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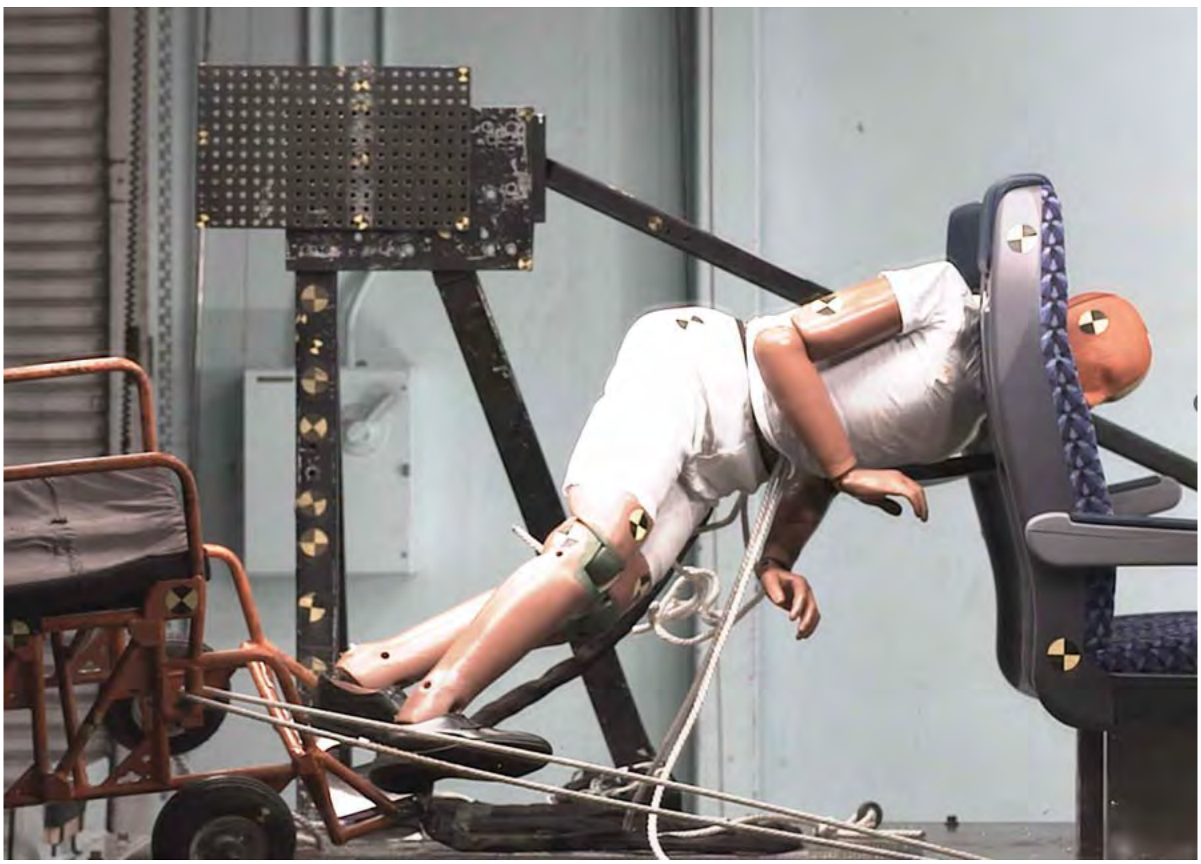
Sled Tests to Evaluate Wheelchair Securement and Occupant Restraint Systems in Simulated Train Impact



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14. ABSTRACT
The Federal Railroad Administration (FRA), with technical direction provided by the Volpe National Transportation Systems Center (Volpe), sponsored University of Michigan Transportation Research Institute (UMTRI) to conduct impact tests using a wheelchair (WC) and an Anthropomorphic Test Device (ATD) between July 2024 and January 2025 in Ann Arbor, Michigan. Over the past decade, FRA funded and led several research initiatives on rail car accessibility. The current research effort focused on evaluating the performance of wheelchairs and occupants under dynamic accident loads represented by an 8-g crash pulse with and without Wheelchair Tiedown and Occupant Restraint Systems (WTORS).

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Executive Summary

The Federal Railroad Administration (FRA), with technical direction provided by the Volpe National Transportation Systems Center, sponsored University of Michigan Transportation Research Institute (UMTRI) to conduct impact tests using a wheelchair (WC) and an Anthropomorphic Test Device (ATD) between July 2024 and January 2025 in Ann Arbor, Michigan. Over the past decade, FRA funded and led several research initiatives on rail car accessibility. The current research effort focused on evaluating the performance of wheelchairs and occupants under dynamic accident loads represented by an 8-*g* crash pulse with and without Wheelchair Tiedown and Occupant Restraint Systems (WTORS).

