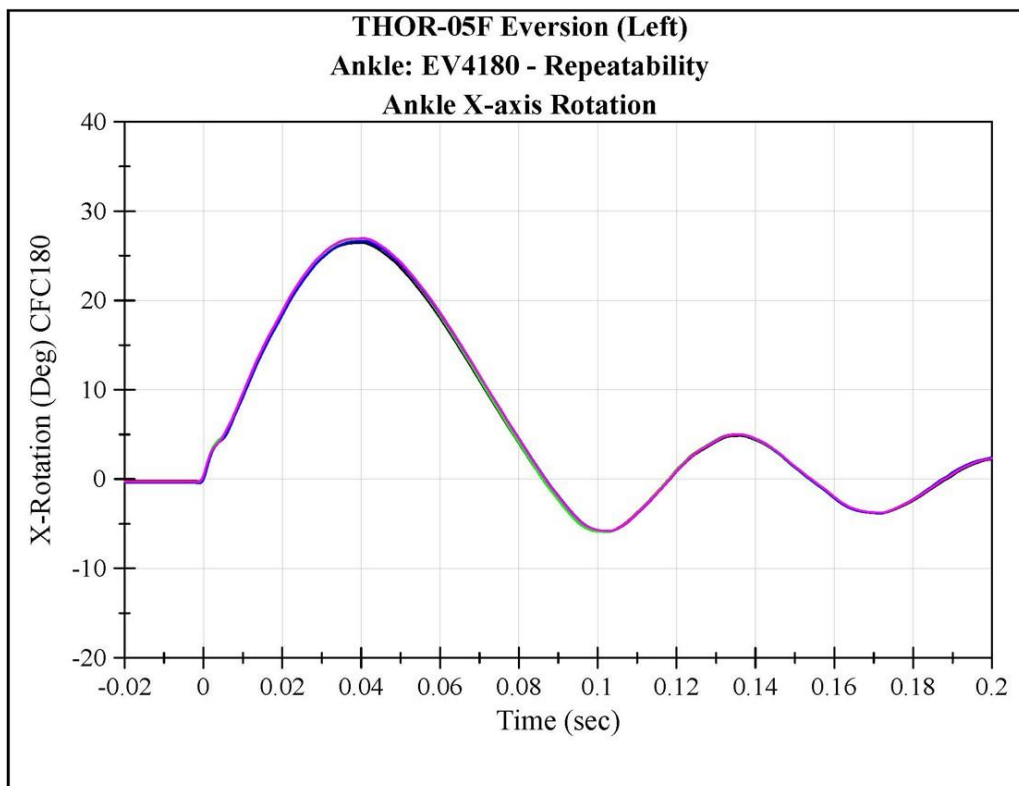


Figure 16-4. VRTC ankle X axis rotation for ankle eversion repeatability tests for EV4180

16.2.2 THOR-05F Left Ankle EV1130 Eversion Testing at VRTC

Repeatability results for ankle eversion testing on Ankle EV1130 (removed from ATD EV0674, left side) at VRTC yielded CV values below 5 percent (Table 16-2, Figure 16-5 through Figure 16-7).

Table 16-2. VRTC THOR-05F Left Ankle Eversion Repeatability Results for EV1130

Test Number	Minimum Lower Tibia Fz (N)	Maximum Ankle M _x (Nm)	Maximum Ankle θ_x (deg)
240605-2	-302	27.6	27.8
240605-3	-303	28.3	28.0
240605-4	-308	28.4	28.1
240605-5	-305	28.3	28.1
240605-6	-307	28.4	28.1
Mean	-305	28.2	28.0
Standard Deviation	2.6	0.3	0.2
CV	0.8%	1.2%	0.6%

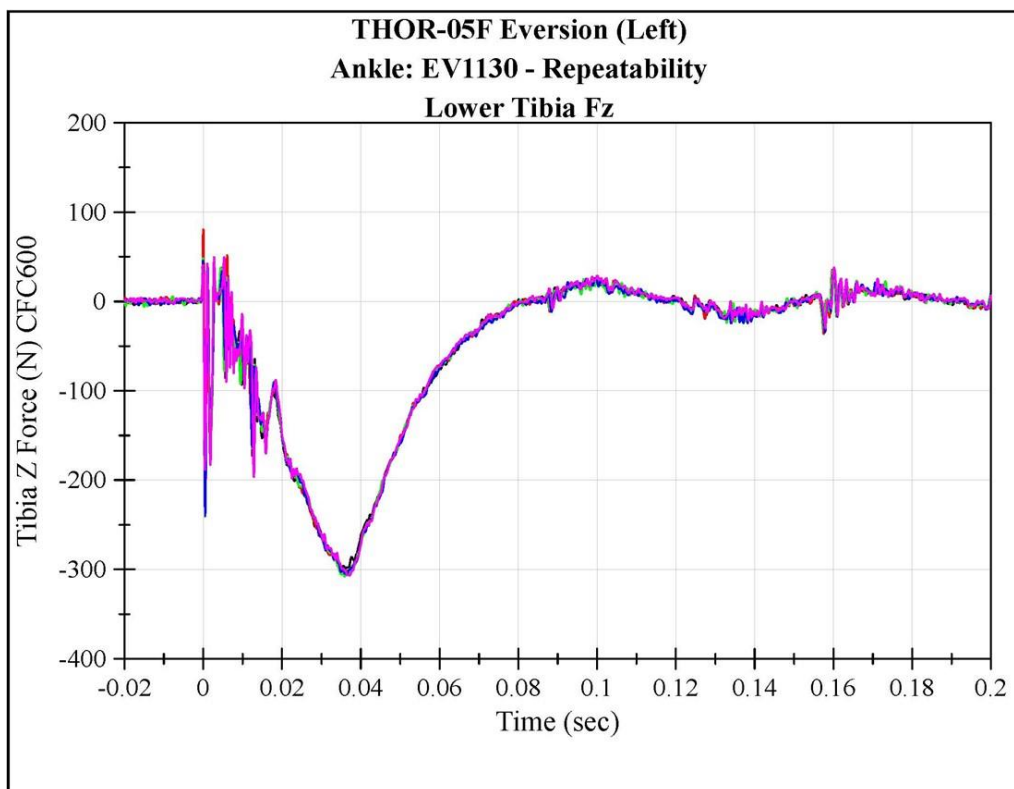


Figure 16-5. VRTC lower tibia force Fz for ankle eversion repeatability tests for EV1130

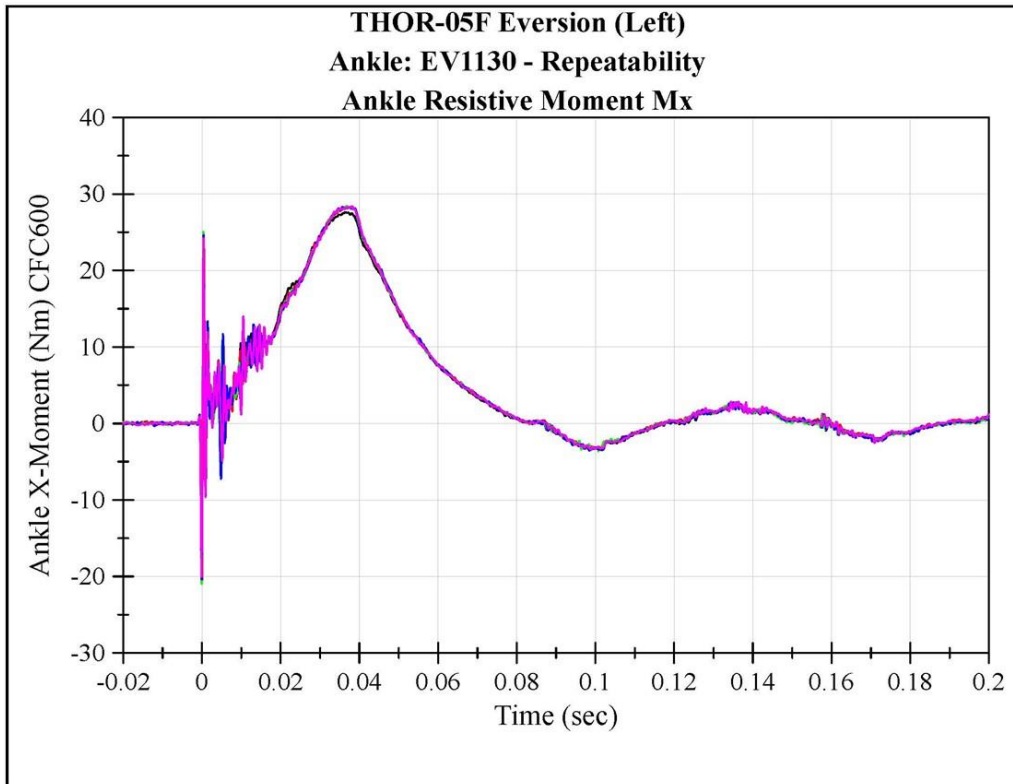


Figure 16-6. VRTC ankle resistive moment Mx for ankle eversion repeatability tests for EV1130

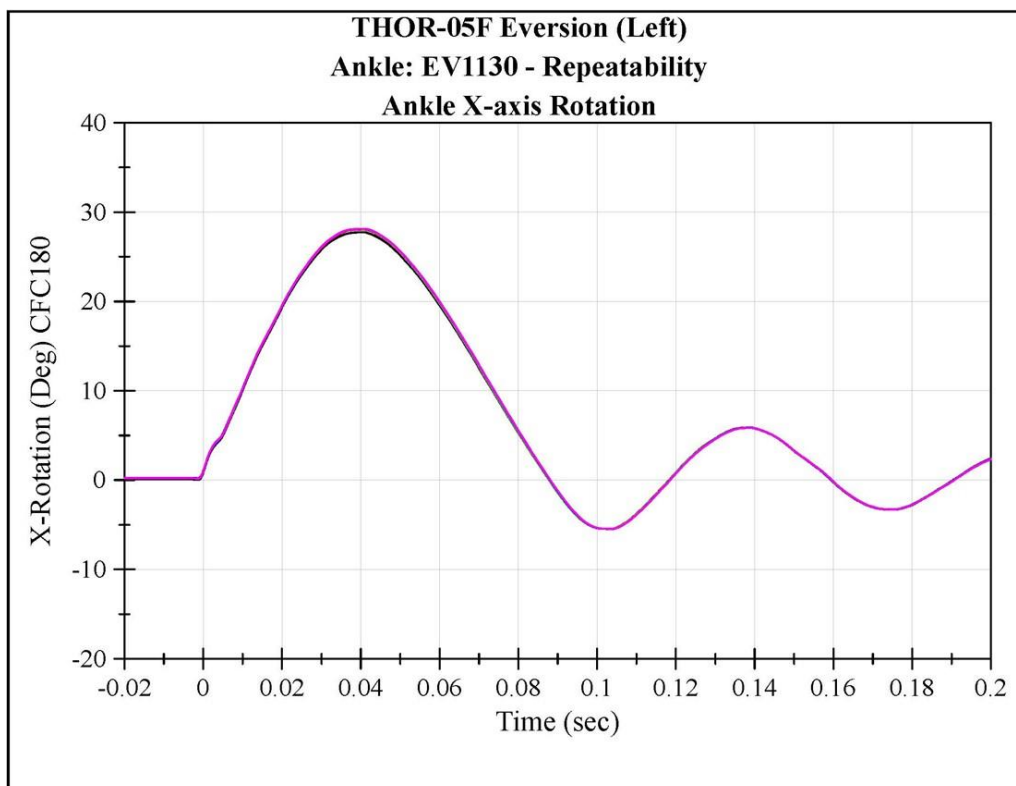


Figure 16-7. VRTC ankle X axis rotation for ankle eversion repeatability tests for EV1130

16.2.3 THOR-05F Left Ankle EV2720 Eversion Testing at VRTC

Repeatability results for ankle testing on Ankle EV2720 (removed from ATD EV4675, left side) at VRTC yielded CV values below 5 percent (Table 16-3 and Figure 16-8 through Figure 16-10).

Table 16-3. VRTC THOR-05F Left Ankle Eversion Repeatability Results for EV2720

Test Number	Minimum Lower Tibia Fz (N)	Maximum Ankle M _x (Nm)	Maximum Ankle θ_x (deg)
240911-8	-291	27.3	27.7
240911-9	-304	28.4	28.0
240911-10	-305	28.5	28.1
240911-11	-307	28.7	28.1
240911-12	-312	28.4	28.2
Mean	-304	28.3	28.0
Standard Deviation	7.8	0.5	0.2
CV	2.6%	1.9%	0.7%

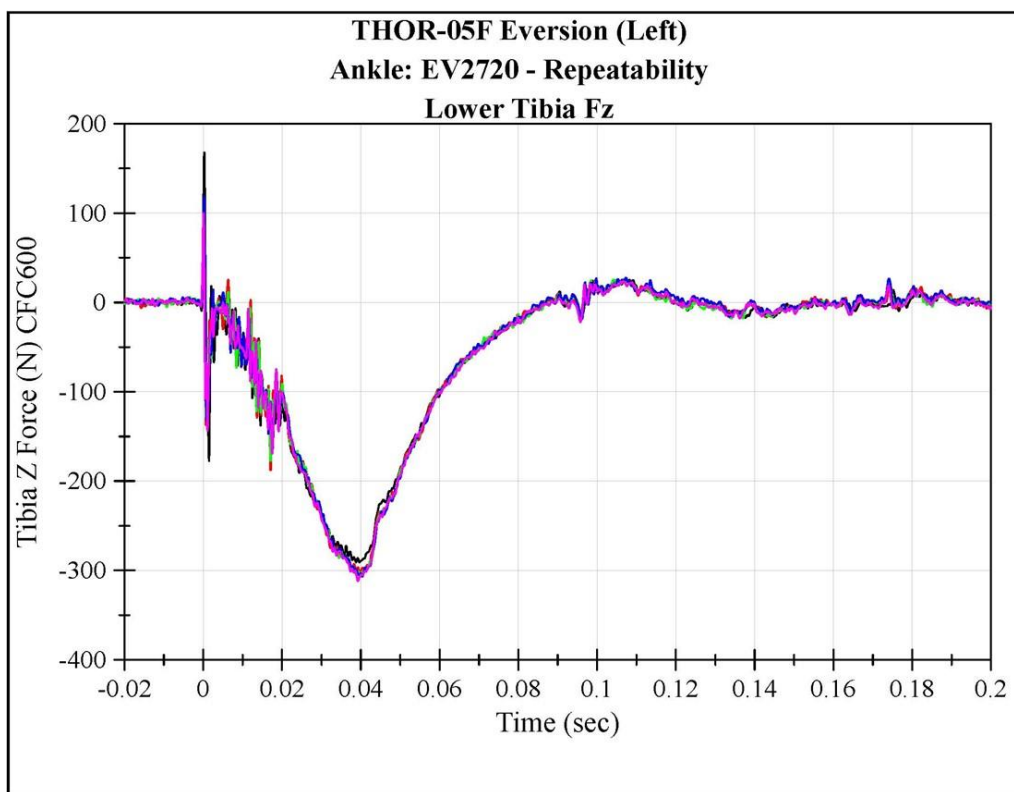


Figure 16-8. VRTC lower tibia force Fz for ankle eversion repeatability tests for EV2720

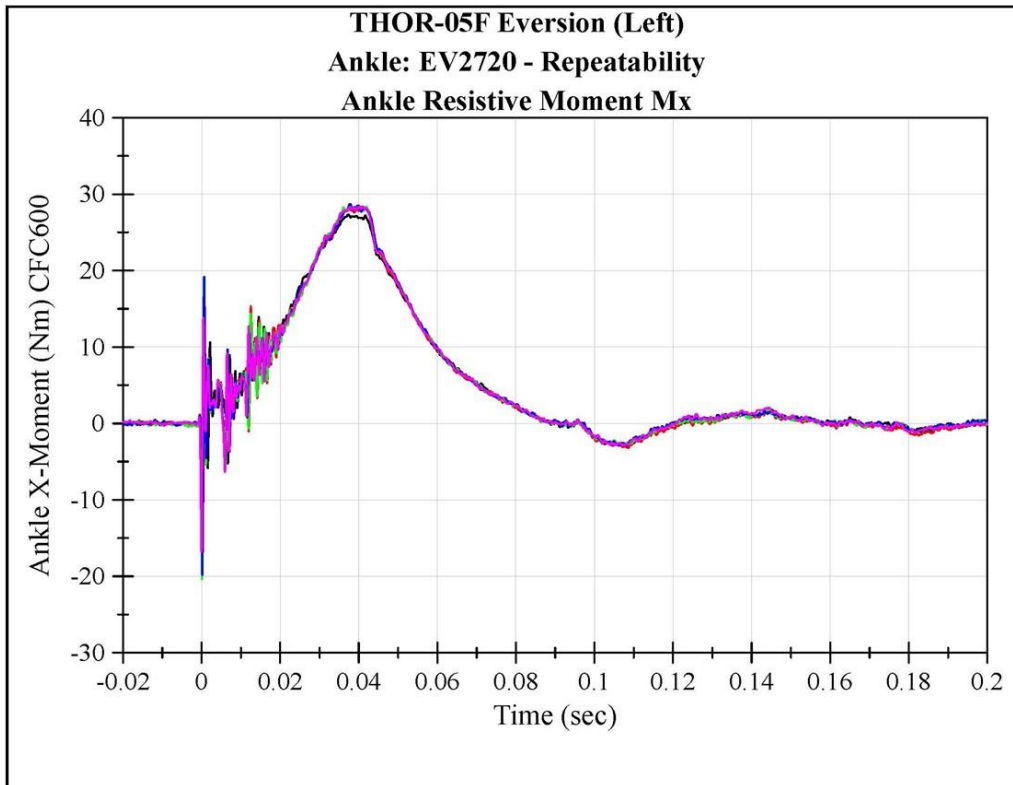


Figure 16-9. VRTC ankle resistive moment Mx for ankle eversion repeatability tests for EV2720

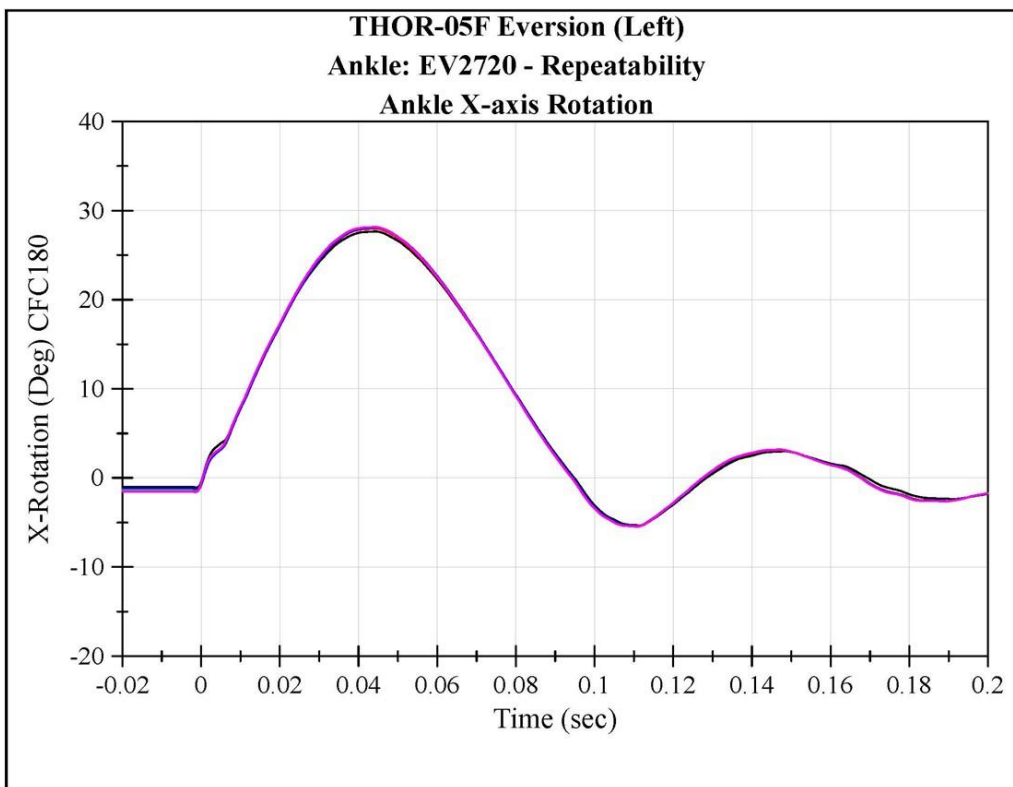


Figure 16-10. VRTC ankle X axis rotation for ankle eversion repeatability tests for EV2720

16.2.4 THOR-05F Left Ankle EV2720 Eversion Testing at Humanetics

Repeatability results for ankle testing on Ankle EV2720 (removed from ATD EV4675, left side) at Humanetics yielded CV values below 5 percent (Table 16-4, Figure 16-11 through Figure 16-13). Ankle data was not collected past 0.12 s at Humanetics, but this difference did not affect the R&R analysis.

Table 16-4. Humanetics THOR-05F Left Ankle Eversion Repeatability Results for EV2720

Test Number	Minimum Lower Tibia F _z (N)	Maximum Ankle M _x (Nm)	Maximum Ankle θ_x (deg)
685931	-328	29.6	27.6
685905	-326	29.6	27.6
685889	-325	29.2	27.4
685897	-323	29.4	27.6
685866	-324	29.5	27.6
Mean	-325	29.4	27.5
Standard Deviation	1.9	0.2	0.1
CV	0.6%	0.6%	0.2%

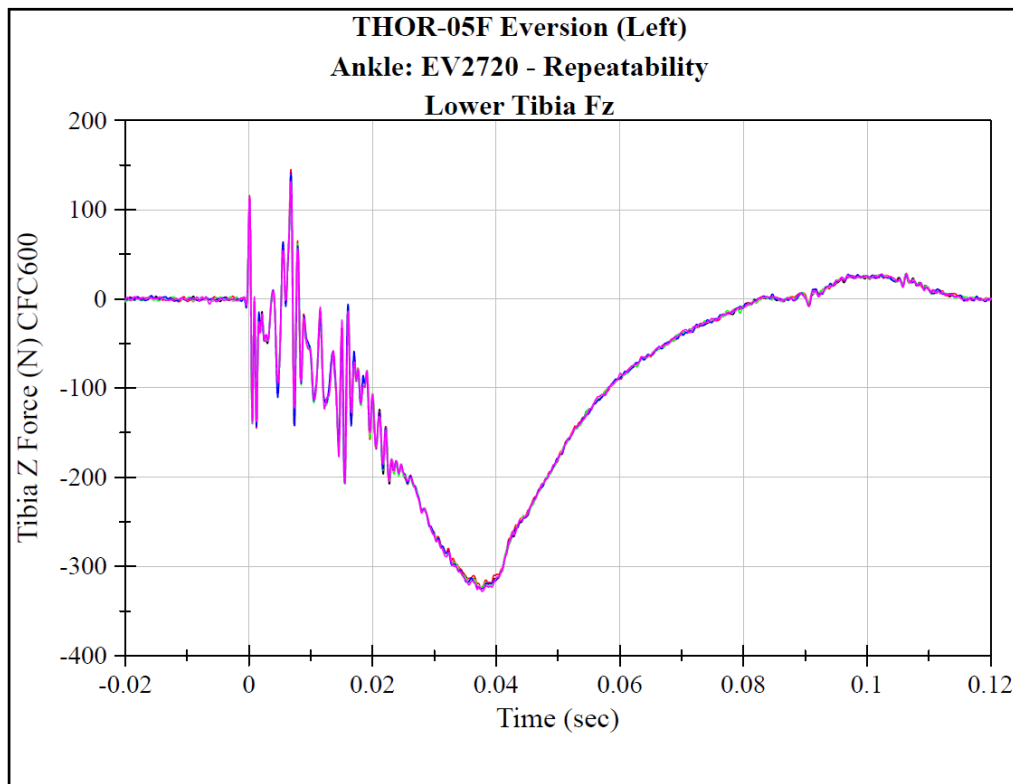


Figure 16-11. Humanetics lower tibia force Fz for ankle eversion repeatability tests for EV2720

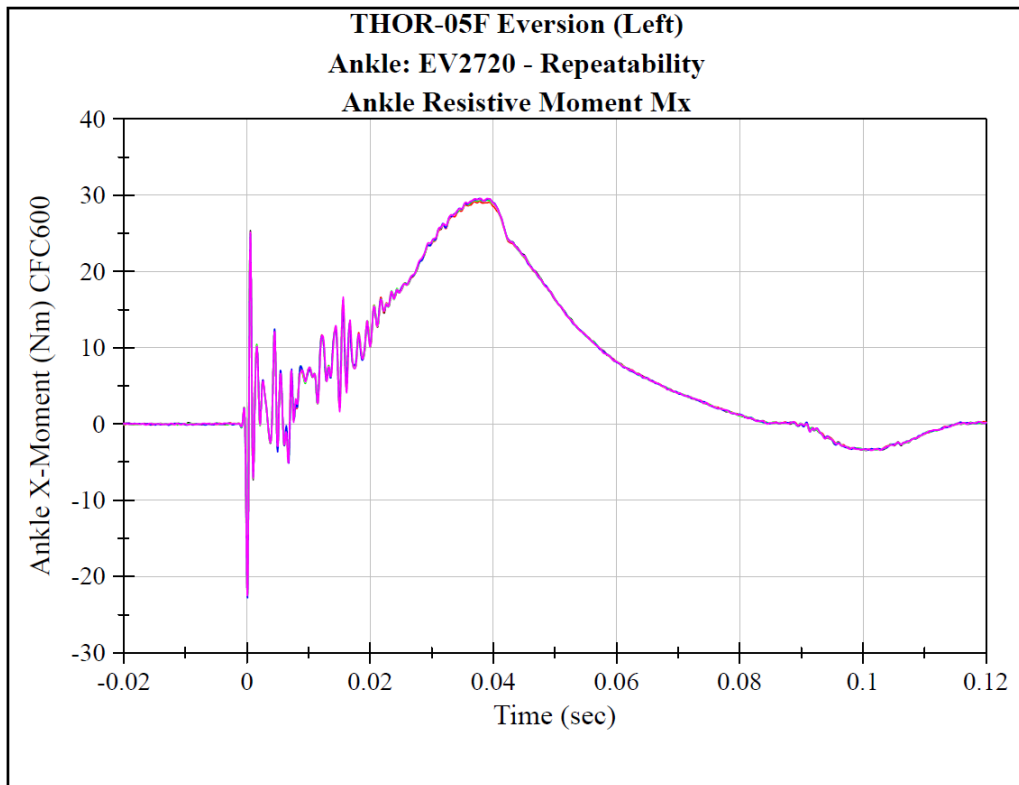


Figure 16-12. Humanetics ankle resistive moment Mx for ankle eversion repeatability tests for EV2720

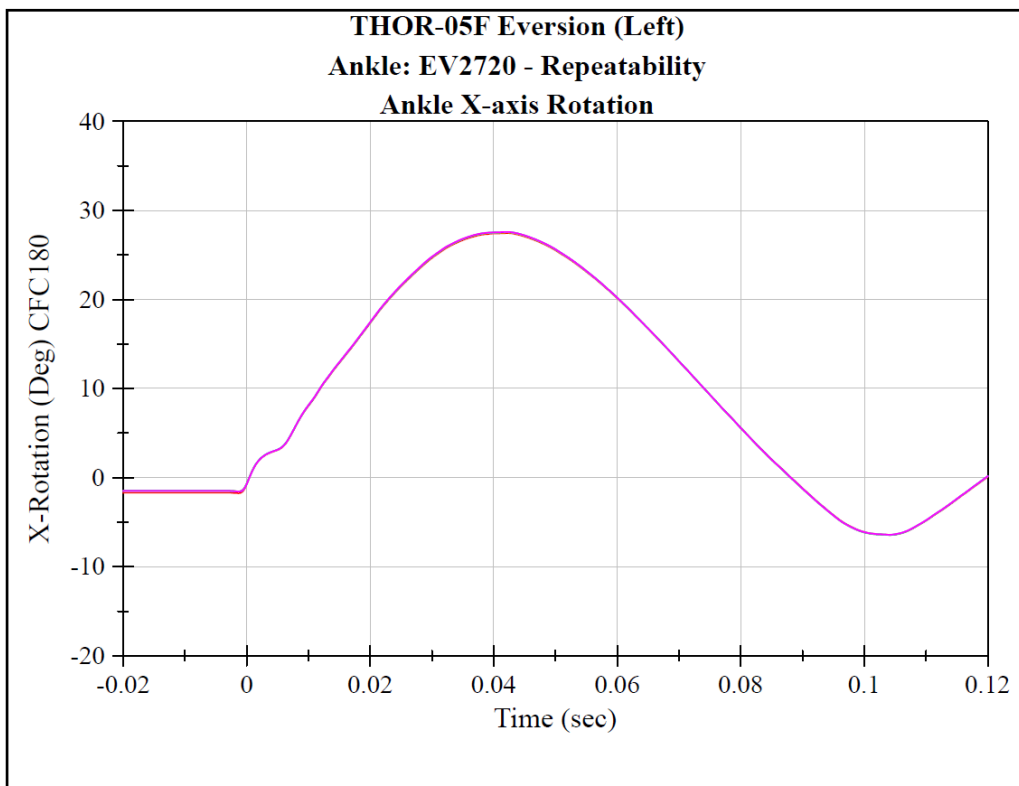


Figure 16-13. Humanetics ankle X-axis rotation for ankle eversion repeatability tests for EV2720

16.2.5 THOR-05F Left Ankle EV2720 Eversion Testing at Calspan

Repeatability results for ankle testing on Ankle EV2720 (removed from ATD EV4675, left side) at Calspan yielded CV values below 5 percent (Table 16-5, Figure 16-14 through Figure 16-16).

Table 16-5. Calspan THOR-05F Left Ankle Eversion Repeatability Results for EV2720

Test Number	Minimum Lower Tibia Fz (N)	Maximum Ankle M _x (Nm)	Maximum Ankle θ_x (deg)
2025_03_28_18_31	-387	30.2	26.9
2025_03_28_19_03	-365	29.1	26.6
2025_03_28_19_37	-357	28.9	26.8
2025_03_28_20_10	-382	29.7	26.8
2025_03_28_20_44	-360	29.5	26.7
Mean	-370	29.5	26.8
Standard Deviation	13.4	0.5	0.1
CV	3.6%	1.7%	0.4%

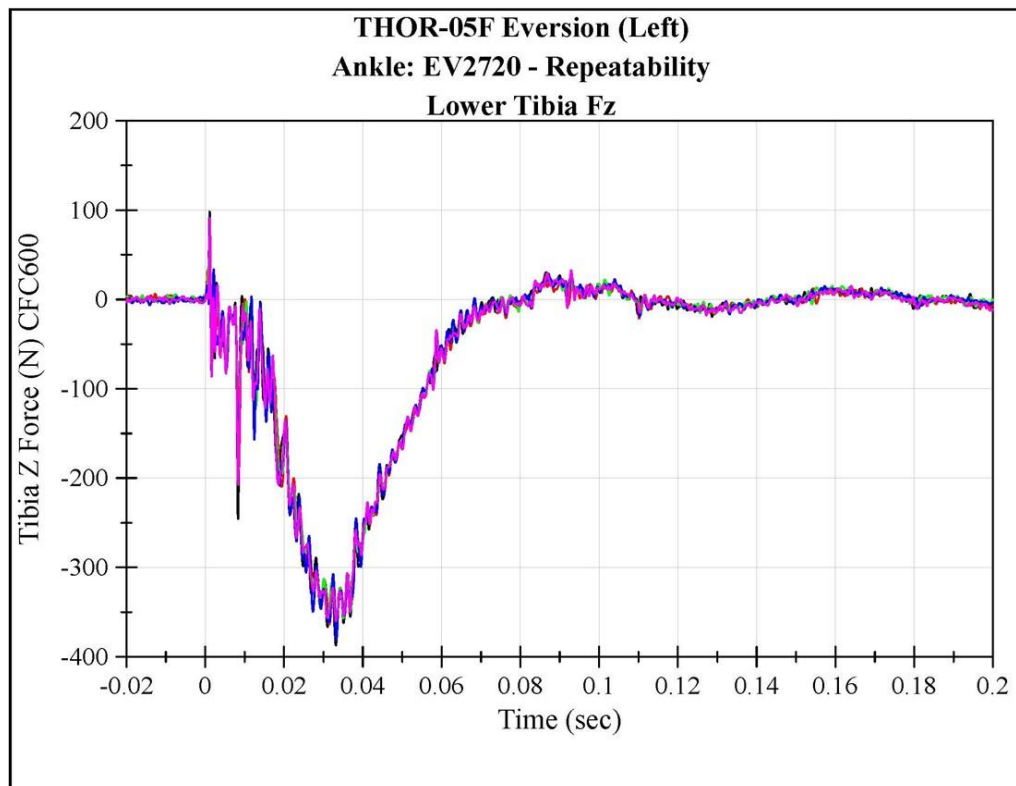


Figure 16-14. Calspan lower tibia force Fz for ankle eversion repeatability tests for EV2720

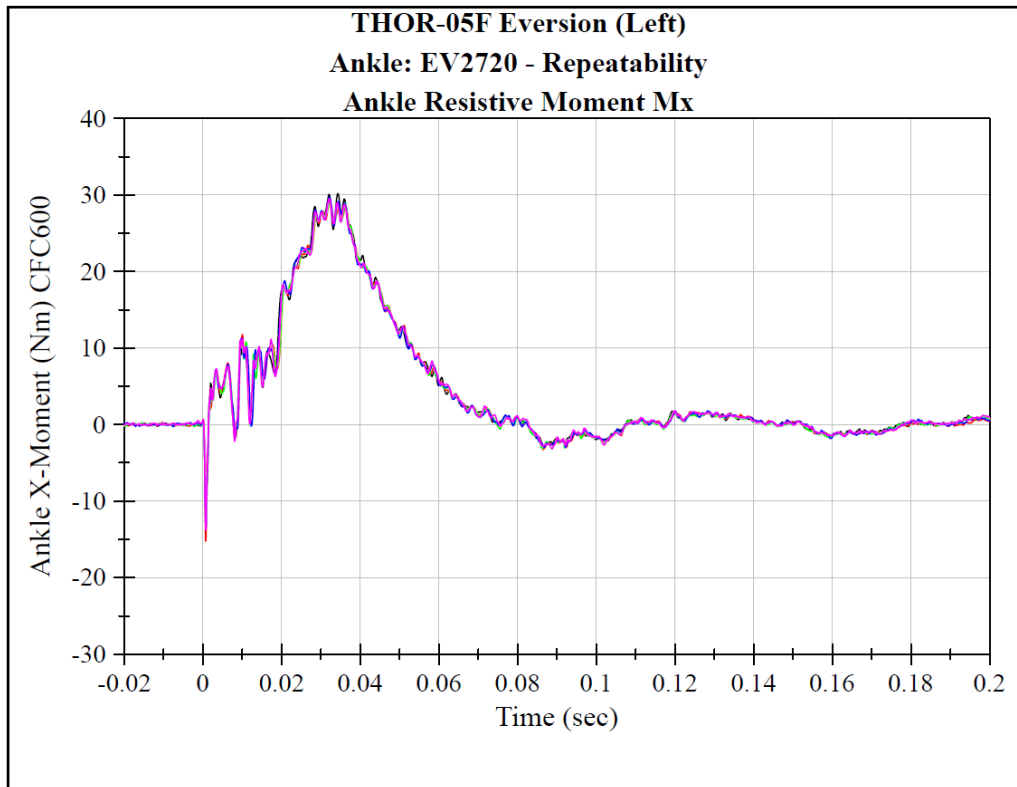


Figure 16-15. Calspan ankle resistive moment Mx for ankle eversion repeatability tests for EV2720

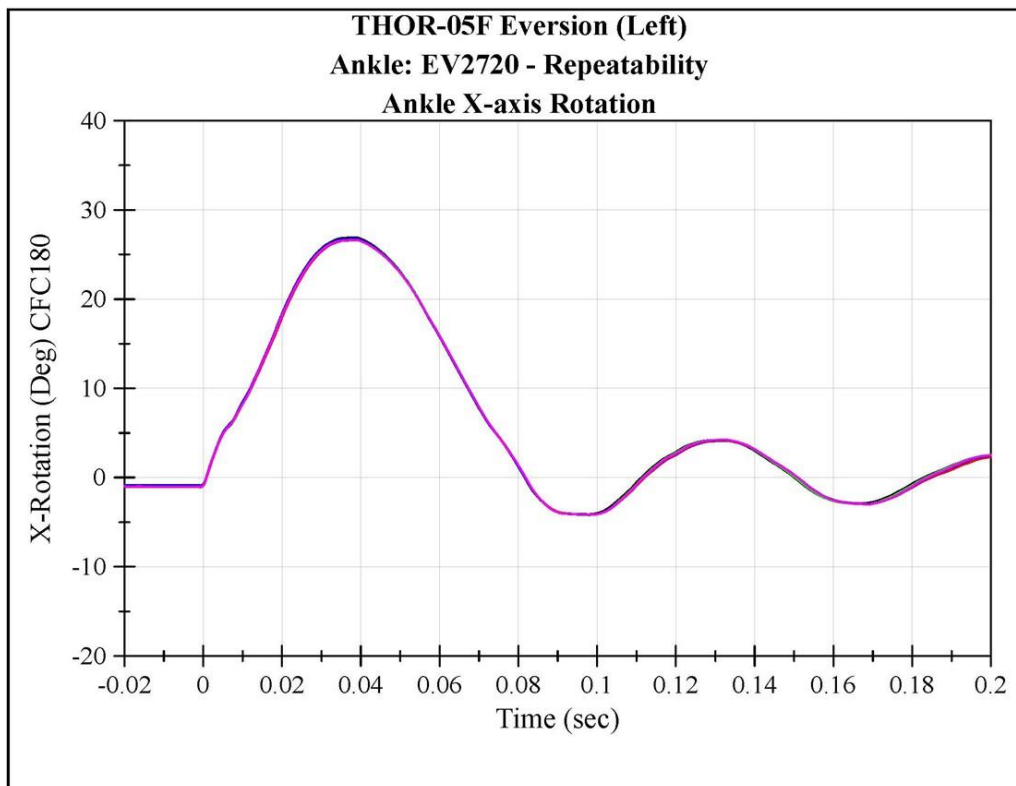


Figure 16-16. Calspan ankle X axis rotation for ankle eversion repeatability tests for EV2720

16.2.6 THOR-05F Left Ankle EV2720 Eversion Testing at TRC

Repeatability results for ankle eversion testing on Ankle EV2720 (removed from ATD EV4675, left side) at TRC yielded CV values below 5 percent (Table 16-6, Figure 16-17 through Figure 16-19).

Table 16-6. TRC THOR-05F Left Ankle Eversion Repeatability Results for EV2720

Test Number	Minimum Lower Tibia Fz (N)	Maximum Ankle M _x (Nm)	Maximum Ankle θ_x (deg)
2025_04_30 10_18	-310	29.6	28.1
2025_04_30 11_19	-318	30.5	28.3
2025_04_30 13_17	-320	30.8	28.4
2025_04_30 14_22	-320	30.8	28.5
2025_04_30 14_59	-323	30.9	28.5
Mean	-318	30.5	28.3
Standard Deviation	5.2	0.5	0.2
CV	1.6%	1.8%	0.6%

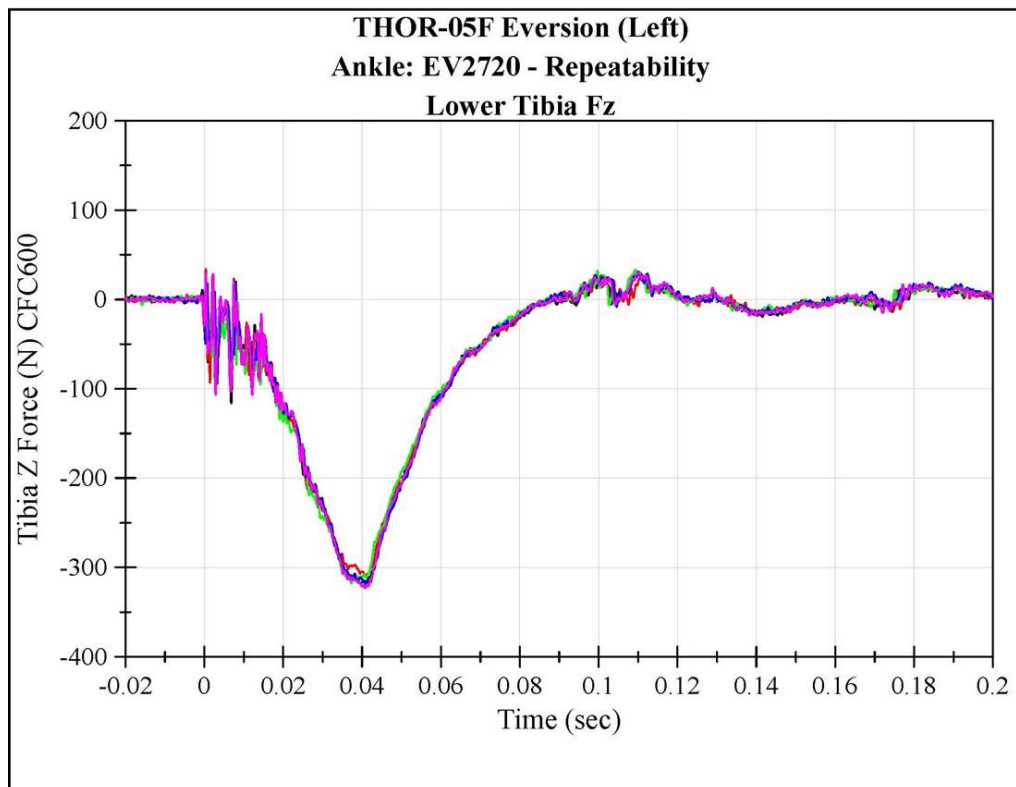


Figure 16-17. TRC lower tibia force Fz for ankle eversion repeatability tests for EV2720

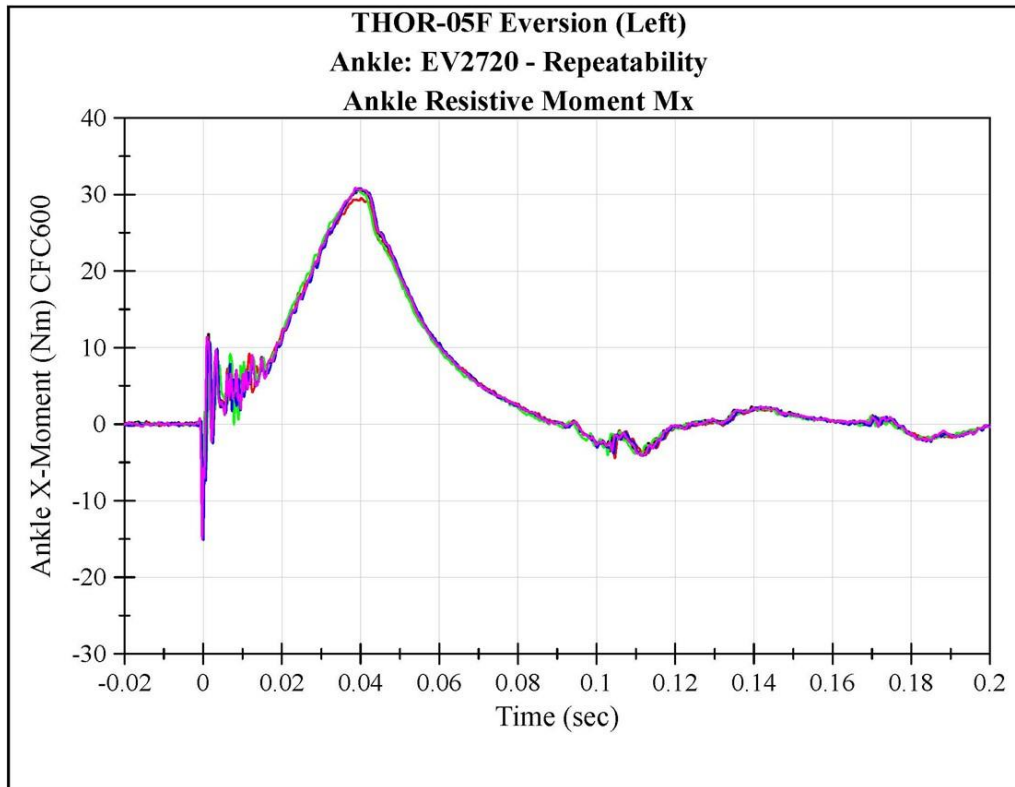


Figure 16-18. TRC ankle resistive moment Mx for ankle eversion repeatability tests for EV2720