Some passengers do not transfer from their wheelchair to conventional vehicle seating during transportation and need to be accommodated while using their wheelchair as a vehicle seat. In road vehicles, common practice uses WTORS to secure the wheelchair and provide protection for the rider, but in many train environments, WTORS are not used. It is common for passengers to ride with their wheelchairs unsecured, without wearing a seatbelt.

The Americans with Disabilities Act (ADA) specifies the size of the wheelchair stations on rail cars. In their 2015 report to the U.S. Access board, the Rail Vehicle Access Advisory Committee (RVAAC) recommended that each rail car be designed with a wheelchair seating location of 32 in x 54 in clear space, or 32 in x 59 in if there is obstruction within the space (RVAAC, 2015). While a large space improves accessibility, the added space potentially degrades the protection offered by compartmentalization, which relies on closely spaced row-to-row seats designed to mitigate forces associated with secondary impacts.

The project team explored the potential safety benefits of using WTORS on trains by conducting 8-*g* forward-facing impact tests, to compare kinematic and injury response outcomes. The 8-*g* crash pulse is specified in Code of Federal Regulations 49 CFR 238.233 for interior fixture attachment strength requirements and in the American Public Transportation Association (APTA) standards PR-CS-S-016 and S-018 for rail passenger seat and table safety testing (APTA, 2023 and APTA, 2022, respectively). Three tests, two with WTORS and one without, were conducted using a surrogate wheelchair (SWC) and an instrumented, mid-sized Hybrid III 50th percentile male (H3-50M) Anthropomorphic Test Device (ATD).

The results show that the WTORS were effective at limiting forward excursion of the SWC and ATD. In the test with no WTORS, the ATD moved forward and lodged its head between the forward pair of passenger seats, while the SWC became a projectile. The ATD injury response measures were 1.3 to 94 times higher when no WTORS was used.

These tests illustrate how WTORS could improve safety for rail passengers riding while seated forward-facing in their wheelchairs, as long as they accommodate a wide range of wheelchairs and allow independent operation by the wheelchair rider.

1. Introduction

The Federal Railroad Administration (FRA), with technical direction provided by the Volpe National Transportation Systems Center (Volpe), sponsored a research team from University of Michigan Transportation Research Institute (UMTRI) to conduct impact tests using a wheelchair and an Anthropomorphic Test Device (ATD) between July 2024 and January 2025 in Ann Arbor, Michigan. Over the past decade, FRA has funded and led several research initiatives on rail car accessibility. The current research effort focused on evaluating the performance of wheelchairs and occupants under dynamic accident loads represented by an 8-*g* crash pulse with and without Wheelchair Tiedown and Occupant Restraint Systems (WTORS).

1.1 Background

According to the 2010 census, approximately 3.6 million people out of the 309 million people in the United States use wheelchairs (US Census, 2010). Use of transportation is essential for access to education, employment, healthcare, and other necessary activities, but not all people who use wheelchairs can safely transfer to conventional vehicle seating and thus must use a wheelchair as a vehicle seat. This is particularly common for those who use complex power wheelchairs, which can weigh over 500 lb.

The U.S. Rail Vehicle Access Advisory Committee (RVAAC) recommends that each rail car be designed with a wheelchair seating location of 32 in x 54 in clear space, or 32 in x 59 in if there is an obstruction within the space (RVAAC, 2015). However, passengers who remain seated in a wheelchair in these spaces during train travel do not benefit from all safety design strategies of the train interior, such as compartmentalization. Compartmentalization is an occupant protection strategy to protect passengers during a collision with another train or large obstacle (i.e., primary impact), by limiting the travel distance and relative velocity of unrestrained occupants before they impact an adjacent fixture (i.e., secondary impact), such as a seat or table. Secondary impact velocity (SIV) is the difference in velocity of the occupant and the train when the secondary impact occurs. The severity of secondary impact injuries is a function of the SIV, the combined mass of the occupant and wheelchair, and the stiffness of the impacted fixture.

Figure 1 depicts the velocity time histories of a train and an occupant during an accident. Prior to an accident, the train and occupant travel at the same speed. Once the train impacts another train or large object, the train begins to slow down, but the occupant continues to travel at the speed of the train prior to impact. The occupant develops speed with respect to the train until the occupant impacts part of the interior, rapidly decelerating the occupant, and often causing secondary impact injuries.

The SIV is a function of the crash pulse or deceleration time history of the train and the interior configuration. The severity of the secondary impact is a function of the SIV, the mass of the passenger and wheelchair, and the stiffness of the interior fixture. An unintended consequence of increasing the clear space in wheelchair seating locations is that the secondary impact injuries for unrestrained passengers seated in unsecured wheelchairs are likely to be more severe.