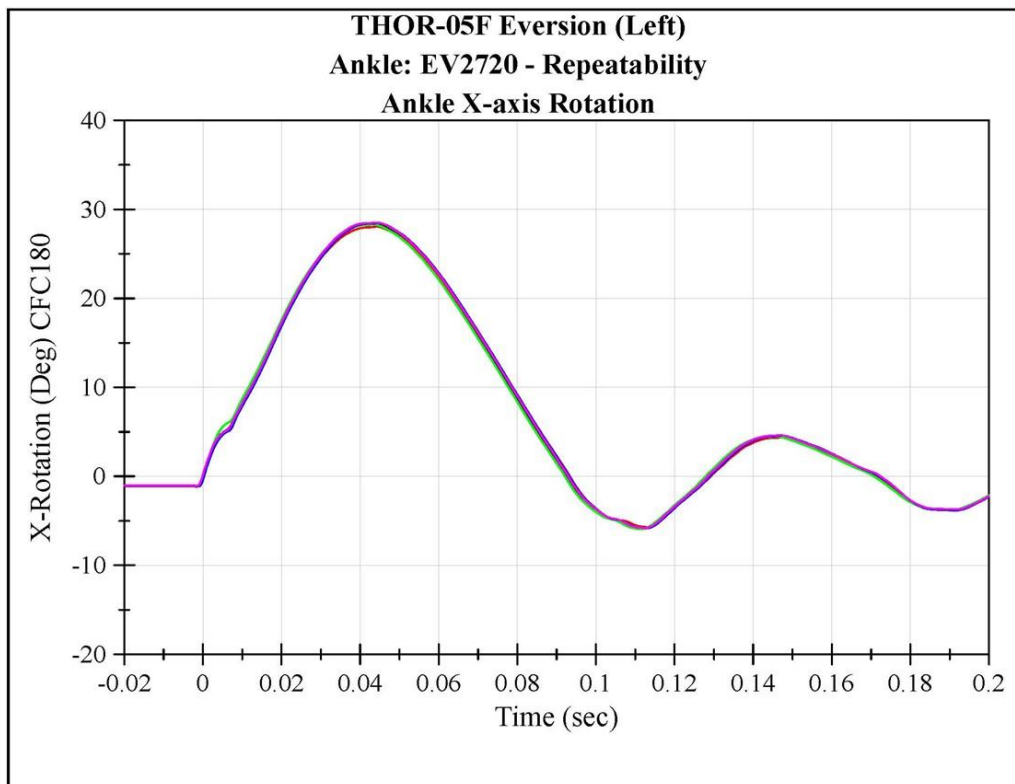


Figure 16-19. TRC ankle X axis rotation for ankle eversion repeatability tests for EV2720

16.3 Ankle Eversion Dummy Reproducibility Results

Dummy Reproducibility results at VRTC for the ankle eversion qualification tests displayed CV values all below 5 percent (Table 16-7).

Table 16-7. THOR-05F Ankle Eversion Reproducibility Results

Ankle Number	Test Number	Minimum Lower Tibia Fz (N)	Maximum Ankle Mx (Nm)	Maximum Ankle θ_x (deg)
VRTC EV4180	240523-21	-297	28.3	26.5
	240523-22	-307	29.3	26.8
	240523-27	-306	29.2	26.9
	240528-4	-298	28.5	26.6
	240528-5	-319	28.7	27.0
VRTC EV1130	240605-2	-302	27.6	27.8
	240605-3	-303	28.3	28.0
	240605-4	-308	28.4	28.1
	240605-5	-305	28.3	28.1
	240605-6	-307	28.4	28.1
VRTC EU2720	240911-8	-291	27.3	27.7
	240911-9	-304	28.4	28.0
	240911-10	-305	28.5	28.1
	240911-11	-307	28.7	28.1
	240911-12	-312	28.4	28.2
Mean		-305	28.4	27.6
Standard Deviation		6.5	0.5	0.6
CV		2.1%	1.7%	2.3%

16.4 Lab-to-Lab Variability

Test Reproducibility results at all four labs for ankle eversion tests yielded CV values below 5 percent, except for minimum lower tibia Z-axis force, which was over 5 percent, but under 10 percent (Figure 16-8).

Table 16-8. THOR-05F Ankle Eversion Qualification Reproducibility Results

Ankle Number	Test Number	Minimum Lower Tibia Fz (N)	Maximum Ankle M_x (Nm)	Maximum Ankle θ_x (deg)
VRTC EV2720	240911-8	-291	27.3	27.7
	240911-9	-304	28.4	28.0
	240911-10	-305	28.5	28.1
	240911-11	-307	28.7	28.1
	240911-12	-312	28.4	28.2
Humanetics EV2720	685931	-328	29.6	27.6
	685905	-326	29.6	27.6
	685889	-325	29.2	27.4
	685897	-323	29.4	27.6
	685866	-324	29.5	27.6
Calspan EV2720	2025_03_28_18_31	-387	30.2	26.9
	2025_03_28_19_03	-365	29.1	26.6
	2025_03_28_19_37	-357	28.9	26.8
	2025_03_28_20_10	-382	29.7	26.8
	2025_03_28_20_44	-360	29.5	26.7
TRC EV2720	2025_04_30_10_18	-310	29.6	28.1
	2025_04_30_11_19	-318	30.5	28.3
	2025_04_30_13_17	-320	30.8	28.4
	2025_04_30_14_22	-320	30.8	28.5
	2025_04_30_14_59	-323	30.9	28.5
Test Reproducibility EV2720				
Mean		-329	29.4	27.7
Standard Deviation		26.6	0.9	0.6
CV		8.1%	3.1%	2.3%

16.5 Corridor Development

All the data used to determine the ankle eversion qualification corridors is shown in Table 16-9. The qualification corridors were calculated using the mean plus or minus 10 percent of the peak for the specified measured or calculated channels (Table 16-10 and Table 16-11).

Table 16-9. THOR-05F Ankle Eversion Qualification Reproducibility Results
(Highlighted values fell outside average $\pm 10\%$.)

Ankle Number	Test Number	Minimum Lower Tibia F _z (N)	Maximum Ankle M _x (Nm)	Maximum Ankle θ_x (deg)
VRTC EV4180	240523-21	-297	28.3	26.5
	240523-22	-307	29.3	26.8
	240523-27	-306	29.2	26.9
	240528-4	-298	28.5	26.6
	240528-5	-319	28.7	27.0
VRTC EV1130	240605-2	-302	27.6	27.8
	240605-3	-303	28.3	28.0
	240605-4	-308	28.4	28.1
	240605-5	-305	28.3	28.1
	240605-6	-307	28.4	28.1
VRTC EU2720	240911-8	-291	27.3	27.7
	240911-9	-304	28.4	28.0
	240911-10	-305	28.5	28.1
	240911-11	-307	28.7	28.1
	240911-12	-312	28.4	28.2
Humanetics EV2720	685931	-328	29.6	27.6
	685905	-326	29.6	27.6
	685889	-325	29.2	27.4
	685897	-323	29.4	27.6
	685866	-324	29.5	27.6
Calspan EV2720	2025_03_28 18_31	-387	30.2	26.9
	2025_03_28 19_03	-365	29.1	26.6
	2025_03_28 19_37	-357	28.9	26.8
	2025_03_28 20_10	-382	29.7	26.8
	2025_03_28 20_44	-360	29.5	26.7
TRC EV2720	2025_04_30 10_18	-310	29.6	28.1
	2025_04_30 11_19	-318	30.5	28.3
	2025_04_30 13_17	-320	30.8	28.4
	2025_04_30 14_22	-320	30.8	28.5
	2025_04_30 14_59	-323	30.9	28.5
Mean		-321	29.1	27.6
Standard Deviation		24.7	0.9	0.6
CV		7.7%	3.1%	2.4%

Table 16-10. Left Ankle Eversion Qualification Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Impact Velocity	m/s	1.95	2.05	2.00	
Minimum Lower Tibia Force F_z	N	-353	-289	-321	10%
Maximum Ankle Resistive Moment M_x	Nm	26.2	32.0	29.1	10%
Maximum Ankle Rotation θ_x	deg	24.8	30.3	27.6	10%

Table 16-11. Right Ankle Eversion Qualification Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Impact Velocity	m/s	1.95	2.05	2.00	
Minimum Lower Tibia Force F_z	N	-353	-289	-321	10%
Minimum Ankle Resistive Moment M_x	Nm	-32.0	-26.2	-29.1	10%
Minimum Ankle Rotation θ_x	deg	-30.3	-24.8	-27.6	10%

Discussion. Highlighted cells in Table 16-9 indicate trial values that did not achieve the respective target response $\pm 10\%$ in Table 16-10 and Table 16-11. Only lower tibia force for the Calspan tests did not meet the respective corridors.

Repeatability CV values were all below 5 percent.

Dummy Reproducibility CV values were all below 5 percent.

Test Reproducibility CV values were below 5 percent for X-axis ankle resistive moment and rotation. The Z-axis tibia force CV value was above 5 percent, but under 10 percent because all Calspan tests were non-conforming for that test parameter, with values exceeding the corridor.

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-05F Qualification Procedures and Requirements*. This test examines the dynamic impact response of the ball of the foot. In these tests, the lower tibia load cell is held rigidly with the tibia horizontal and the toes pointing up (Figure 17-1). The test utilizes the NHTSA Dynamic Impactor (TLX-9000-007, TLX-9000-006) with an effective mass of 8.52 ± 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 2.00 ± 0.05 m/s. During these tests, the lower tibia force (F_z) and Y-axis rotation were measured; the ankle resistive moment about the Y-axis was calculated from F_x and M_y .

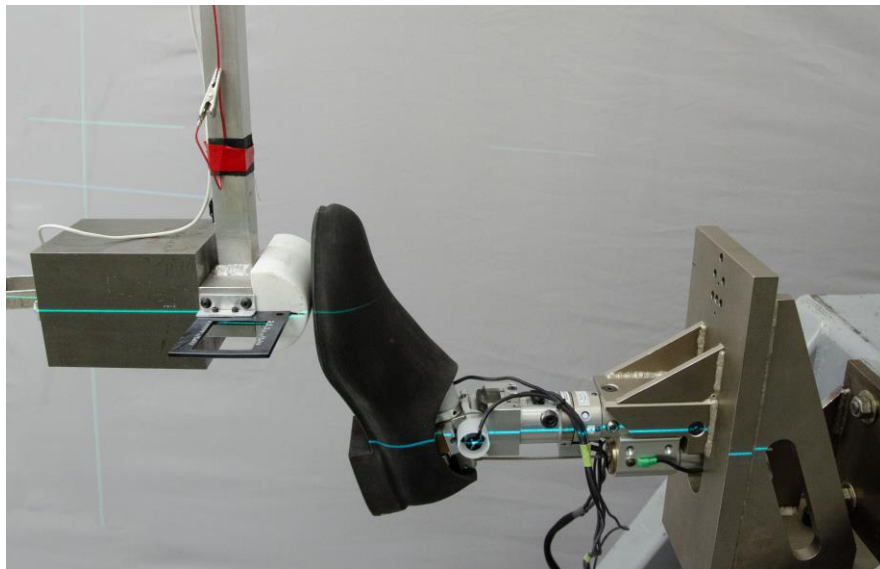


Figure 17-1. Ball of Foot Test

17.2 Ball of Foot Impact Repeatability Results

Sections 17.2.1 through 17.2.6 illustrate the results of the ball of foot repeatability tests. Each section contains a table providing the test data, followed by plot overlays of the five repeat tests conducted at all four labs. Since this is a component-level test and the left and right side designs are symmetric, only the left ankle was tested. 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-05F Left Ankle EV4180 Ball-of-Foot Testing at VRTC

Repeatability results for ball of foot testing on Ankle EV4180 (removed from ATD EV0668, left side) at VRTC yielded CV values below 5 percent (Table 17-1, Figure 17-2 through Figure 17-4).

Table 17-1. VRTC THOR-05F Left Ball of Foot Repeatability Results for EV4180

Test Number	Minimum Lower Tibia Fz after 10 ms (N)	Maximum Ankle M _Y (Nm)	Minimum Ankle θ_Y (deg)
240529-5	-814	44.9	32.9
240529-6	-796	43.8	32.7
240529-7	-777	42.6	32.6
240529-8	-777	42.0	32.5
240529-9	-772	41.7	32.5
Mean	-787	43.0	32.6
Standard Deviation	17.5	1.4	0.2
CV	2.2%	3.2%	0.6%

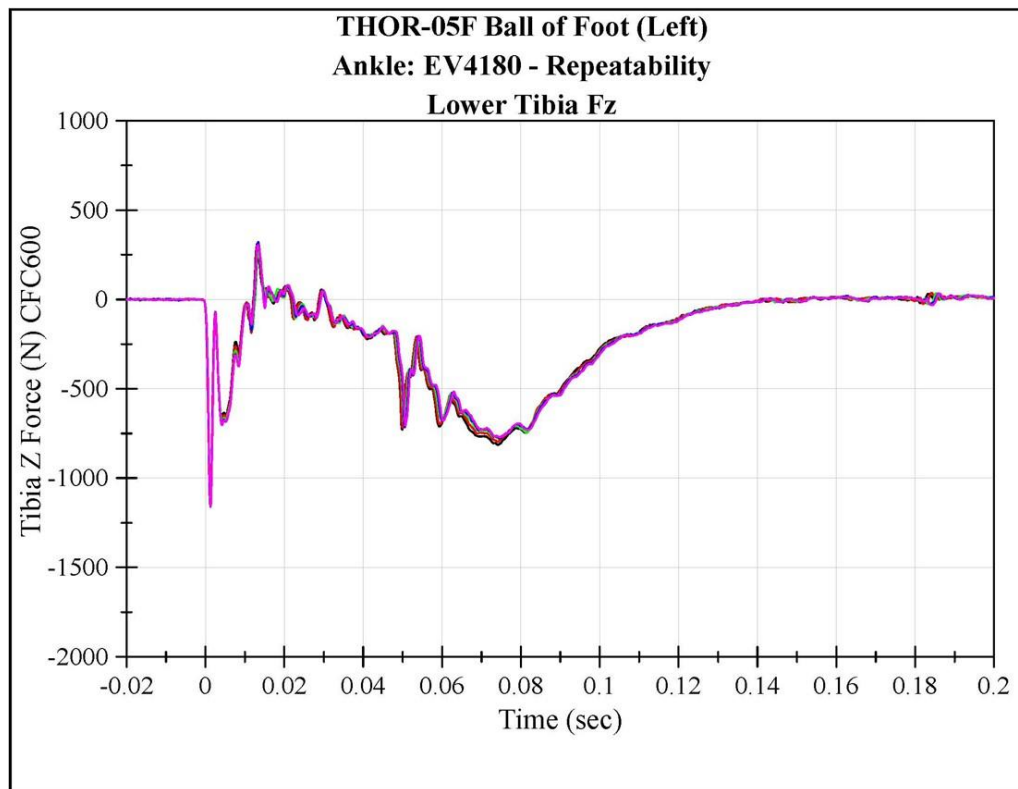


Figure 17-2. VRTC lower tibia force Fz for ball of foot impact repeatability tests for EV4180

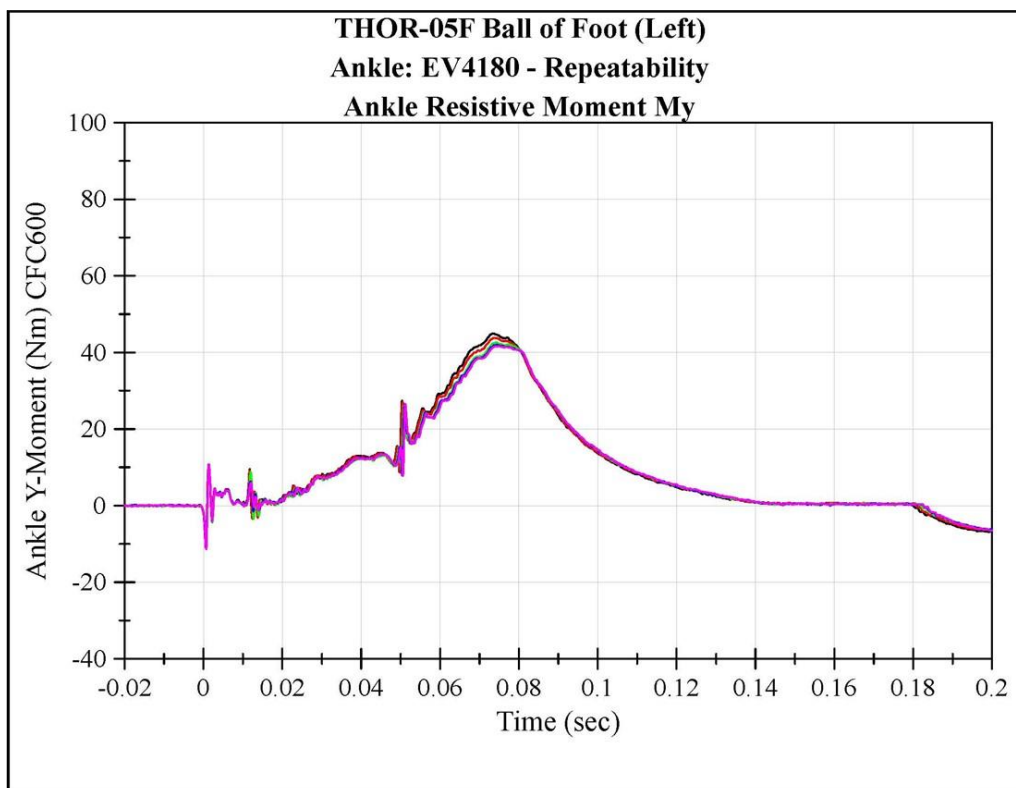


Figure 17-3. VRTC ankle resistive moment My for ball of foot impact repeatability tests for EV4180

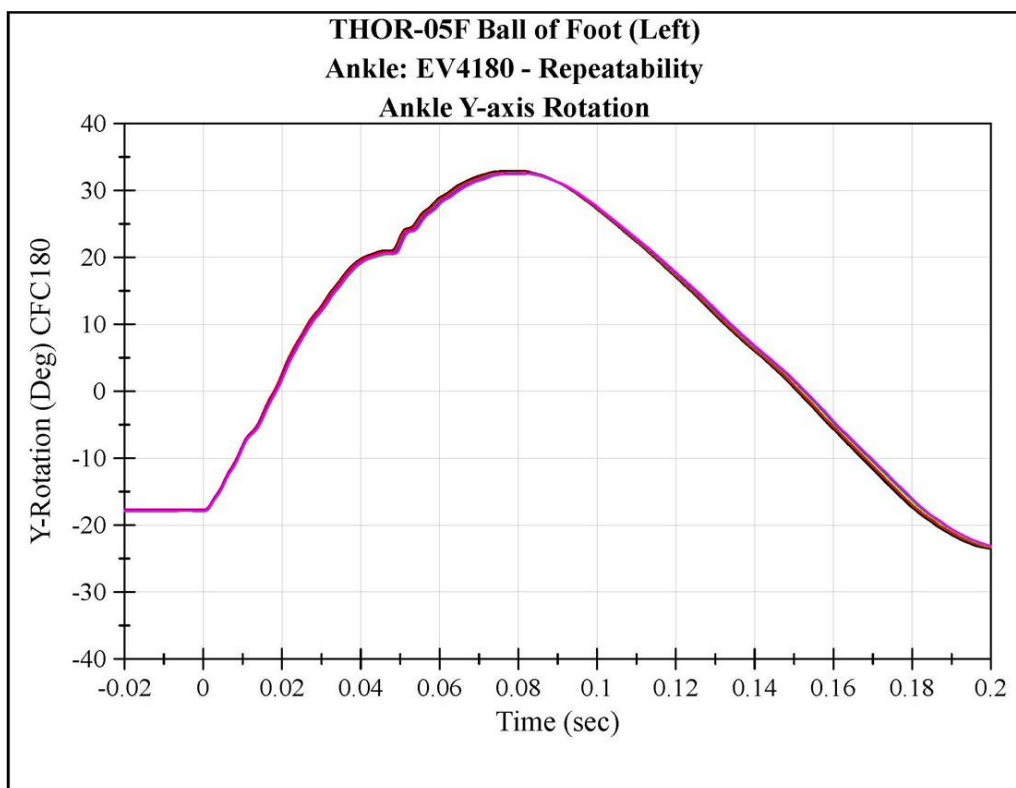


Figure 17-4. VRTC ankle Y axis rotation for ball of foot impact repeatability tests for EV4180

17.2.2 THOR-05F Left Ankle EV1130 Ball-of-Foot Testing at VRTC

Repeatability results for ball of foot testing on Ankle EV1130 (removed from ATD EV0674, left side) at VRTC yielded CV values below 5 percent (Table 17-2, Figure 17-5 through Figure 17-7).

Table 17-2. VRTC THOR-05F Left Ball of Foot Repeatability Results for EV1130

Test Number	Minimum Lower Tibia Fz after 10 ms (N)	Maximum Ankle M _Y (Nm)	Minimum Ankle θ_Y (deg)
240605-28	-973	51.9	29.5
240605-29	-980	52.9	29.9
240606-1	-946	50.1	29.7
240606-2	-947	51.1	29.9
240606-3	-953	50.8	30.0
Mean	-960	51.4	29.8
Standard Deviation	15.6	1.1	0.2
CV	1.6%	2.1%	0.6%

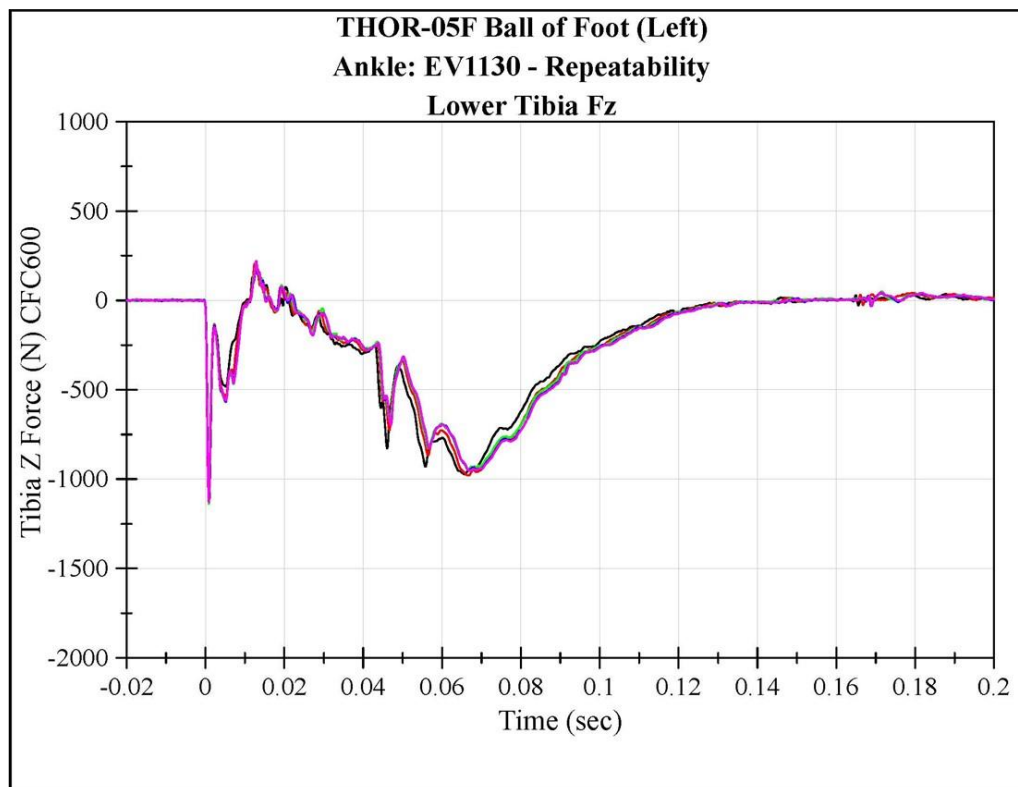


Figure 17-5. VRTC lower tibia force Fz for ball of foot impact repeatability tests for EV1130

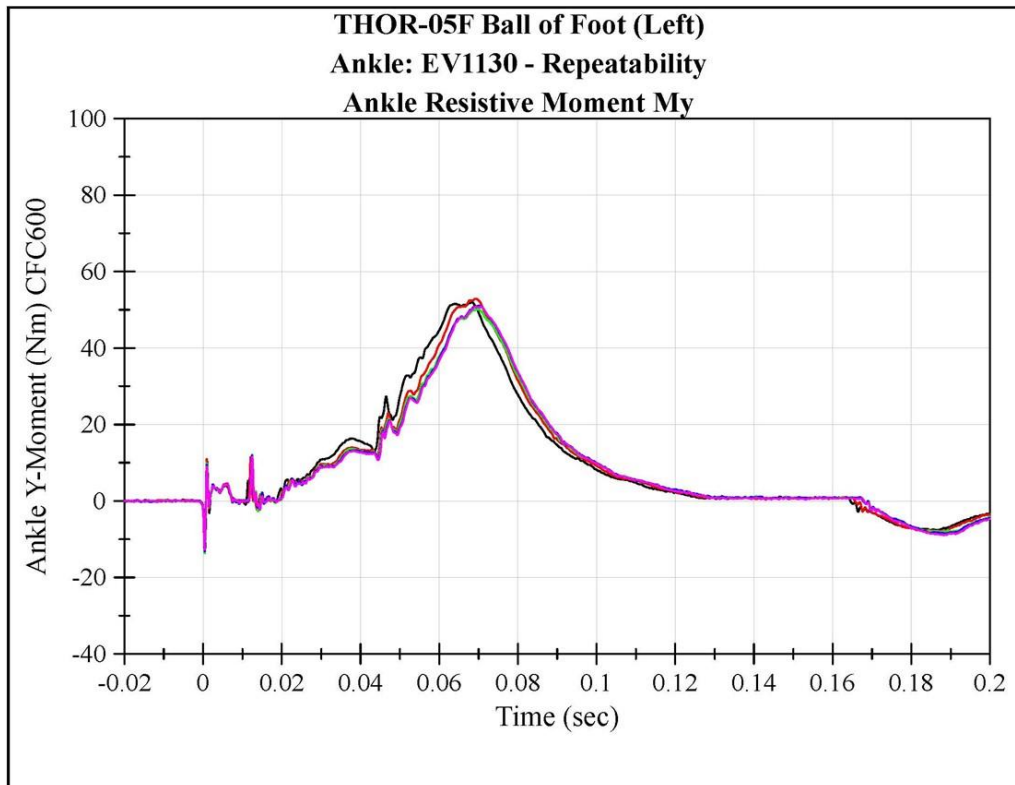


Figure 17-6. VRTC ankle resistive moment My for ball of foot impact repeatability tests for EV1130

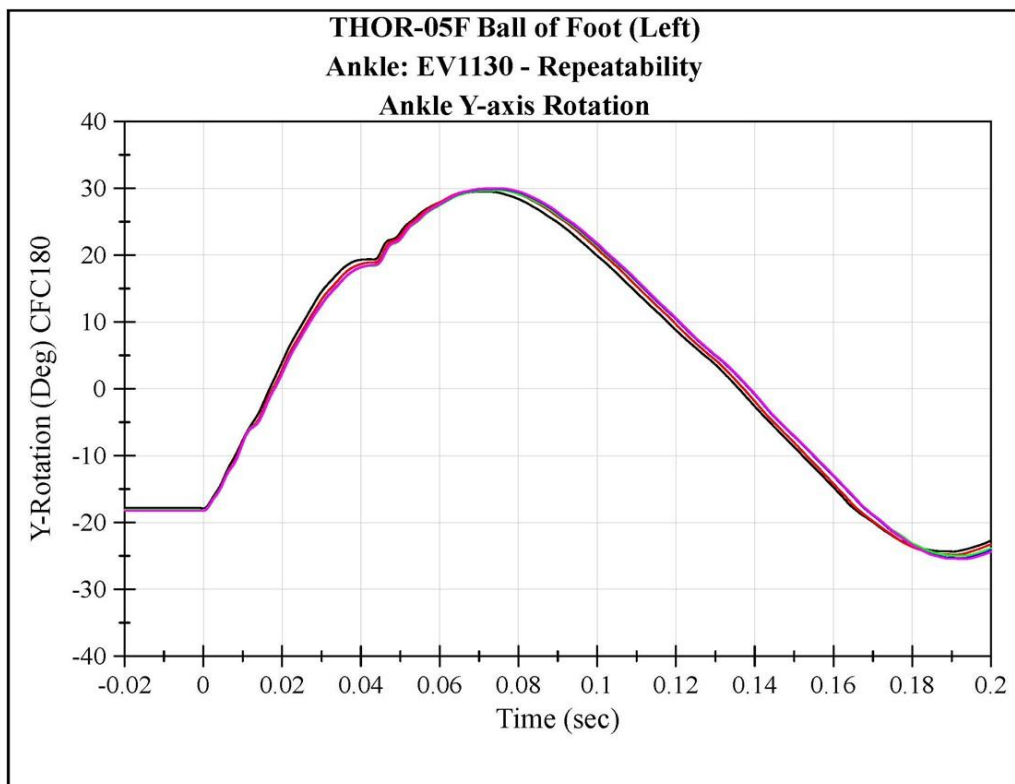


Figure 17-7. VRTC ankle Y axis rotation for ball of foot impact repeatability tests for EV1130

17.2.3 THOR-05F Left Ankle EV2720 Ball-of-Foot Testing at VRTC

Repeatability results for ball of foot testing on Ankle EV2720 (removed from ATD EU9863, left side) at VRTC yielded CV values below 5 percent (Table 17-3, Figure 17-8 through Figure 17-10).

Table 17-3. VRTC THOR-05F Left Ball of Foot Repeatability Results for EV2720

Test Number	Minimum Lower Tibia Fz after 10 ms (N)	Maximum Ankle M _Y (Nm)	Minimum Ankle θ_Y (deg)
250602-1	-914	43.5	35.1
250602-2	-947	46.1	35.6
250602-3	-944	46.1	35.6
250602-4	-934	44.5	35.4
250602-5	-946	46.2	35.7
Mean	-937	45.3	35.5
Standard Deviation	13.9	1.2	0.2
CV	1.5%	2.7%	0.6%

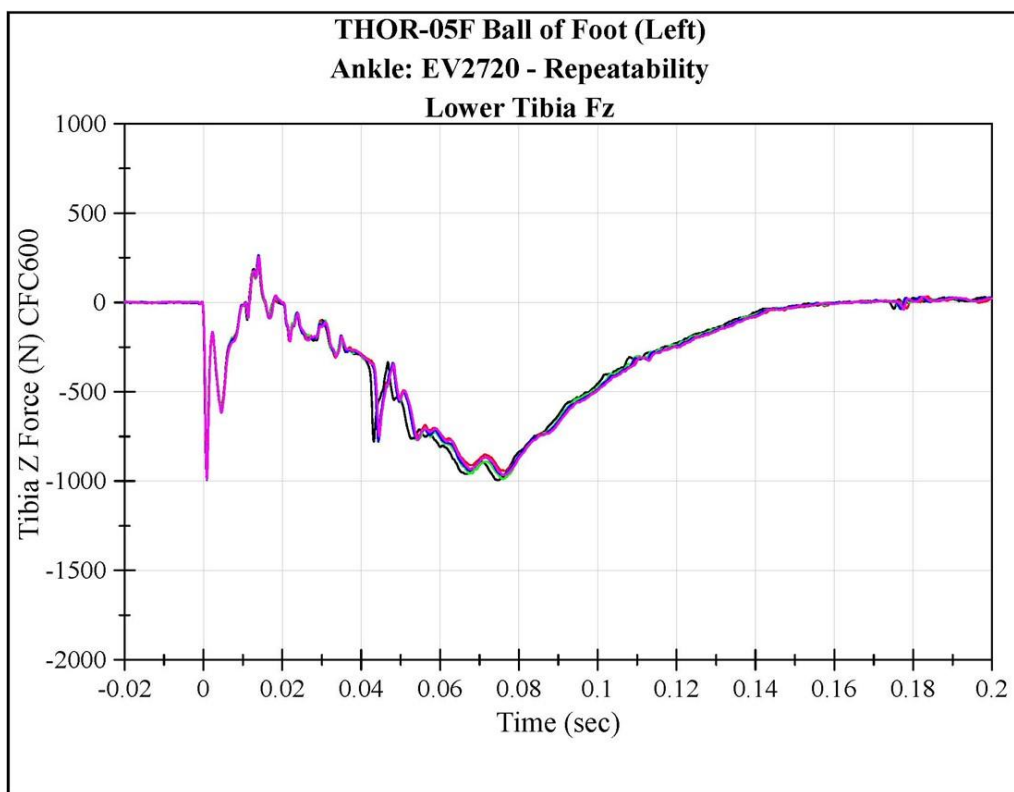


Figure 17-8. VRTC lower tibia force Fz for ball of foot impact repeatability tests for EV2720

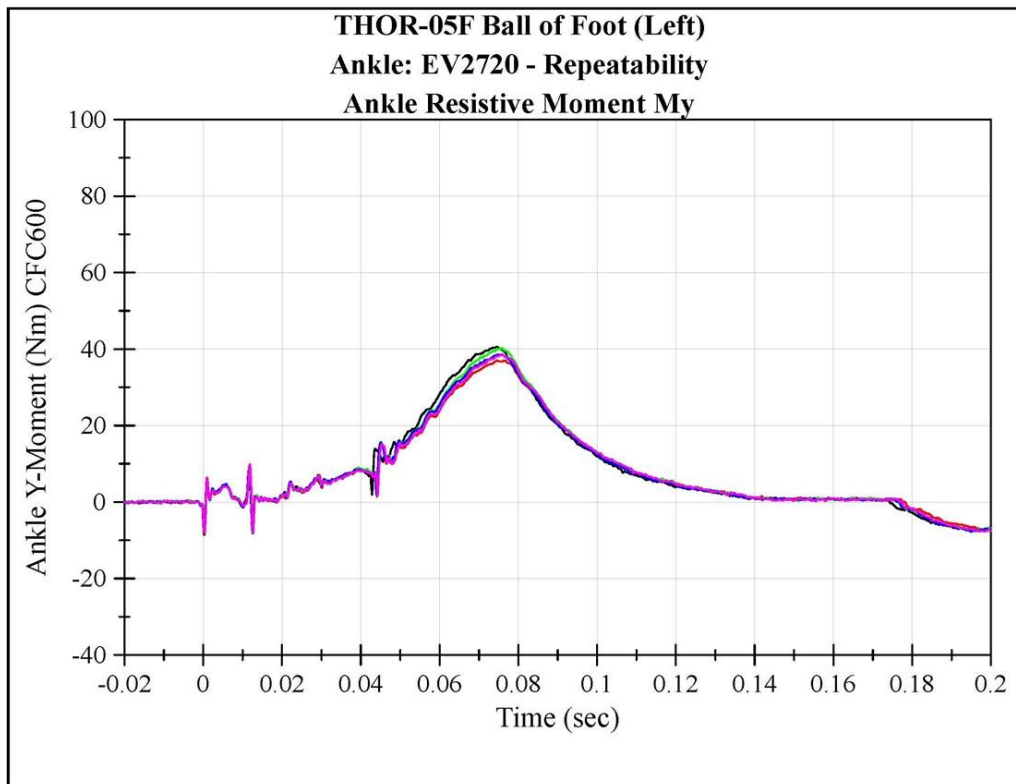


Figure 17-9. VRTC ankle resistive moment My for ball of foot impact repeatability tests for EV2720

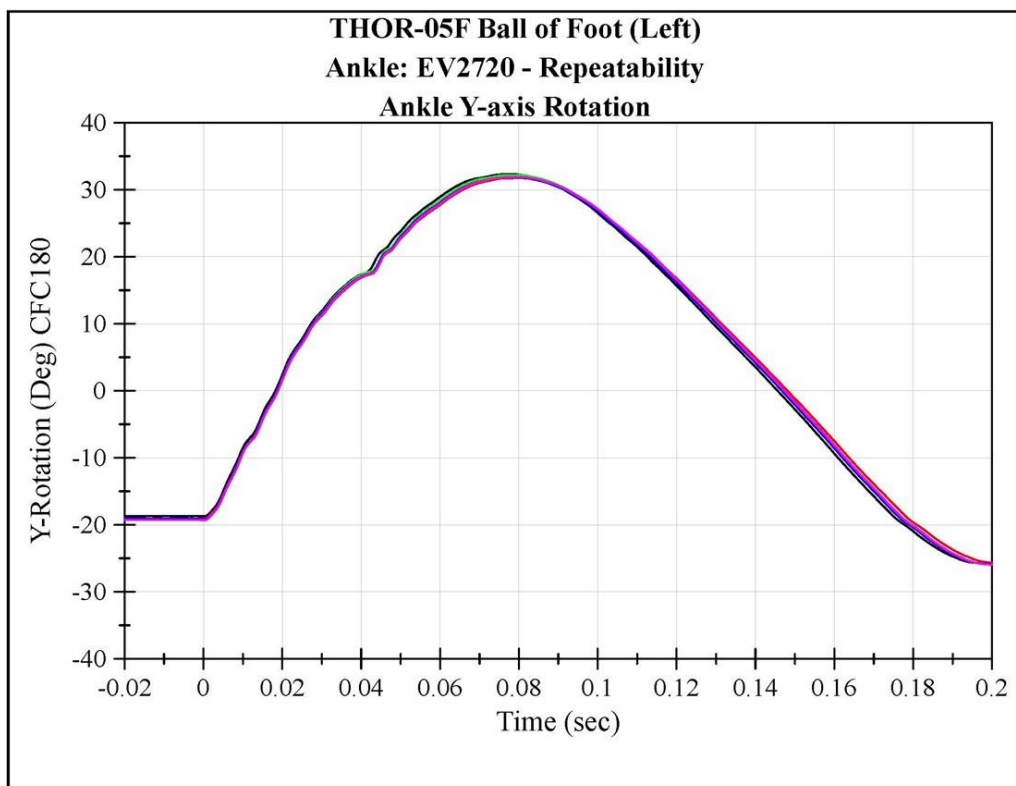


Figure 17-10. VRTC ankle Y axis rotation for ball of foot impact repeatability tests for EV2720

17.2.4 THOR-05F Left Ankle EV2720 Ball-of-Foot Testing at Humanetics

Repeatability results for ball of foot testing on Ankle EV2720 (removed from ATD EV4675, left side) at Humanetics yielded CV values below 5 percent (Table 17-4, Figure 17-11 through Figure 17-13). Ankle data was not collected past 0.12 s at Humanetics, but this difference did not affect the R&R analysis.

Table 17-4. Humanetics THOR-05F Left Ball of Foot Repeatability Results for EV2720

Test Number	Minimum Lower Tibia F _z after 10 ms (N)	Maximum Ankle M _y (Nm)	Minimum Ankle θ_y (deg)
686721	-984	50.3	35.1
686742	-965	49.7	35.2
686703	-996	51.3	35.1
686574	-998	51.7	34.9
686752	-969	49.8	35.2
Mean	-983	50.5	35.1
Standard Deviation	15.3	0.9	0.1
CV	1.6%	1.7%	0.3%

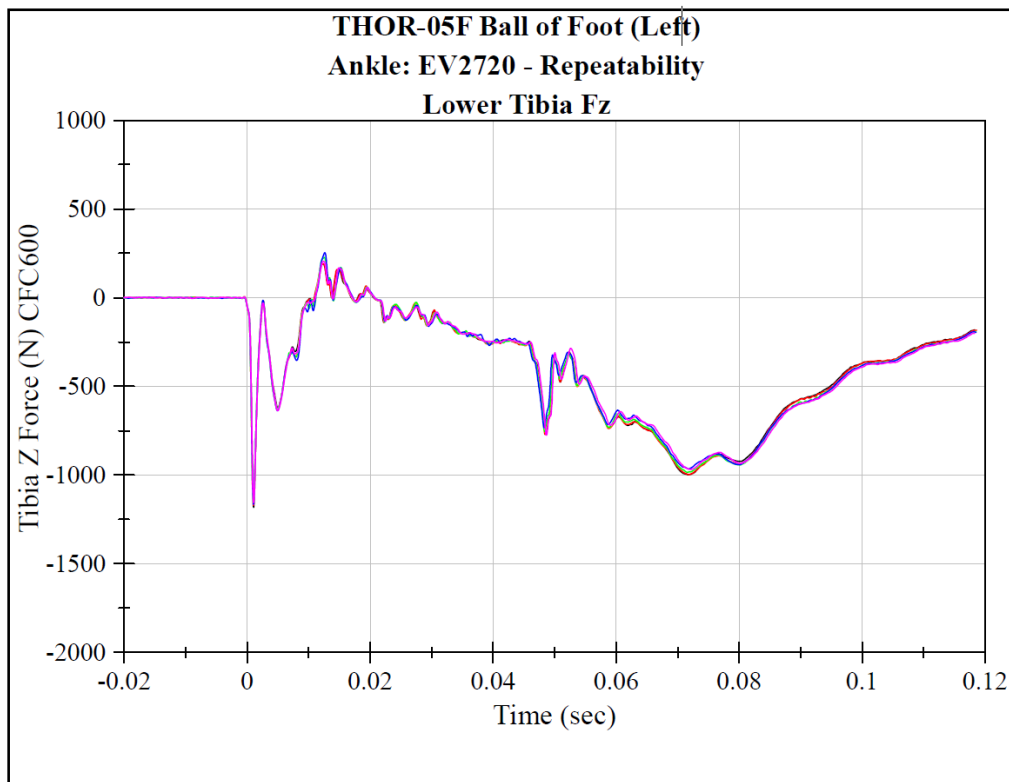


Figure 17-11. Humanetics lower tibia force Fz for ball of foot impact repeatability tests for EV2720

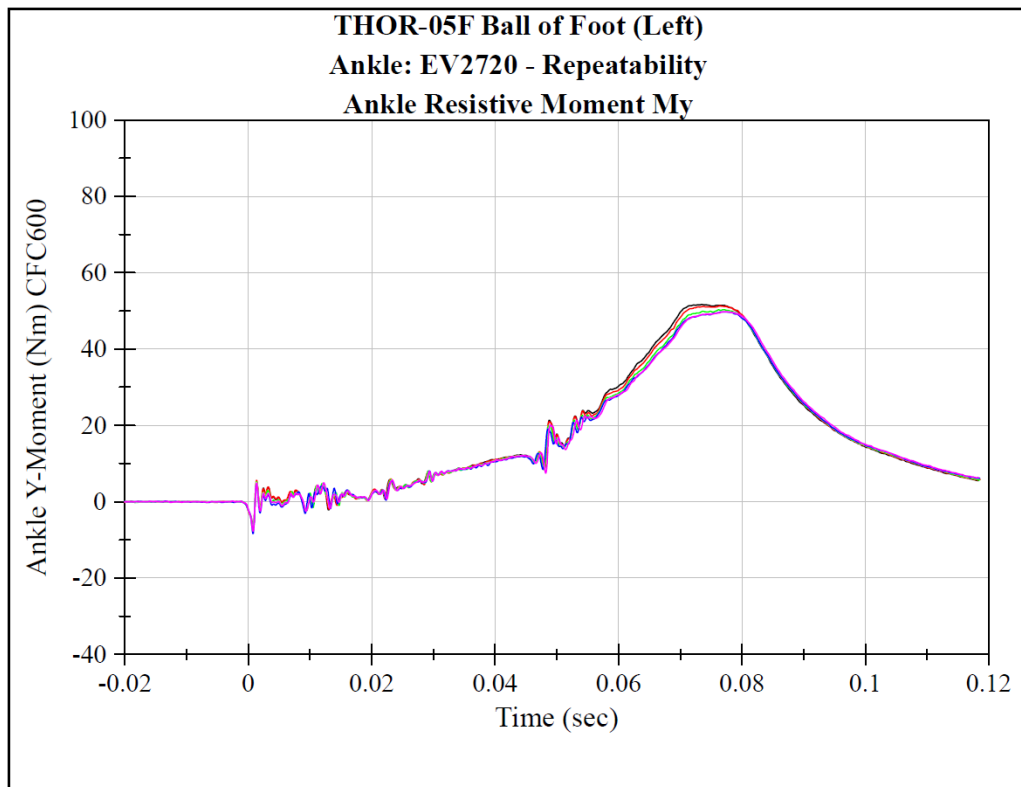


Figure 17-12. Humanetics ankle resistive moment My for ball of foot impact repeatability tests for EV2720