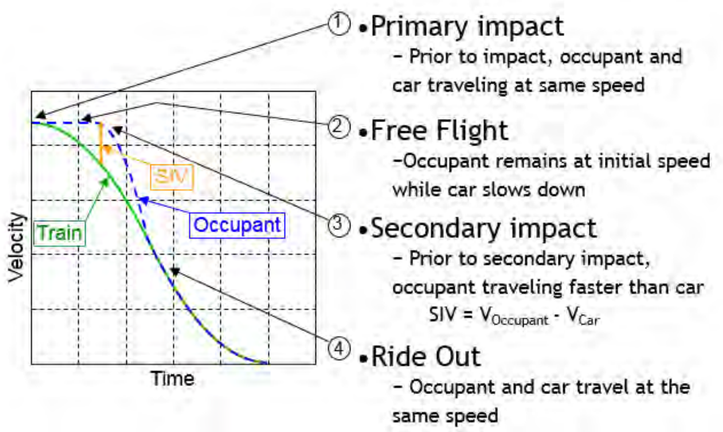

Figure 1. Velocity Time History of Train and Occupant During a Collision

Currently, wheelchairs are not required to be secured for train travel. However, this risks protection for the wheelchair-seated passenger as well as the safety of others sharing a passenger compartment with a heavy, unsecured wheelchair. Some wheelchair users feel more comfortable riding in a secured wheelchair and may want to use a seatbelt. However, seatbelts integrated in the rail car potentially impede wheelchair users' independence. It is essential for wheelchair users to have access to transportation, so any safety improvements should not negatively impact access or personal independence.

The ideal characteristics of a WTORS for rail applications are:

1. A single fixture that can secure a wide range of wheelchair types and offer a seat belt to protect the rider
2. Able to be operated by the wheelchair user without assistance from a caregiver or railroad employee
3. Provides good crash protection under 8-*g* conditions used to test passenger rail seating.

The Universal Docking Interface Geometry (UDIG) system, also simplified as UDIG in this report, plus an automated seatbelt-donning system, is one solution that meets the ideal characteristics of a WTORS and is an ideal docking station for trains and other types of public transportation settings where one wheelchair station must secure many types of wheelchairs. UDIG defines an interface geometry and location so that vehicle docking stations can secure UDIG-compliant wheelchairs. The interface geometry is two vertical bars located on the back of the wheelchair frame with an optional third horizontal bar, if needed to control rotation on a heavy wheelchair. A prototype UDIG system implemented on a manual wheelchair is shown in Figure 2, with red arrows to identify the vertical bars, while Figure 3 shows how the UDIG system was implemented on the wheelchair fixture used in for this test series. This concept is akin to the standardization of trailer hitches that allow any semi-tractor to attach and tow any trailer. Because UDIG attachments are located to the rear of the wheelchair, the design has the advantage of not decreasing ground clearance on equipped wheelchairs. The UDIG is intended to be paired with a seat belt system designed by UMTRI to create a full WTORS.

Figure 2. Example of the UDIG Prototype Hardware on a Commercial Manual Wheelchair

Figure 3. Example of the UDIG on the Wheelchair Test Fixture

Although the UDIG has been defined, prototyped, crash tested to 20-*g*s, field tested, and meets the three criteria listed above, it has not been incorporated into any commercial products (Klinich, 2022). Specifications for UDIG are included in informative and normative annexes of current Rehabilitation Engineering Society of North America (RESNA) and International Standards Organization (ISO) wheelchair transportation safety standards (RESNA 2017, ISO 2022, ISO 2012). The increased prominence of automated vehicles (AVs) has renewed interest in the UDIG concept, since AV manufacturers want to find ways that wheelchair users can travel independently and safely in scenarios where an AV is summoned from a public fleet on demand. The current vision for UDIG on wheelchairs is that it would be a feature designed into the wheelchair by the manufacturer.

The Q'Straint QLK™, shown in Figure 4, is a commercially available, crashworthy docking system that secures a wheelchair that has been fitted with a custom bracket designed for that make and model of wheelchair. QLK™ includes a seatbelt to create a complete WTORS. The same seatbelt system developed by UMTRI and tested with the UDIG was implemented in the

QLK™ test. The QLK™ bracket attaches to the underside of the wheelchair and adds a hanging bolt feature to the bottom of the wheelchair frame. This bolt is then captured by a floor-mounted dock to secure the wheelchair when the user drives forward into the system. A separate stabilizer bracket, shown in Figure 5, adds another connection point between the vehicle and the wheelchair.