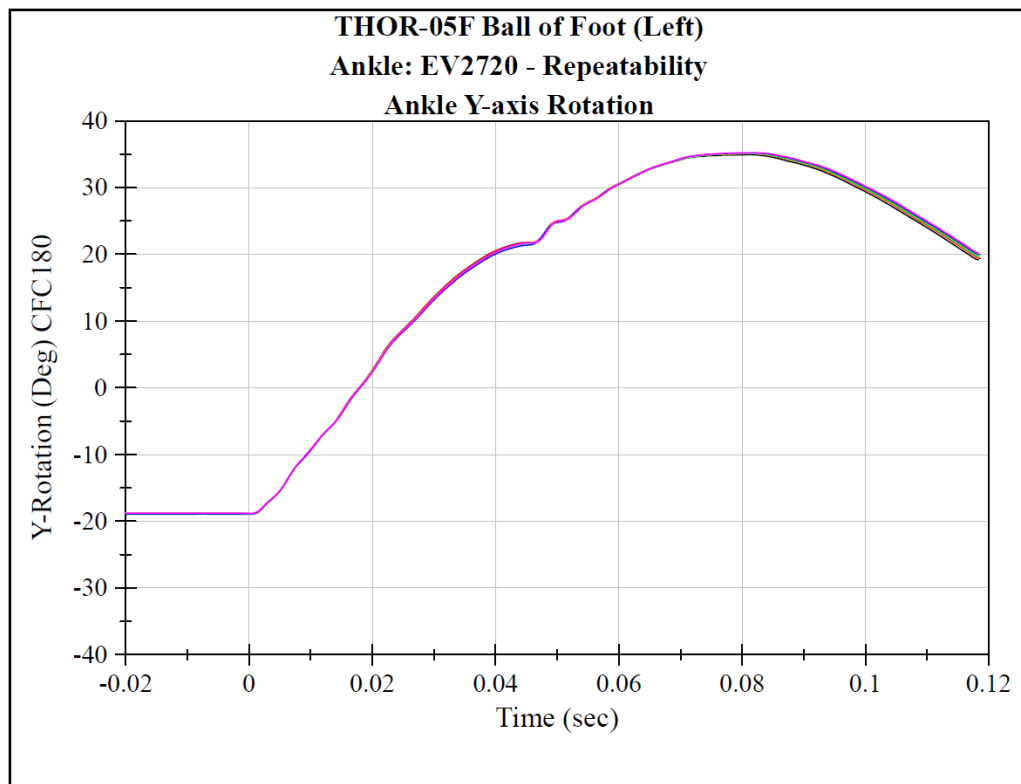


Figure 17-13. Humanetics ankle Y axis rotation for ball of foot impact repeatability tests for EV2720

17.2.5 THOR-05F Left Ankle EV2720 Ball-of-Foot Testing at Calspan

Repeatability results for ball of foot testing on Ankle EV2720 (removed from ATD EV4675, left side) at Calspan yielded CV values below 5 percent (Table 17-5, Figure 17-14 through Figure 17-16).

Table 17-5. Calspan THOR-05F Left Ball of Foot Repeatability Results for EV2720

Test Number	Minimum Lower Tibia F _Z after 10 ms (N)	Maximum Ankle M _Y (Nm)	Minimum Ankle θ_Y (deg)
2025_06_19_11_00	-936	44.2	32.3
2025_06_19_11_54	-943	45.7	35.4
2025_06_19_12_30	-939	46.1	35.5
2025_06_19_13_41	-902	43.2	35.0
2025_06_19_14_15	-907	43.4	35.1
Mean	-925	44.5	34.7
Standard Deviation	19.1	1.3	1.3
CV	2.1%	3.0%	3.9%

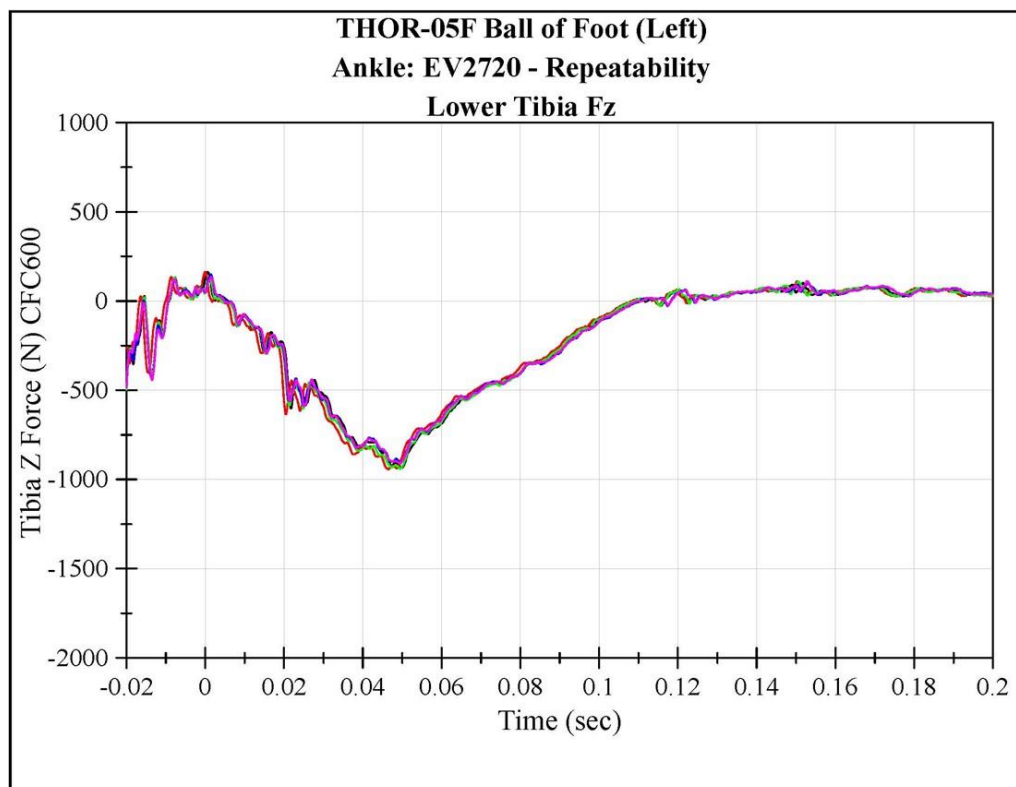


Figure 17-14. Calspan lower tibia force Fz for ball of foot impact repeatability tests for EV2720

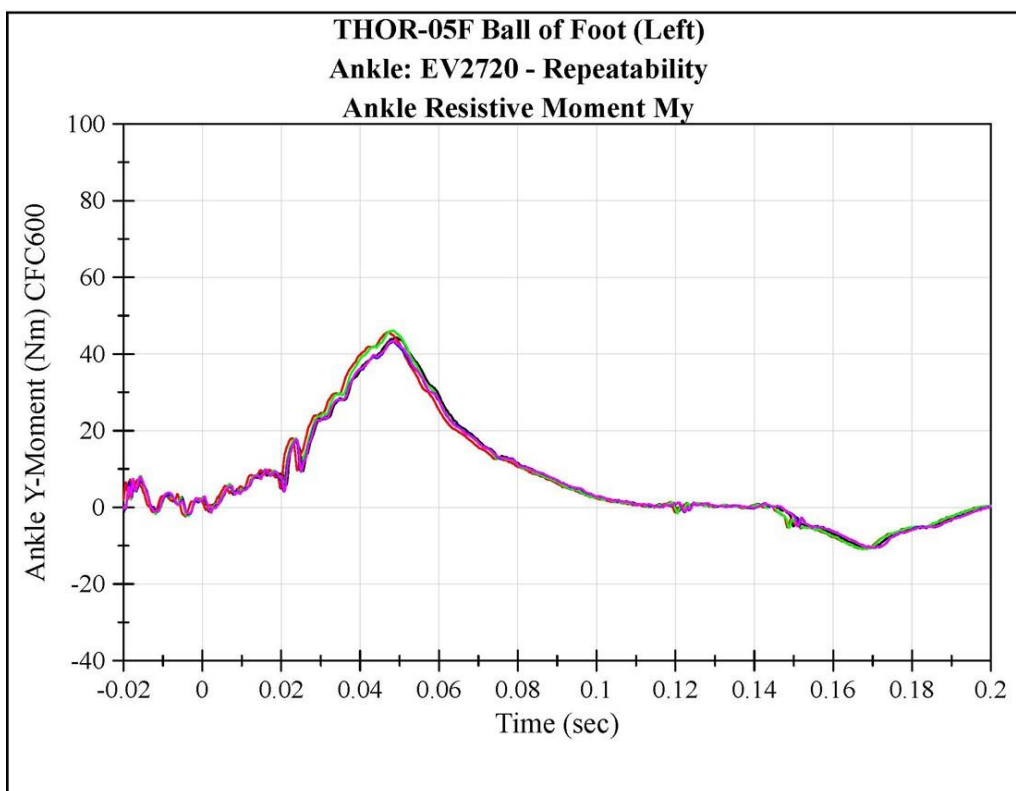


Figure 17-15. Calspan ankle resistive moment My for ball of foot impact repeatability tests for EV2720

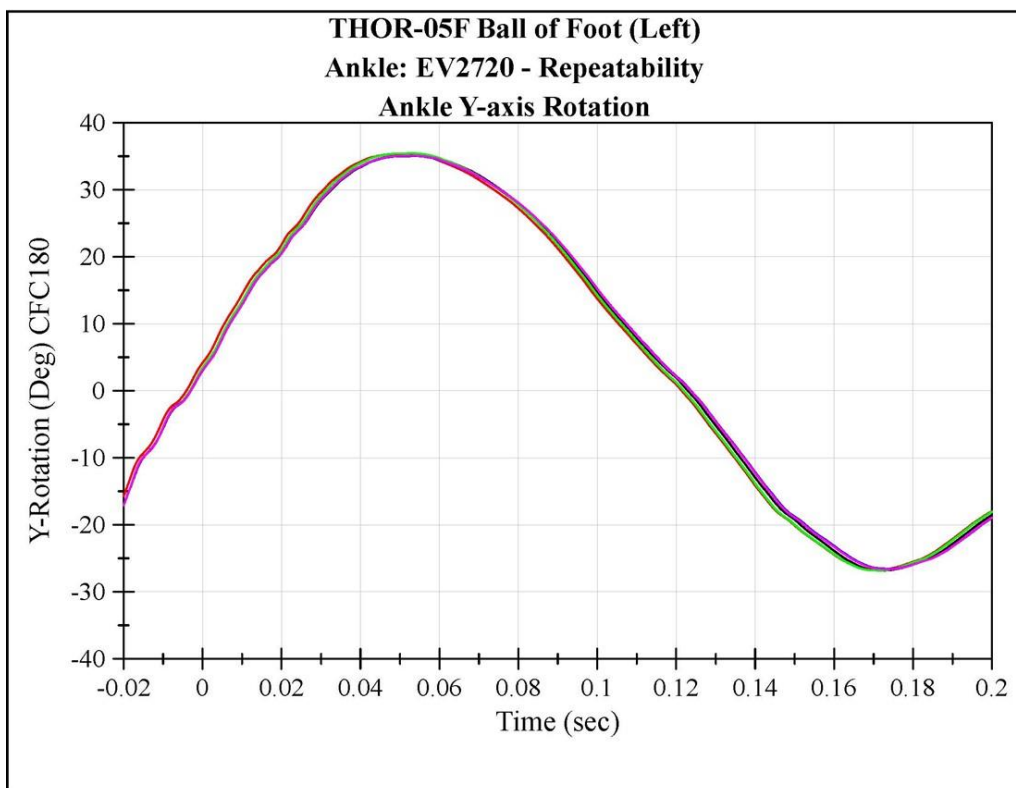


Figure 17-16. Calspan ankle Y axis rotation for ball of foot impact repeatability tests for EV2720

17.2.6 THOR-05F Left Ankle EV2720 Ball-of-Foot Testing at TRC

Repeatability results for ball of foot testing on Ankle EV2720 (removed from ATD EV4675, left side) at TRC yielded CV values below 5 percent (Table 17-6, Figure 17-17 through Figure 17-19).

Table 17-6. TRC THOR-05F Left Ball of Foot Repeatability Results for EV2720

Test Number	Minimum Lower Tibia Fz after 10 ms (N)	Maximum Ankle M _y (Nm)	Minimum Ankle θ_y (deg)
2025_04_25 14_02	-976	50.8	35.9
2025_04_25 14_34	-941	50.1	35.8
2025_04_28 12_57	-971	50.7	35.9
2025_04_28 13_51	-992	52.3	36.2
2025_04_28 14_36	-989	52.2	36.2
Mean	-974	51.2	36.0
Standard Deviation	20.6	1.0	0.2
CV	2.1%	1.9%	0.6%

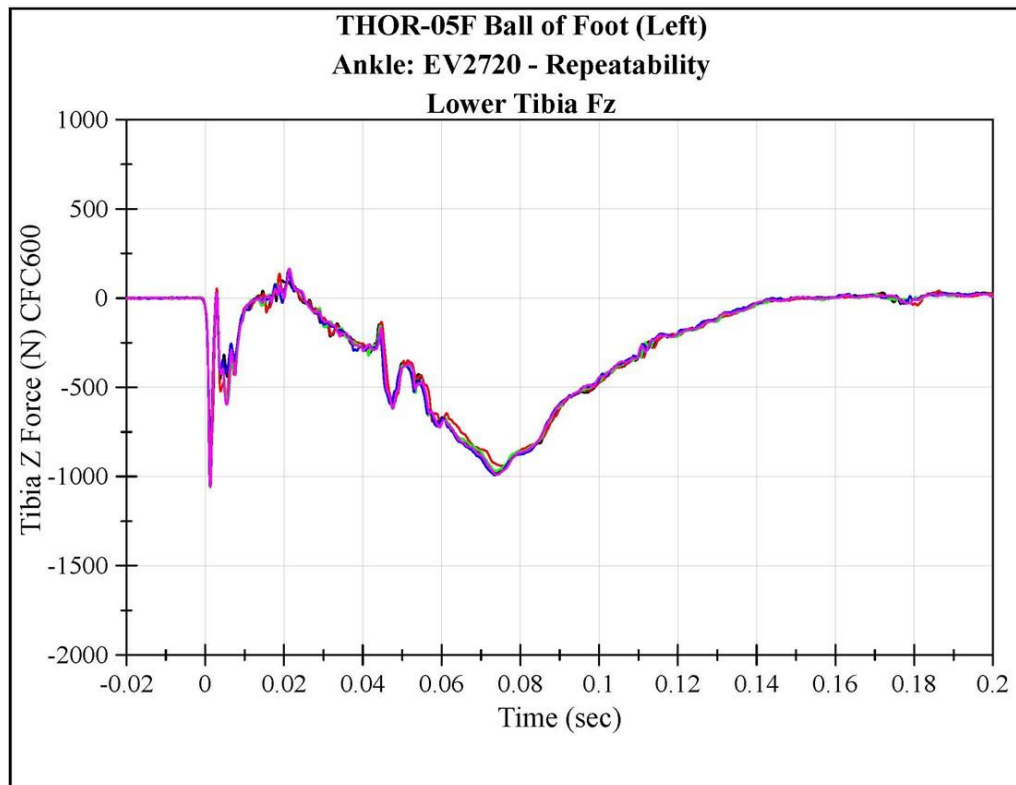


Figure 17-17. TRC lower tibia force Fz for ball of foot impact repeatability tests for EV2720

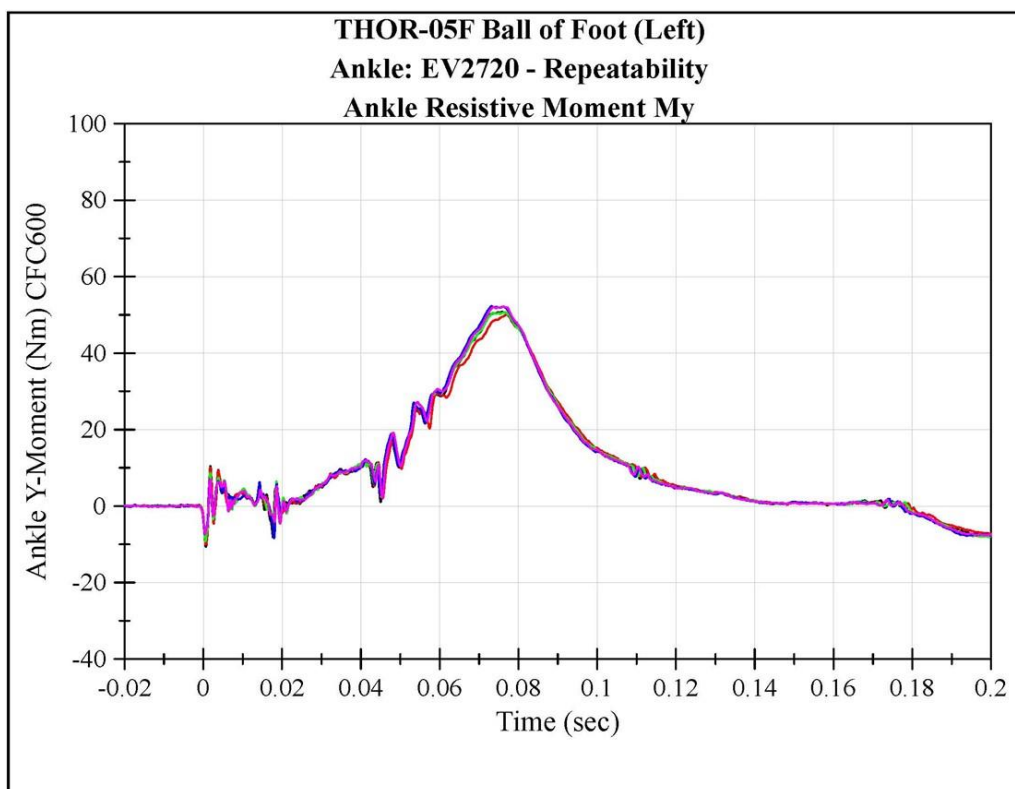


Figure 17-18. TRC ankle resistive moment My for ball of foot impact repeatability tests for EV2720

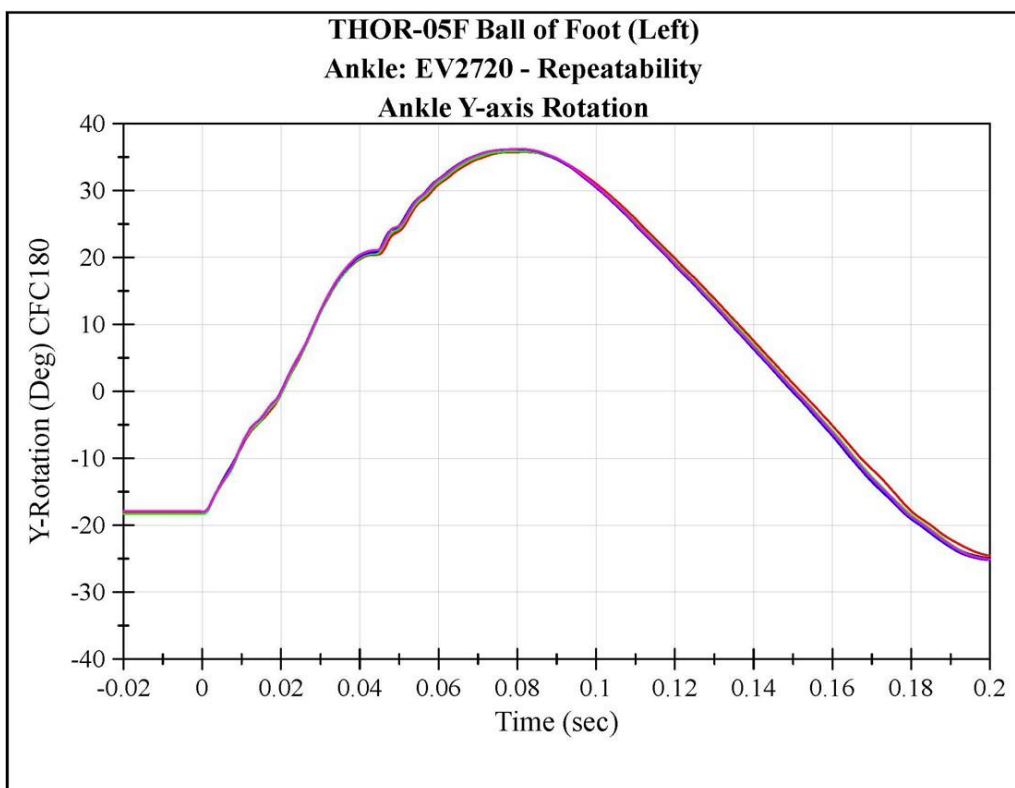


Figure 17-19. TRC ankle Y axis rotation for ball of foot impact repeatability tests for EV2720

17.3 Ball of Foot Impact Dummy Reproducibility Results

Dummy Reproducibility results at VRTC for ball of foot testing yielded CV values above 5 percent, but under 10 percent for all specifications (Table 17-7).

Table 17-7. THOR-05F Ball of Foot Reproducibility Results

Ankle Number	Test Number	Minimum Lower Tibia F_z after 10 ms (N)	Maximum Ankle M_y (Nm)	Minimum Ankle θ_y (deg)
VRTC EV4180	240529-5	-814	44.9	32.9
	240529-6	-796	43.8	32.7
	240529-7	-777	42.6	32.6
	240529-8	-777	42.0	32.5
	240529-9	-772	41.7	32.5
VRTC EV1130	240605-28	-973	51.9	29.5
	240605-29	-980	52.9	29.9
	240606-1	-946	50.1	29.7
	240606-2	-947	51.1	29.9
	240606-3	-953	50.8	30.0
VRTC EV2720	250602-1	-914	43.5	35.1
	250602-2	-947	46.1	35.6
	250602-3	-944	46.1	35.6
	250602-4	-934	44.5	35.4
	250602-5	-946	46.2	35.7
Mean		-895	46.6	32.6
Standard Deviation		80.6	3.8	2.4
CV		9.0%	8.2%	7.3%

17.4 Lab-to-Lab Variability Analysis

Dummy Reproducibility results at all four labs for ball of foot testing yielded CV values below 5 percent for lower tibia Z-axis force and ankle rotation; the CV value for maximum ankle Y-axis resistive moment as above 5 percent, but under 10 percent (Table 17-8).

Table 17-8. THOR-05F Ball of Foot Reproducibility Results

Ankle Number	Test Number	Minimum Lower Tibia F _Z after 10 ms (N)	Maximum Ankle M _Y (Nm)	Minimum Ankle θ _Y (deg)
VRTC EV2720	250602-1	-914	43.5	35.1
	250602-2	-947	46.1	35.6
	250602-3	-944	46.1	35.6
	250602-4	-934	44.5	35.4
	250602-5	-946	46.2	35.7
Humanetics EV2720	686721	-984	50.3	35.1
	686742	-965	49.7	35.2
	686703	-996	51.3	35.1
	686574	-998	51.7	34.9
	686752	-969	49.8	35.2
Calspan EV2720	2025_06_19_11_00	-936	44.2	32.3
	2025_06_19_11_54	-943	45.7	35.4
	2025_06_19_12_30	-939	46.1	35.5
	2025_06_19_13_41	-902	43.2	35.0
	2025_06_19_14_15	-907	43.4	35.1
TRC EV2720	2025_04_25_14_02	-976	50.8	35.9
	2025_04_25_14_34	-941	50.1	35.8
	2025_04_28_12_57	-971	50.7	35.9
	2025_04_28_13_51	-992	52.3	36.2
	2025_04_28_14_36	-989	52.2	36.2
Test Reproducibility EV2720				
Mean		-955	47.9	35.3
Standard Deviation		29.5	3.2	0.8
CV		3.1%	6.8%	2.3%

17.5 Corridor Development

All the data used to determine the ball of foot qualification corridors is shown in Table 17-9. The qualification corridors were calculated using the mean plus or minus 10 percent of the peak for the specified measured or calculated channels (Table 17-10).

Table 17-9. THOR-05F Ball of Foot Qualification Corridor Results
(Highlighted values fell outside average $\pm 10\%$.)

Ankle Number	Test Number	Minimum Lower Tibia F _z after 10 ms (N)	Maximum Ankle M _y (Nm)	Minimum Ankle θ_y (deg)
VRTC EV4180	240529-5	-814	44.9	32.9
	240529-6	-796	43.8	32.7
	240529-7	-777	42.6	32.6
	240529-8	-777	42.0	32.5
	240529-9	-772	41.7	32.5
VRTC EV1130	240605-28	-973	51.9	29.5
	240605-29	-980	52.9	29.9
	240606-1	-946	50.1	29.7
	240606-2	-947	51.1	29.9
	240606-3	-953	50.8	30.0
VRTC EV2720	250602-1	-914	43.5	35.1
	250602-2	-947	46.1	35.6
	250602-3	-944	46.1	35.6
	250602-4	-934	44.5	35.4
	250602-5	-946	46.2	35.7
Humanetics EV2720	686721	-984	50.3	35.1
	686742	-965	49.7	35.2
	686703	-996	51.3	35.1
	686574	-998	51.7	34.9
	686752	-969	49.8	35.2
Calspan EV2720	2025_06_19 11_00	-936	44.2	32.3
	2025_06_19 11_54	-943	45.7	35.4
	2025_06_19 12_30	-939	46.1	35.5
	2025_06_19 13_41	-902	43.2	35.0
	2025_06_19 14_15	-907	43.4	35.1
TRC EV2720	2025_04_25 14_02	-976	50.8	35.9
	2025_04_25 14_34	-941	50.1	35.8
	2025_04_28 12_57	-971	50.7	35.9
	2025_04_28 13_51	-992	52.3	36.2
	2025_04_28 14_36	-989	52.2	36.2
Mean		-928	47.7	33.9
Standard Deviation		68.8	3.7	2.2
CV		7.4%	7.7%	6.5%

Table 17-10. Ball of Foot Qualification Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width ±%
Impact Velocity	m/s	1.95	2.05	2.00	
Minimum Lower Tibia Force F_z after 10 ms	N	-1,020	-835	-928	10%
Maximum Ankle Resistive Moment M_Y	Nm	42.9	52.4	47.7	10%
Minimum Ankle Rotation (in dorsiflexion) θ_Y	deg	30.6	37.3	33.9	10%

Discussion. Highlighted cells in Table 17-9 indicate test values that did not achieve their respective target response $\pm 10\%$ in Table 17-10. All tests for VRTC ankle EV4180 and VRTC ankle EV1130 were non-conforming for at least one of the specification requirements.

Repeatability showed all CV values below 5 percent.

Dummy Reproducibility results showed all tests for VRTC ankle EV4180 were non-conforming for lower tibia force measurements; in three cases, they were also non-conforming for ankle Y-axis resistive moment. VRTC ankle EV1130 was also non-conforming, due to low ankle Y-axis rotation. These differences are likely the result of variations in test setup procedure and will be minimized by an improved procedure found in *THOR-05F Qualification Procedures and Requirements*. In investigating sources of variation, we found that some test technicians applied foil contact tape to the shoe bottom and the probe as a redundant time-of-impact marker, which affected results. The procedure was updated to explicitly prohibit any material between the probe and the shoe.

Test Reproducibility yielded all CV values above 5 percent. Despite the CV values above 5 percent, all lab-to-lab test results for ankle EV2720 at the four labs were within the corridor range.

18 HEEL

18.1 Methodology

Repeatability and reproducibility tests were performed using the heel qualification procedures described in the *THOR-05F Qualification Procedures and Requirements*. This test examines the dynamic impact response of the heel of the foot. In these tests, the molded shoe was utilized as described in *THOR-05F 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 4.00 ± 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 lower tibia force (F_z) and probe force were measured.

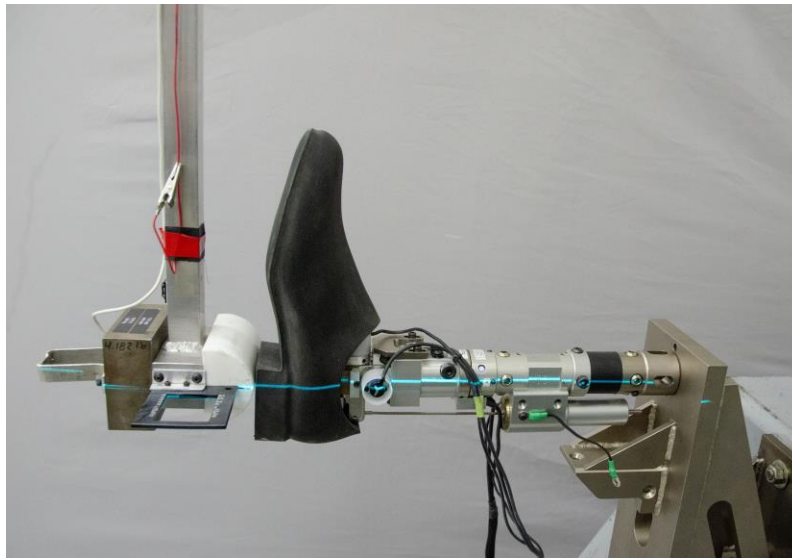


Figure 18-1. Heel impact test setup

18.2 Heel Impact Repeatability Results

Sections 18.2.1 through 18.2.6 illustrate the results of the heel repeatability tests. Each section contains a table providing the test data, followed by plot overlays of the five repeat tests conducted at all four labs. Since this is a component-level test and the left and right side designs are symmetric, only the left leg was tested. 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-05F Left Leg EV4180 Heel Testing at VRTC

Repeatability results at VRTC for heel testing on Leg EV4180 (removed from ATD EV0668, left side) yielded CV values below 5 percent (Table 18-1, Figure 18-2 through Figure 18-3).

Table 18-1. VRTC THOR-05F Left Heel of Foot Repeatability Results for Leg EV4180

Test Number	Maximum Probe Force (N)	Minimum Lower Tibia Force F_z (N)
240530-1	3,964	-2,132
240530-2	3,959	-2,107
240530-3	3,955	-2,093
240530-4	3,953	-2,096
240530-5	3,945	-2,100
Mean	3,955	-2,106
Standard Deviation	7.0	15.7
CV	0.2%	0.7%

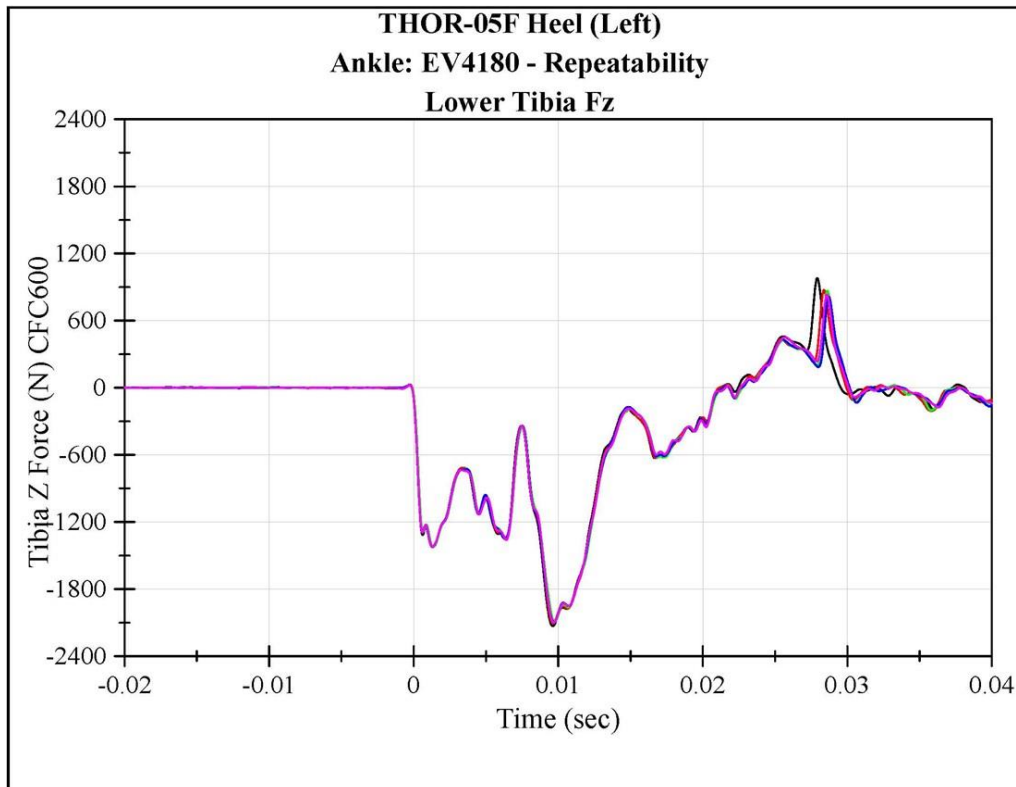


Figure 18-2. VRTC lower tibia force Fz for heel of foot impact repeatability tests for Leg EV4180

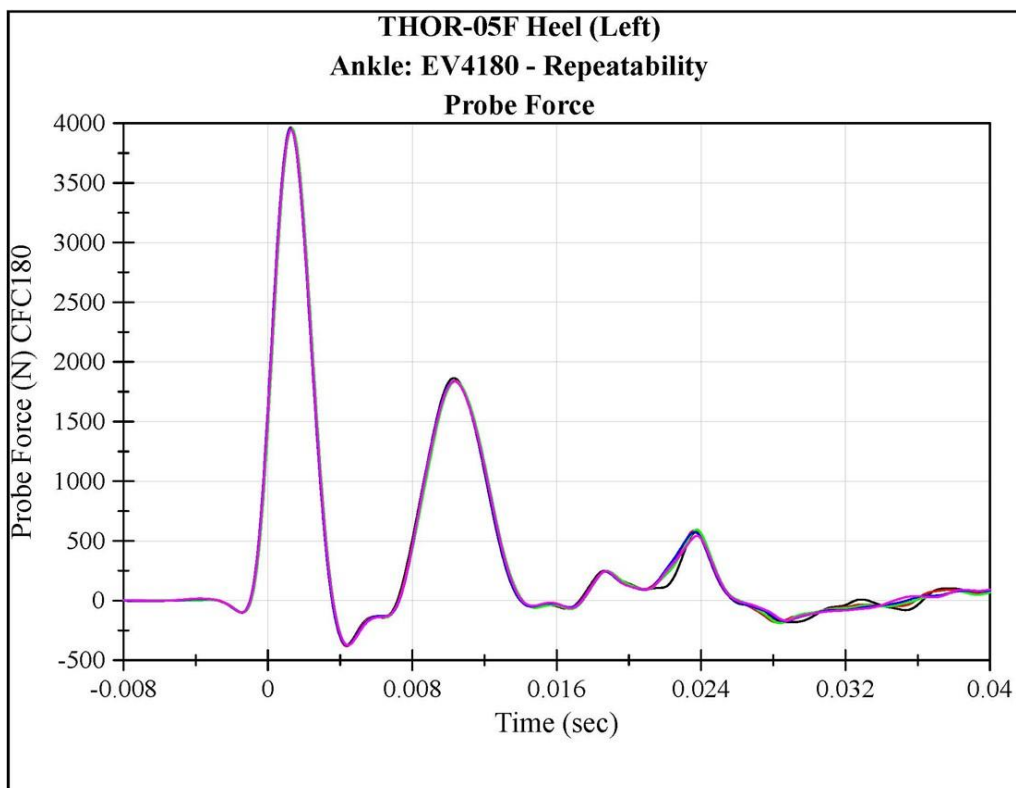


Figure 18-3. VRTC probe force for heel of foot impact repeatability tests for Leg EV4180

18.2.2 THOR-05F Left Leg EV1130 Heel Testing at VRTC

Repeatability results at VRTC for heel testing on Leg EV1130 (removed from ATD EV0674, left side) at yielded CV values below 5 percent (Table 18-2, Figure 18-4 through Figure 18-5).

Table 18-2. VRTC THOR-05F Left Heel of Foot Repeatability Results for Leg EV1130

Test Number	Maximum Probe Force (N)	Minimum Lower Tibia Force F_z (N)
240606-4	4,110	-2,254
240606-5	4,072	-2,289
240606-6	4,056	-2,325
240606-7	4,050	-2,296
240606-8	4,043	-2,289
Mean	4,066	-2,291
Standard Deviation	26.4	25.3
CV	0.6%	1.1%

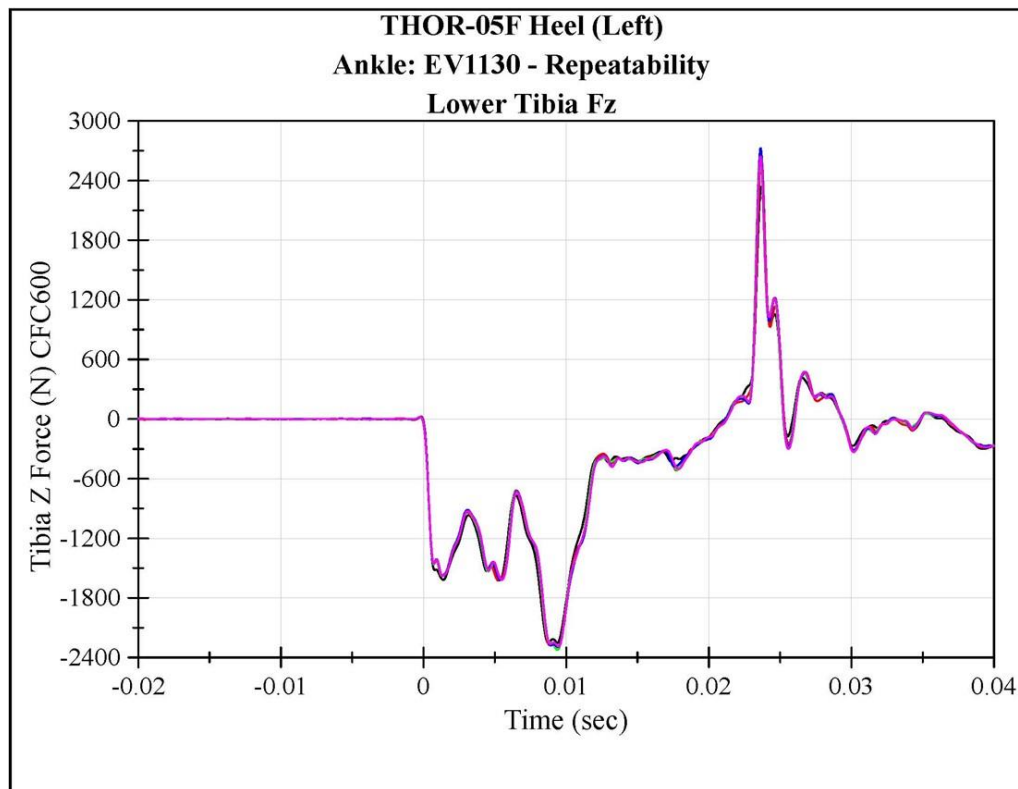


Figure 18-4. VRTC lower tibia force Fz for heel of foot impact repeatability tests for Leg EV1130

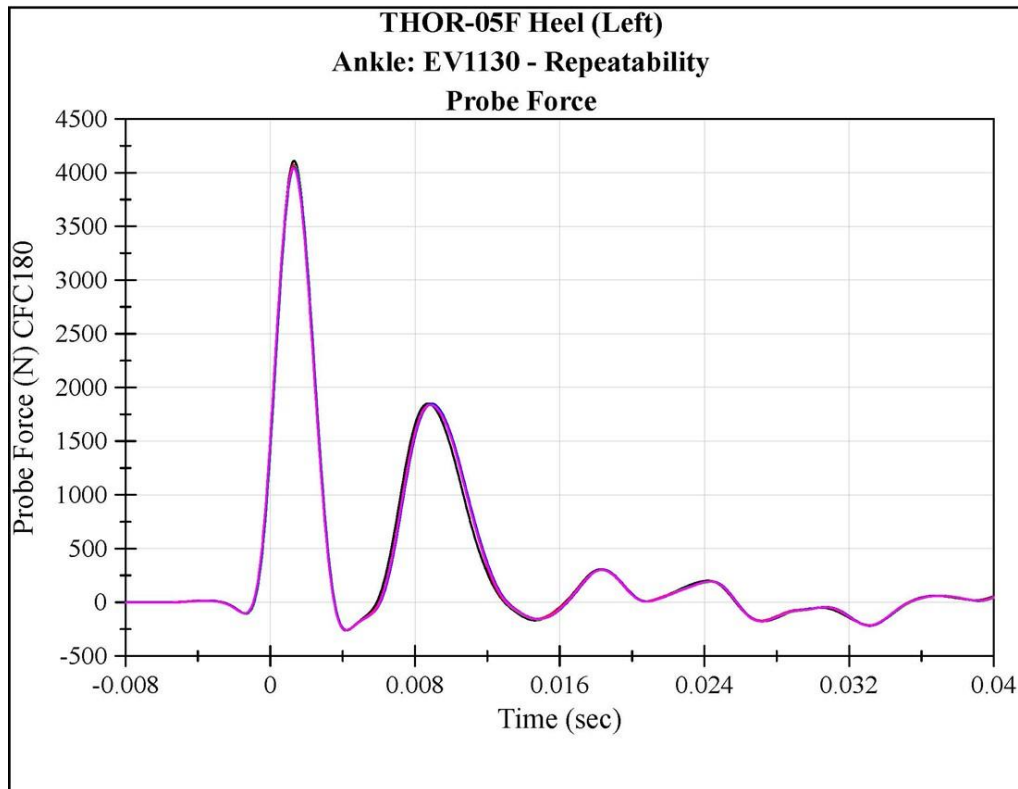


Figure 18-5. VRTC probe force for heel of foot impact repeatability tests for Leg EV1130

18.2.3 THOR-05F Left Leg EV2720 Heel Testing at VRTC

Repeatability results at VRTC for heel testing on Leg EV2720 (removed from ATD EV4675, left side) at VRTC yielded CV values below 5 percent (Table 18-3, Figure 18-6 through Figure 18-7).

Table 18-3. VRTC THOR-05F Left Heel of Foot Repeatability Results for Leg EV2720

Test Number	Maximum Probe Force (N)	Minimum Lower Tibia Force F_z (N)
240912-14	3,853	-2,083
240912-15	3,835	-2,058
240912-16	3,836	-2,028
240912-17	3,823	-2,027
240912-24	3,824	-2,054
Mean	3,834	-2,050
Standard Deviation	12.2	23.5
CV	0.3%	1.1%

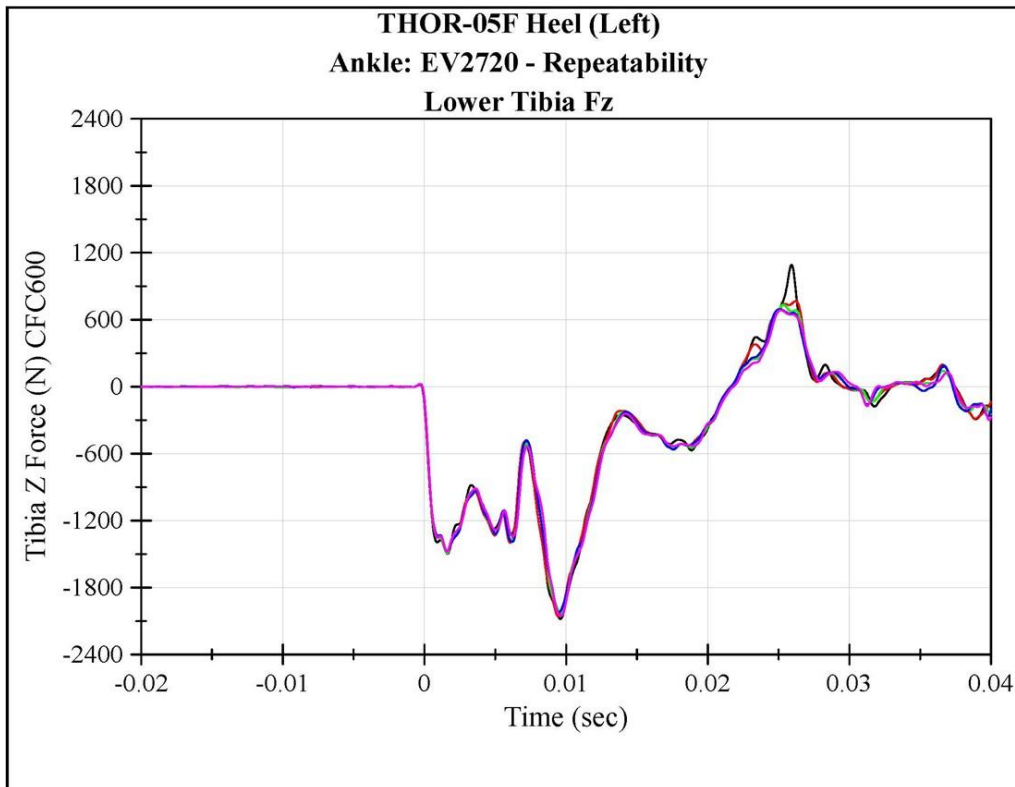


Figure 18-6. VRTC lower tibia force Fz for heel of foot impact repeatability tests for Leg EV2720

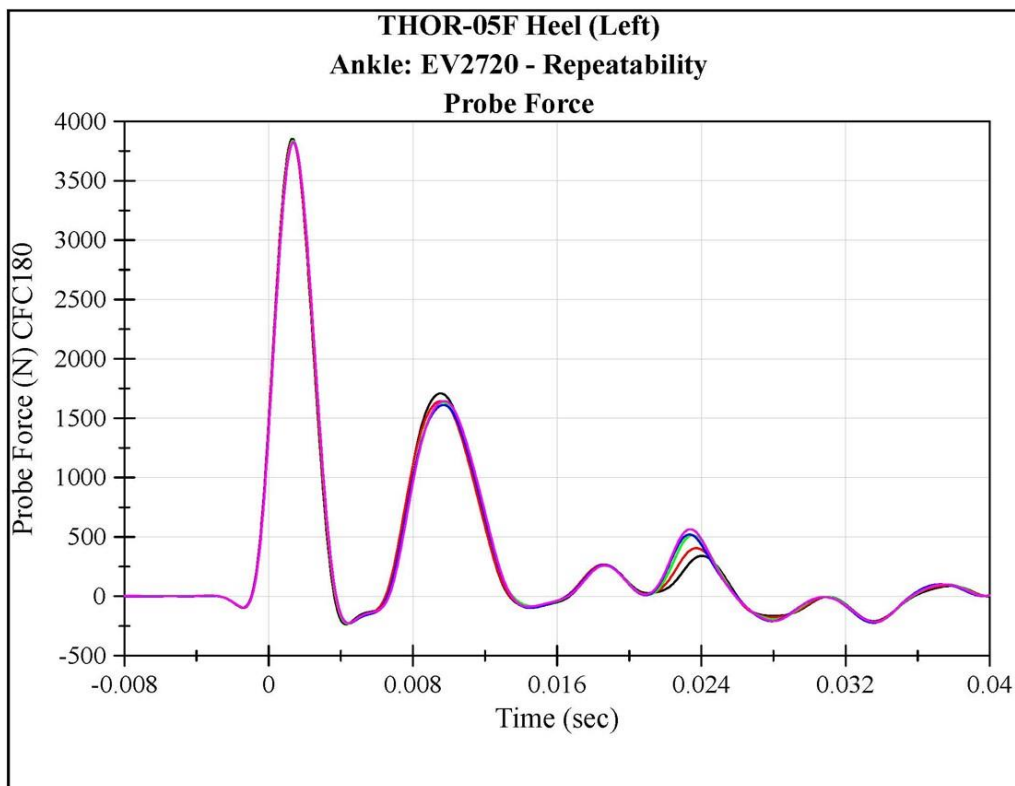


Figure 18-7. VRTC probe force for heel of foot impact repeatability tests for Leg EV2720

18.2.4 THOR-05F Left Leg EV2720 Heel Testing at Humanetics

Repeatability results at Humanetics for heel testing on Leg EV2720 (removed from ATD EV4675, left side) yielded CV values below 5 percent (Table 18-4, Figure 18-8 through Figure 18-9).

Table 18-4. Humanetics THOR-05F Left Heel of Foot Repeatability Results for Leg EV2720

Test Number	Maximum Probe Force (N)	Minimum Lower Tibia Force F_z (N)
686534	3,922	-1,986
686553	3,935	-1,995
686542	3,925	-1,974
686526	3,943	-1,974
686352	3,943	-1,928
Mean	3,934	-1,972
Standard Deviation	9.9	25.7
CV	0.3%	1.3%

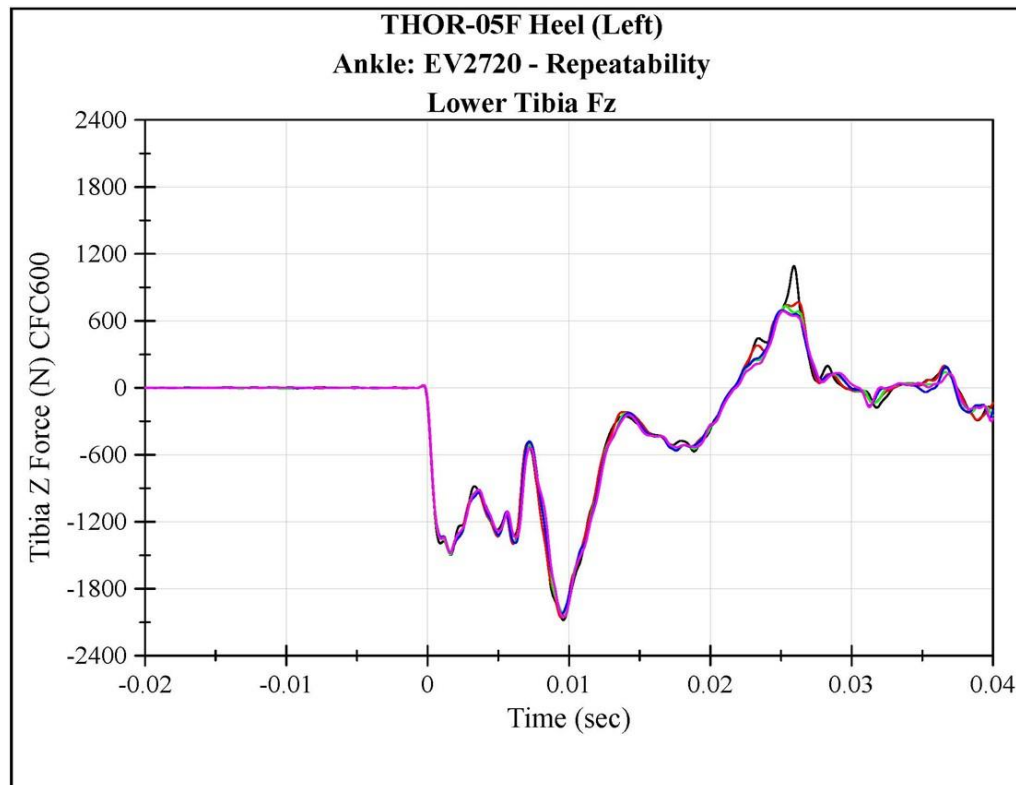


Figure 18-8. Humanetics lower tibia force Fz for heel of foot impact repeatability tests for Leg EV2720

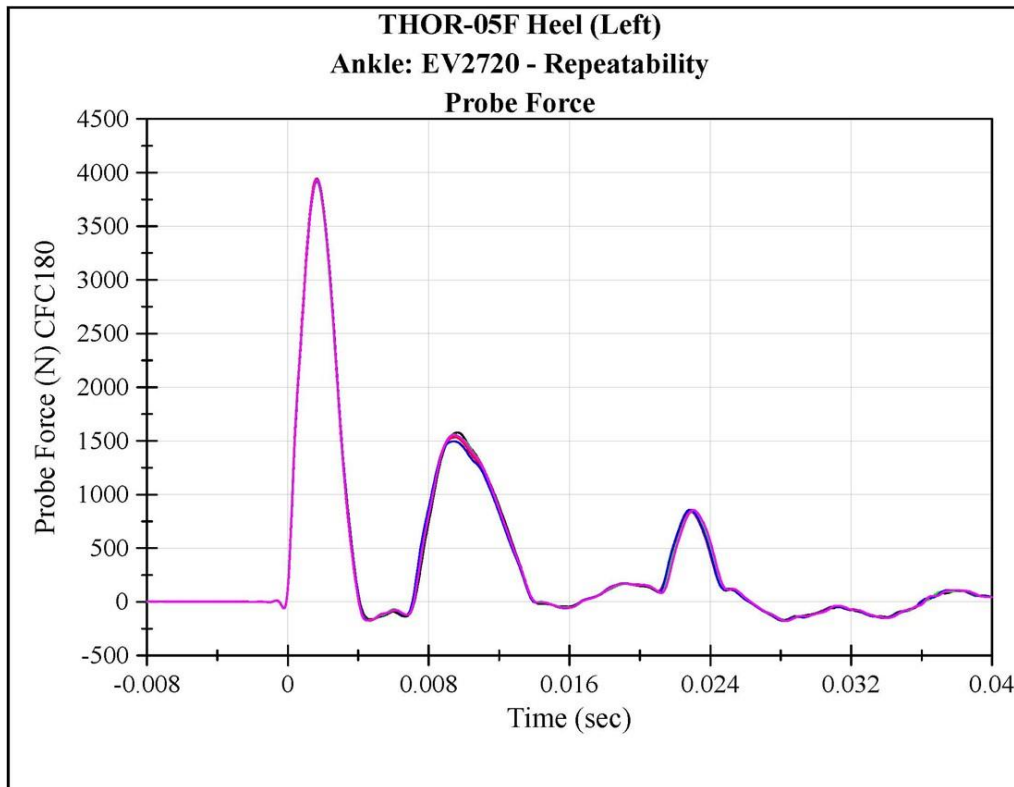


Figure 18-9. Humanetics probe force for heel of foot impact repeatability tests for Leg EV2720

18.2.5 THOR-05F Left Leg EV2720 Heel Testing at Calspan

Repeatability results at Calspan for heel testing on Leg EV2720 (removed from ATD EV4675, left side) yielded CV values below 5 percent (Table 18-5, Figure 8-10 through Figure 8-11).

Table 18-5. Calspan THOR-05F Left Heel of Foot Repeatability Results for Leg EV2720

Test Number	Maximum Probe Force (N)	Minimum Lower Tibia Force F_z (N)
2025_03_28 14_36	3,614	-1,729
2025_03_28 15_08	3,620	-1,780
2025_03_28 15_41	3,630	-1,807
2025_03_28 16_13	3,597	-1,761
2025_03_28 16_45	3,580	-1,723
Mean	3,608	-1,760
Standard Deviation	19.5	35.3
CV	0.5%	2.0%

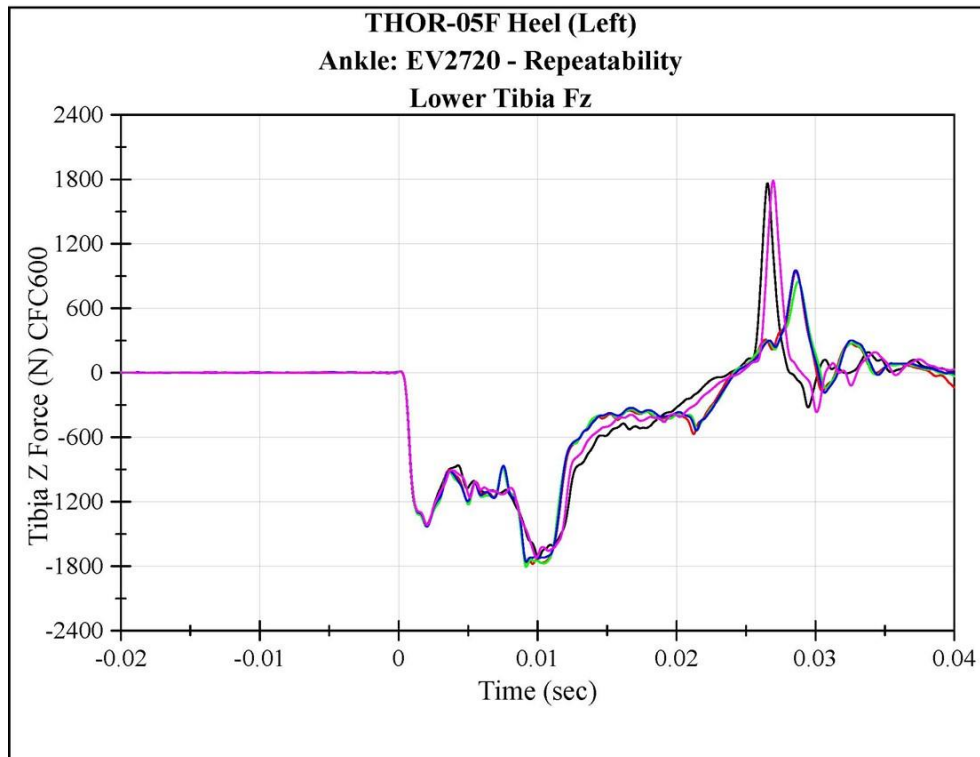


Figure 18-10. Calspan lower tibia force Fz for heel of foot impact repeatability tests for Leg EV2720

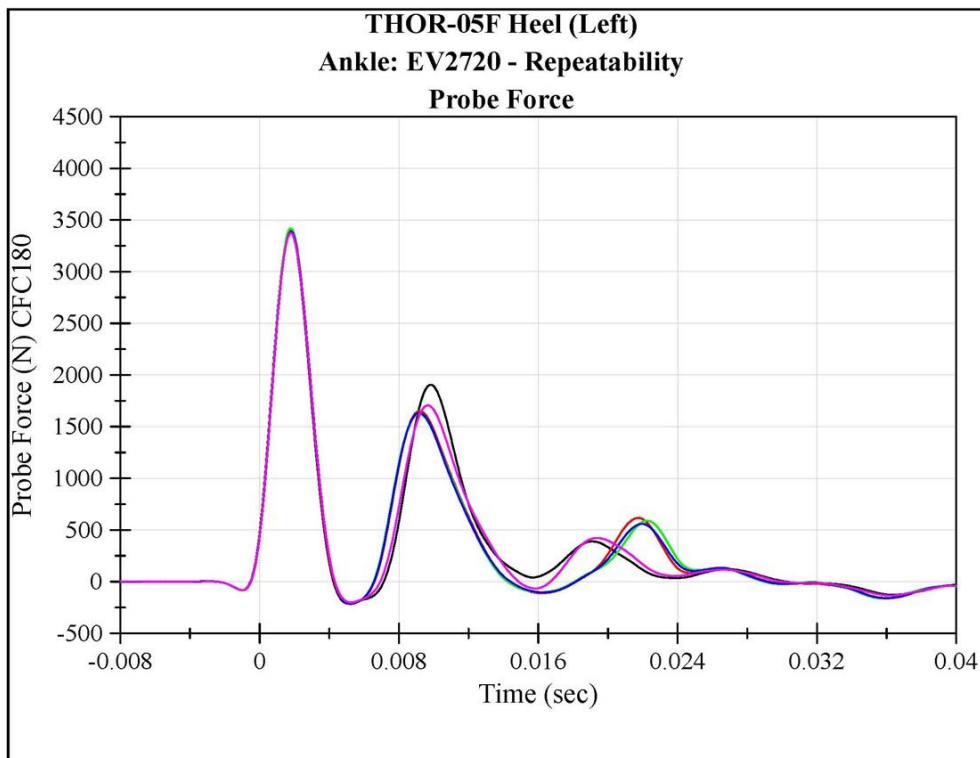


Figure 18-11. Calspan probe force for heel of foot impact repeatability tests for Leg EV2720

18.2.6 THOR-05F Left Leg EV2720 Heel testing at TRC

Repeatability results at TRC for heel testing on Leg EV2720 (removed from ATD EV4675, left side) yielded CV values below 5 percent (Table 18-6, Figure 18-12 through Figure 18-13).

Table 18-6. TRC THOR-05F Left Heel of Foot Repeatability Results for Leg EV2720

Test Number	Maximum Probe Force (N)	Minimum Lower Tibia Force F_z (N)
2025_04_29 10_16	3,605	-1,970
2025_04_29 11_23	3,553	-1,962
2025_04_29 12_10	3,594	-1,866
2025_04_29 12_43	3,546	-1,950
2025_04_29 13_27	3,600	-1,907
Mean	3,580	-1,931
Standard Deviation	27.7	43.8
CV	0.8%	2.3%

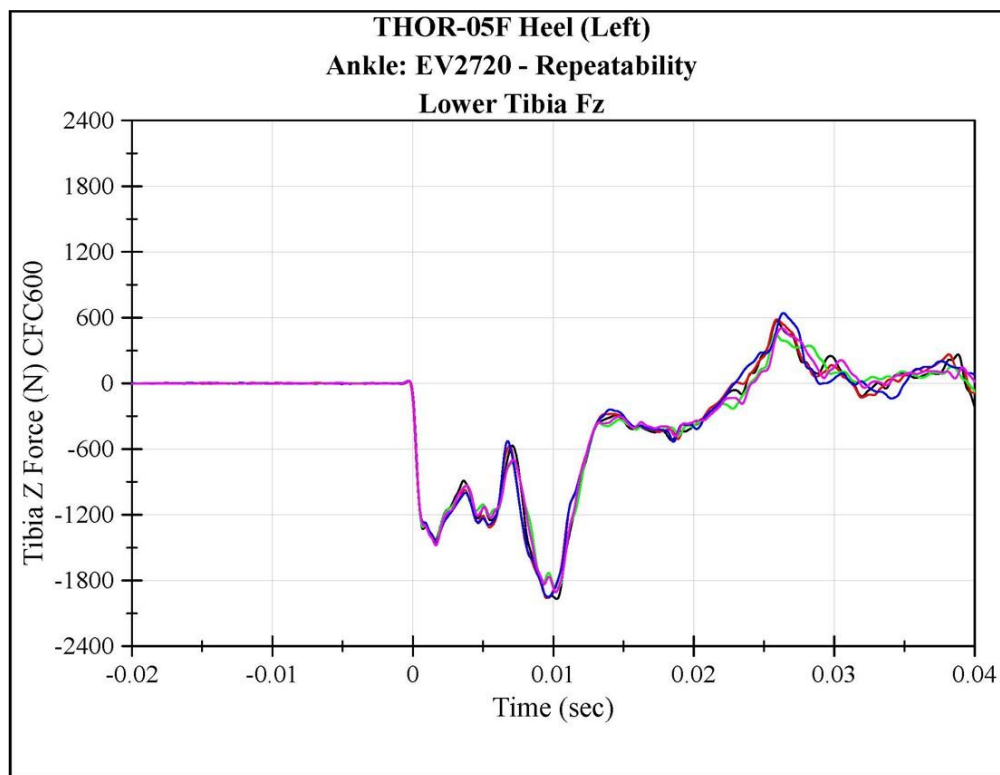


Figure 18-12. TRC lower tibia force Fz for heel of foot impact repeatability tests for Leg EV2720

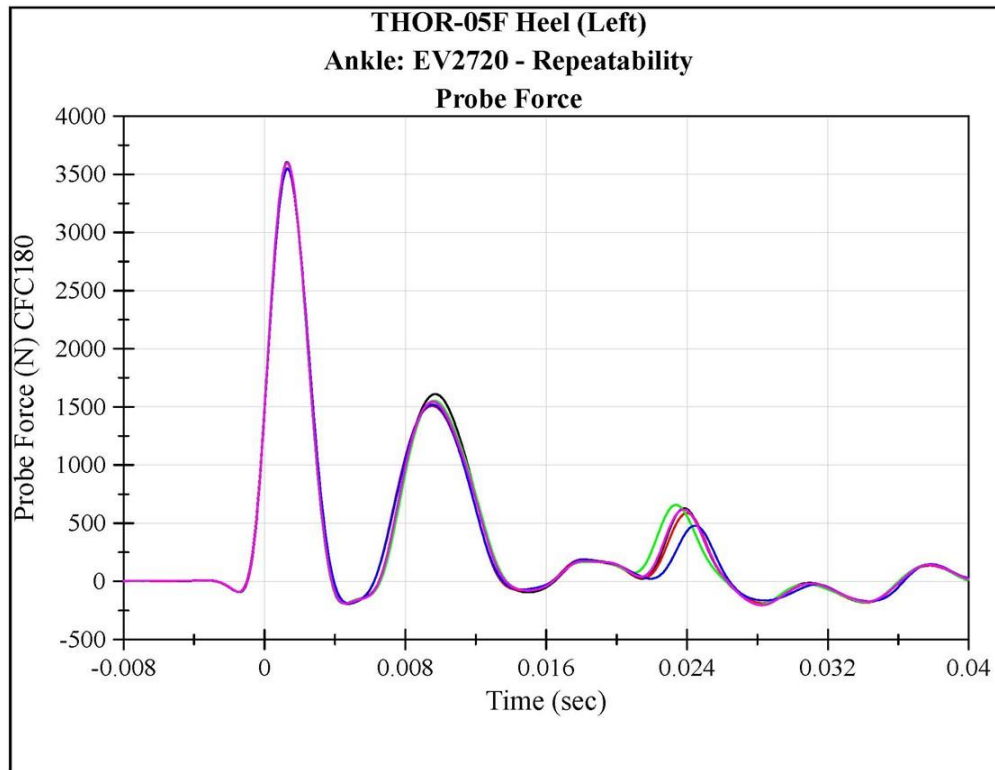


Figure 18-13. TRC probe force for heel of foot impact repeatability tests for Leg EV2720

18.3 Heel Impact Dummy Reproducibility Results

Dummy Reproducibility results at VRTC for the heel yielded CV values at 5 percent or below (Table 18-7).

Table 18-7. THOR-05F Heel Impact Qualification Reproducibility Results

Leg Number	Test Number	Maximum Probe Force (N)	Minimum Lower Tibia Force F_z (N)
VRTC EV0668 Ankle 4180	240530-1	3,964	-2,132
	240530-2	3,959	-2,107
	240530-3	3,955	-2,093
	240530-4	3,953	-2,096
	240530-5	3,945	-2,100
VRTC EV0674 Ankle EV1130	240606-4	4,110	-2,254
	240606-5	4,072	-2,289
	240606-6	4,056	-2,325
	240606-7	4,050	-2,296
	240606-8	4,043	-2,289
VRTC EV4675 Ankle 2720	240912-14	3,853	-2,083
	240912-15	3,835	-2,058
	240912-16	3,836	-2,028
	240912-17	3,823	-2,027
	240912-24	3,824	-2,054
Mean		3,952	-2,149
Standard Deviation		99.4	108
CV		2.5%	5.0%

18.4 Lab-to-Lab Variability Analysis

Test Reproducibility results at all four labs for the heel impact tests yielded CV values below 5 percent for probe force and above 5 percent, but under 10 percent for minimum lower tibia force (Table 18-8).

Table 18-8. THOR-05F Heel Impact Qualification Reproducibility Results

Leg Number	Test Number	Maximum Probe Force (N)	Minimum Lower Tibia Force F_z (N)
VRTC EV4675 Ankle EV2720	240912-14	3,853	-2,083
	240912-15	3,835	-2,058
	240912-16	3,836	-2,028
	240912-17	3,823	-2,027
	240912-24	3,824	-2,054
Humanetics EV4675 Ankle EV2720	686534	3,922	-1,986
	686553	3,935	-1,995
	686542	3,925	-1,974
	686526	3,943	-1,974
	686352	3,943	-1,928
Calspan EV4675 Ankle EV2720	2025_03_28 14_36	3,614	-1,729
	2025_03_28 15_08	3,620	-1,780
	2025_03_28 15_41	3,630	-1,807
	2025_03_28 16_13	3,597	-1,761
	2025_03_28 16_45	3,580	-1,723
TRC EV4675 Ankle EV2720	2025_04_29 10_16	3,605	-1,970
	2025_04_29 11_23	3,553	-1,962
	2025_04_29 12_10	3,594	-1,866
	2025_04_29 12_43	3,546	-1,950
	2025_04_29 13_27	3,600	-1,907
Test Reproducibility EV2720			
Mean		3,739	-1,928
Standard Deviation		154	113
CV		4.1%	5.9%

18.5 Corridor Development

All the data used to determine the heel impact qualification corridors is shown in Table 18-9. The qualification corridors were calculated using the mean plus or minus 10 percent of the peak for the specified measured or calculated channels (Table 18-10).

Table 18-9. THOR-05F Heel Impact Qualification Reproducibility Results
(Highlighted values fell outside average $\pm 10\%$.)

Leg Number	Test Number	Maximum Probe Force (N)	Minimum Lower Tibia Force F_z (N)
VRTC EV0668 Leg 4180	240530-1	3,964	-2,132
	240530-2	3,959	-2,107
	240530-3	3,955	-2,093
	240530-4	3,953	-2,096
	240530-5	3,945	-2,100
VRTC EV0674 Leg EV1130	240606-4	4,110	-2,254
	240606-5	4,072	-2,289
	240606-6	4,056	-2,325
	240606-7	4,050	-2,296
	240606-8	4,043	-2,289
VRTC EV4675 Leg 2720	240912-14	3,853	-2,083
	240912-15	3,835	-2,058
	240912-16	3,836	-2,028
	240912-17	3,823	-2,027
	240912-24	3,824	-2,054
Humanetics EV4675 Leg EV2720	686534	3,922	-1,986
	686553	3,935	-1,995
	686542	3,925	-1,974
	686526	3,943	-1,974
	686352	3,943	-1,928
Calspan EV4675 Leg EV2720	2025_03_28_14_36	3,614	-1,729
	2025_03_28_15_08	3,620	-1,780
	2025_03_28_15_41	3,630	-1,807
	2025_03_28_16_13	3,597	-1,761
	2025_03_28_16_45	3,580	-1,723
TRC EV4675 Leg EV2720	2025_04_29_10_16	3,605	-1,970
	2025_04_29_11_23	3,553	-1,962
	2025_04_29_12_10	3,594	-1,866
	2025_04_29_12_43	3,546	-1,950
	2025_04_29_13_27	3,600	-1,907
Mean		3,830	-2,018
Standard Deviation		184	168
CV		4.8%	8.3%

Table 18-10. Heel Qualification Response Requirements

Parameter	Units	Min.	Max.	Nominal Target	Corridor Width %
Impact Velocity	m/s	3.95	4.05	4.00	
Maximum Probe Force	N	3,447	4,212	3,830	10%
Minimum Lower Tibia F_z	N	-2,220	-1,816	-2,018	10%

Discussion. Highlighted cells in Table 18-9 indicate test values that did not meet the respective target response $\pm 10\%$. The tests at Calspan (EV2720) all revealed low tibia Z-axis force. Leg EV1130 at VRTC also fell outside of the respective corridors for lower tibia Z-axis force, but these values were above the specification range. The probe force CV values were all below 5 percent.

Dummy Repeatability showed all CV values below 5 percent.

Dummy Reproducibility yielded all CV values 5 percent and below.

In the case of *Test Repeatability*, CV values were under 5 percent for probe force and above 5 percent for lower tibia Z-axis force. All five tests at Calspan were below the lower specification value for this test measurement, so this increased the CV value.

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	Maximum Probe Force (N)	Maximum Head CG Resultant Acceleration (G)
Nominal Target	5,073	155.7
Acceptance Corridor	4,566 – 5,581	140.1 – 171.2
<i>Dummy/Test Repeatability: Average CV (range)</i>	<i>0.7% (0.1 – 1.8%)</i>	<i>1.5% (0.3 – 3.4%)</i>
<i>Test Reproducibility: CV</i>	<i>2.7%</i>	<i>3.2%</i>
<i>Dummy Reproducibility: CV</i>	<i>3.3%</i>	<i>2.2%</i>

Special needs: None. All tests were within the ± 10 percent range. Since the dummy reproducibility CV was less than 10% for all data channels, the comprehensive data set was considered suitable to use for qualification criteria development.

2. Face Impact

Requirements:

Measurement	Maximum Probe Force (N)
Nominal Target	6,076
Acceptance Corridor	5,469 – 6,684
<i>Dummy/Test Repeatability: Average CV (range)</i>	<i>3.6% (1.8 – 4.9%)</i>
<i>Test Reproducibility: CV</i>	<i>5.8%</i>
<i>Dummy Reproducibility: CV</i>	<i>9.5%</i>

Special needs: Variation in this test mode may have 2 sources: dummy-to-dummy differences (*Dummy Reproducibility*) and differences in the test setup (*Test Reproducibility*) due to lab-to-lab setup differences. The response is driven by the thermoset face insert, so changes in material properties have the potential to critically influence results. Additionally, some labs may need to fine-tune the setup to achieve the specified force. Since the dummy reproducibility CV was less than 10%, the comprehensive data set was considered suitable to use for qualification criteria development.

3. Neck – Flexion

Requirements:

Measurement	Max Upper Neck (My) (N-m)	Max Upper Neck (Fz @ < 40 ms) (N)	Min Head Angular Velocity (ω_y) (deg/s)	Min Head Rotation (deg)
Nominal Target	17.8	770	2,136	78.2
Acceptance Corridor	16.0 – 19.5	693 - 847	2,350 -1,923	86.1 -70.4
<i>Dummy/Test Repeatability: Average CV (range)</i>	<i>1.1% (0.3 - 1.7%)</i>	<i>2.6% (1.9 - 3.4%)</i>	<i>0.9% (0.8 – 1.6%)</i>	<i>0.7% (0.3 -1.1%)</i>
<i>Test Reproducibility: CV</i>	<i>3.0%</i>	<i>9.7%</i>	<i>5.3%</i>	<i>2.6%</i>
<i>Dummy Reproducibility: CV</i>	<i>1.7%</i>	<i>2.9%</i>	<i>3.2%</i>	<i>1.4%</i>

Special needs: Lab-to-lab setup differences are evident in the upper neck Z-axis force requirement as shown by the 9.7% CV value. Also, labs may need to adjust the input pulse by experimenting with honeycomb cell configurations to achieve the target response. Since the dummy reproducibility CV was less than 10% for all data channels, the comprehensive data set was considered suitable to use for qualification criteria development.

4. Neck - Extension

Requirements:

Measurement	Min Upper Neck (My) (N-m)	Min Upper Neck (Fz) (N)	Max Head Angular Velocity (ω_y) (deg/s)	Max Head Rotation (deg)
Nominal Target	18.9	1,335	2,393	87.9
Acceptance Corridor	20.8 -17.0	1,469 -1,202	2,154 – 2,632	79.1 – 96.7
<i>Dummy/Test Repeatability: Average CV (range)</i>	<i>3.9% (1.0-13.9%)</i>	<i>2.1% (1.1 – 4.3%)</i>	<i>0.7% (0.3 – 1.2%)</i>	<i>0.9% (0.5 – 1.2%)</i>
<i>Test Reproducibility: CV</i>	<i>6.2%</i>	<i>7.5%</i>	<i>3.0%</i>	<i>1.2%</i>
<i>Dummy Reproducibility: CV</i>	<i>9.0%</i>	<i>7.3%</i>	<i>2.0%</i>	<i>1.9%</i>

Special needs: Dummy-to-dummy differences are likely the source of force and moment variation for *Dummy Reproducibility*. Also, labs may need to adjust the input pulse by experimenting with honeycomb cell configurations to achieve the target response. Since the dummy reproducibility CV was less than 10% for all data channels, the comprehensive data set was considered suitable to use for qualification criteria development.

5. Neck – Lateral

Requirements:

Measurement	Peak Upper Neck (M _x) (M _x @ > 40 ms) (N-m)	First Peak Head Angular Velocity (ω_y) (deg/s)	Peak Head Rotation (deg)
Nominal Target	30.7	1,359	49.3
Acceptance Corridor	27.6 – 33.7	1,223 – 1,495	44.4 – 54.2
<i>Dummy/Test Repeatability: Average CV (range)</i>	<i>1.8% (0.9 – 3.2%)</i>	<i>1.2% (0.8 -2.0%)</i>	<i>1.2% (0.9 – 1.9%)</i>
<i>Test Reproducibility: CV</i>	<i>4.9%</i>	<i>4.5%</i>	<i>10.6%</i>
<i>Dummy Reproducibility: CV</i>	<i>3.8%</i>	<i>2.5%</i>	<i>3.4%</i>

Special needs: Lab-to-lab differences are noted for *Test Reproducibility* for peak head rotation. Individual lab setup differences could be the cause and should be monitored. Also, labs may need to adjust the input pulse by experimenting with honeycomb cell configurations to achieve the target response. Since the dummy reproducibility CV was less than 10% for all data channels, the comprehensive data set was considered suitable to use for qualification criteria development.

6. Neck – Torsion

Requirements:

Measurement	Peak Upper Neck (M _z) (N-m)	Peak Neck Angular Velocity (ω_y) (deg/s)	Peak Neck Fixture Rotation (deg)
Nominal Target	20.4	1,284	51.5
Acceptance Corridor	18.3 – 22.4	1,156 – 1,413	46.3 – 56.6
<i>Dummy/Test Repeatability: Average CV (range)</i>	<i>0.9% (0.5 – 1.5 %)</i>	<i>1.2% (0.4 – 1.7%)</i>	<i>1.2% (0.7 – 1.8%)</i>
<i>Test Reproducibility: CV</i>	<i>2.6%</i>	<i>2.9%</i>	<i>4.0%</i>
<i>Dummy Reproducibility: CV</i>	<i>2.4%</i>	<i>1.3%</i>	<i>2.3%</i>

Special needs: None. All tests were within the ± 10 percent range. Since the dummy reproducibility CV was less than 10% for all data channels, the comprehensive data set was considered suitable to use for qualification criteria development.

7. Upper Thorax

Requirements:

Measurement	Maximum Probe Force (N)	Maximum Upper Resultant Deflection (mm)	Force @ Max Resultant Deflection (N)
Nominal Target	1,995	35.3	1,796
Acceptance Corridor	1,796 – 2,195	31.7 – 38.8	1,616 – 1,976
<i>Dummy/Test Repeatability: Average CV (range)</i>	<i>3.0% (1.8 – 6.1%)</i>	<i>3.6% (1.6 – 4.6%)</i>	<i>2.0% (0.9 – 2.9%)</i>
<i>Test Reproducibility: CV</i>	<i>5.1%</i>	<i>6.8%</i>	<i>4.3%</i>
<i>Dummy Reproducibility: CV</i>	<i>3.5%</i>	<i>5.4%</i>	<i>3.5%</i>

Special needs: To assure symmetrical impacts, the difference between the left and right resultant deflections should be calculated and observed 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 nonsymmetrical impact or could indicate a problem with the instrumentation. Since the dummy reproducibility CV was less than 10% for all data channels, the comprehensive data set was considered suitable to use for qualification criteria development.

8. Lower Thorax

Requirements:

Measurement	Maximum Probe Force (N)	Resultant Deflection @ Max Force (mm)
Nominal Target	2,008	42.7
Acceptance Corridor	1,807 – 2,209	38.4 – 46.9
<i>Dummy/Test Repeatability: Average CV (range)</i>	<i>2.9% (1.5 – 7.1%)</i>	<i>4.4% (1.9 – 7.3%)</i>
<i>Test Reproducibility: CV</i>	<i>3.9%</i>	<i>9.3%</i>
<i>Dummy Reproducibility: CV</i>	<i>5.5%</i>	<i>7.2%</i>

Special needs: *Test Reproducibility* should be monitored for lab-to-lab setup differences based on the CV value for the resultant deflection at peak force. Since the dummy reproducibility CV was less than 10% for all data channels, the comprehensive data set was considered suitable to use for qualification criteria development.

9. Abdomen

Requirements:

Measurement	Maximum Probe Force (N)	Maximum Abdomen Pressure (kPa)
Nominal Target	4,502	210
Acceptance Corridor	4,052 – 4,952	189 - 231
<i>Dummy/Test Repeatability: Average CV (range)</i>	<i>1.7% (1.3 – 2.2%)</i>	<i>2.4% (1.6 – 3.5%)</i>
<i>Test Reproducibility: CV</i>	<i>2.2%</i>	<i>3.8%</i>
<i>Dummy Reproducibility: CV</i>	<i>2.0%</i>	<i>3.0%</i>

Special needs: All tests were within the ± 10 percent range. To assure symmetrical impacts, the difference between the left and right abdomen pressures should be calculated and observed to assure an even impact to the abdomen. Ideally, the difference should be zero in a symmetrical impact scenario. Any large differences would likely be attributed to setup variations which allowed a nonsymmetrical impact or could indicate a problem with the pressure transducers. Since the dummy reproducibility CV was less than 10% for all data channels, the comprehensive data set was considered suitable to use for qualification criteria development.

10. Upper Leg

Requirements:

Measurement	Maximum Probe Force (N)	Minimum Femur Force (Fz) (N)	Maximum Resultant Acetabulum Force (N)
Nominal Target	7,894	4,123	2,033
Acceptance Corridor	7,105 – 8,684	4,535 -3,711	1,829 – 2,236
<i>Dummy/Test Repeatability: Average CV (range)</i>	<i>2.6% (1.1 – 3.9%)</i>	<i>4.0% (1.4 – 8.0%)</i>	<i>4.0% (2.5 – 7.3%)</i>
<i>Test Reproducibility: CV</i>	<i>6.4%</i>	<i>6.2%</i>	<i>6.1%</i>
<i>Dummy Reproducibility: CV</i>	<i>4.4%</i>	<i>7.5%</i>	<i>5.9%</i>

Special needs: Lab-to-lab *Test Reproducibility* variability in setup should be monitored. Some labs may need to fine-tune setup to achieve the specified femur force. Impact alignment is critical for accurate results. Since the dummy reproducibility CV was less than 10% for all data channels, the comprehensive data set was considered suitable to use for qualification criteria development.

11. Knee

Requirements:

Measurement	Minimum Femur Z-Axis Force (N)	Knee Deflection @ Min Femur Force (mm)
Nominal Target	3,818	13.8
Acceptance Corridor	4,194 -3,431	15.2 -12.4
<i>Dummy/Test Repeatability: Average CV (range)</i>	<i>4.4% (1.5 – 6.0%)</i>	<i>0.7% (0.4 – 1.6%)</i>
<i>Test Reproducibility: CV</i>	<i>5.8%</i>	<i>2.2%</i>
<i>Dummy Reproducibility: CV</i>	<i>7.6%</i>	<i>1.0%</i>

Special needs: A “break-in” effect was evident wherein the femur force and knee deflection were lower in the first trial. This is only a concern if a qualification test produces femur forces and deflections that are just below the upper qualification limits, since subsequent tests may be expected to produce slightly higher forces and deflections (which might be out of the qualification range). Dummy reproducibility CV values may indicate manufacturing differences that are affecting test results. Since the dummy reproducibility CV was less than 10% for all data channels, the comprehensive data set was considered suitable to use for qualification criteria development.

12. Ankle Inversion

Requirements:

Measurement	Minimum Lower Tibia Fz (N)	Minimum Ankle X-axis Resistive Moment (N-m)	Minimum Ankle X-axis Rotation (deg)
Nominal Target	318	28.6	27.8
Acceptance Corridor	349 -286	25.7 – 31.4	25.0 – 30.6
<i>Dummy/Test Repeatability: Average CV (range)</i>	<i>1.4% (0.6 – 2.3%)</i>	<i>1.4% (0.7 – 2.1%)</i>	<i>0.6% (0.1 – 1.1%)</i>
<i>Test Reproducibility: CV</i>	<i>7.5%</i>	<i>3.2%</i>	<i>3.9%</i>
<i>Dummy Reproducibility: CV</i>	<i>4.6%</i>	<i>1.3%</i>	<i>1.4%</i>

Special needs: Given that one lab’s tibia force consistently had a higher magnitude than the other labs, lab-to-lab setup differences are likely the source of tibia force variation for *Test Reproducibility*. Since the dummy reproducibility CV was less than 10% for all data channels, the comprehensive data set was considered suitable to use for qualification criteria development.

13. Ankle Eversion

Requirements:

Measurement	Minimum Lower Tibia Fz (N)	Maximum Ankle X-axis Resistive Moment (N-m)	Maximum Ankle X-axis Rotation (deg)
Nominal Target	321	29.1	27.6
Acceptance Corridor	353 - 289	26.2 - 32.0	24.8 – 30.3
<i>Dummy/Test Repeatability: Average CV (range)</i>	2.0% (0.6 – 3.6%)	1.5% (0.6 – 1.9%)	0.5% (0.2 – 0.7%)
<i>Test Reproducibility: CV</i>	8.1%	3.1%	2.3%
<i>Dummy reproducibility: CV</i>	2.1%	1.7%	2.3%

Special needs: Similar to inversion, lab-to-lab setup differences are likely the source of tibia force variation for *Test Reproducibility*. Since the dummy reproducibility CV was less than 10% for all data channels, the comprehensive data set was considered suitable to use for qualification criteria development.

14. Ball of foot

Requirements:

Measurement	Minimum Lower Tibia Fz @ > 10 ms (N)	Maximum Ankle Y-axis Resistive Moment (N-m)	Maximum Ankle Y-axis Rotation (deg)
Nominal Target	928	47.7	33.9
Acceptance Corridor	1,020 - 835	42.9 – 52.4	30.6 – 37.3
<i>Dummy/Test Repeatability: Average CV (range)</i>	1.8% (1.5 – 2.2%)	2.4% (1.7 – 3.2%)	1.1% (0.3 – 3.9%)
<i>Test Reproducibility: CV</i>	3.1%	6.8%	2.3%
<i>Dummy Reproducibility: CV</i>	9.0%	8.2%	7.3%

Special needs: Variation in this test mode may have 2 sources: dummy-to-dummy differences (*Dummy Reproducibility*) and differences in the initial test setup (*Test Reproducibility*) due to lab-to-lab setup differences. Test labs may need to adjust their setups and fixtures (within allowable tolerances) to attain a response within 10 percent of the specifications. Since the dummy reproducibility CV was less than 10% for all data channels, the comprehensive data set was considered suitable to use for qualification criteria development.

15. Heel

Requirements:

Measurement	Maximum Probe Force (N)	Minimum Lower Tibia Fz (N)
Nominal Target	3,830	2,018
Acceptance Corridor	3,447 – 4,212	2,220 -1,816
<i>Dummy/Test Repeatability: Average CV (range)</i>	<i>0.5% (0.2 – 0.8%)</i>	<i>1.4% (0.7 – 2.3%)</i>
<i>Test Reproducibility: CV</i>	<i>4.1%</i>	<i>5.9%</i>
<i>Dummy Reproducibility: CV</i>	<i>2.5%</i>	<i>5.0%</i>

Special needs: Given that one lab’s tibia force consistently had a lower magnitude than the other labs, lab-to-lab setup differences are likely the source of tibia force variation for *Test Reproducibility*. Since the dummy reproducibility CV was less than 10% for all data channels, the comprehensive data set was considered suitable to use for qualification criteria development.

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