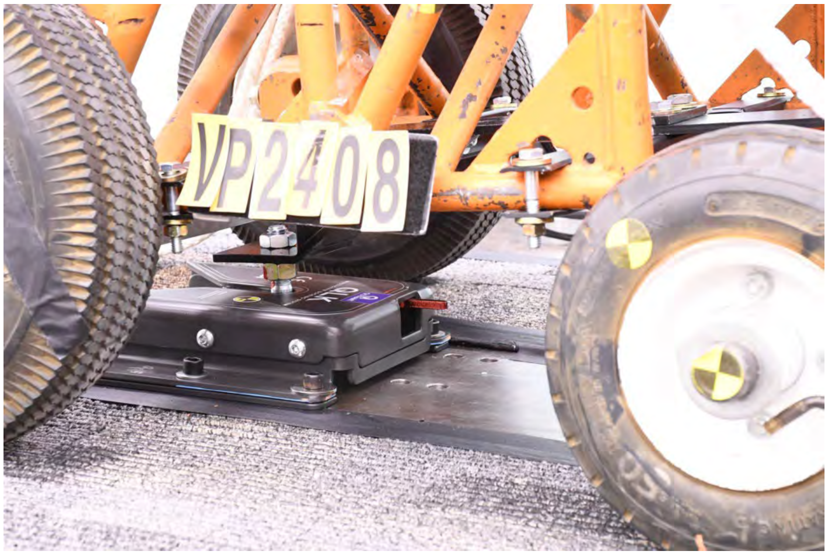

Figure 4. Q'Straint QLK™ docking hardware, as used on the test wheelchair

Figure 5. Q'Straint QLK™ Stabilizer Bracket, as used on the test wheelchair

QLK™ allows independent wheelchair securement in privately-owned vehicles that have been modified to secure one specific wheelchair. However, it is not meant to be used in a public vehicle where many different wheelchairs need to be secured. Precise alignment between the bolt and the dock is essential, and this is controlled during the vehicle modification process. Small changes in the bolt height, which may occur with changes in wheelchair tire pressure/wear, can interfere with successful docking. The hanging bolt also reduces the ground clearance of the wheelchairs and makes the wheelchair more likely to get caught on uneven surfaces or floor features, like doorway thresholds. Attachment of the bracket to the wheelchair happens after the point of sale and usually voids the wheelchair warranty.

1.2 Objectives

This project examines the effectiveness of two wheelchair securement and occupant protection strategies and compares it to the baseline case with no securement or restraint systems. The research team used these tests to evaluate these strategies using the scenario of passengers who travel on trains while seated in their wheelchairs facing the direction of train travel (forward-facing).

1.3 Overall Approach

The work employs a sled impact simulation of a train-to-train in-line collision event to compare the performance of a UDIG WTORS, a QLK™ WTORS, and a no-WTORS condition. The team then compared the motions of the WC and ATD and the ATD injury measures are compared.

1.4 Scope

This work compared the forward-facing impact response of the wheelchair and occupant under three wheelchair securement and occupant protection methods. The primary goal was to examine and illustrate occupant safety issues. Key factors not addressed are the cost, accessibility, usability, and availability of the potential solutions.

1.5 Organization of the Report

Section 2 describes how the testing was conducted. Section 3 describes the kinematic and signal outcomes from the three tests. Section 4 includes a summary and discussion of the outcomes of this project.

2. Methods

The research team conducted a series of tests at the UMTRI sled impact facility in December 2024. The three tests were designed to closely match in impact severity to demonstrate the differences in occupant protection and wheelchair securement in the three scenarios.

2.1 UMTRI Sled Facility

Figure 6 shows the UMTRI impact sled used for the test series. The sled operates on the rebound principle, achieving the desired change in velocity by reversing direction during the impact event. Although different in mechanism to other sleds, if the crash deceleration pulse is the same, the ATD kinematics and injury results will be identical to a test using an acceleration or deceleration sled device. The UMTRI sled crash pulse is trapezoidal in shape and is reported as an average and peak deceleration level in *g*. The sled velocity is monitored immediately before and after impact.

Figure 6. UMTRI Sled Impact Laboratory

2.2 Test Pulse

The APTA passenger rail seat and table safety standards specify a triangular crash pulse with an 8-*g* peak to simulate a train collision. These standards refer to SAE AS8049 to evaluate crash pulse compliance. Section 5.3.9.2 of the SAE AS8049 document defines five properties used to evaluate an acquired test pulse to ensure the minimum requirements are satisfied (SAE, 2020). The UMTRI sled approximated the total pulse energy associated with the triangular pulse using a trapezoidal pulse. Figure 7 shows a sample comparison of the UMTRI pulse and the APTA pulse. The two pulses have similar peak accelerations and velocity change, but both occur earlier in the impact event. Researchers worked with modelers at Volpe to fine-tune the UMTRI pulse to create the best match. UMTRI conducted a set of pulse calibration/refinement runs, some with an unsecured wheelchair, and some with a secured wheelchair prior to the actual test series to make sure that the pulse was optimized under the desired conditions with the appropriate amount of ATD coupling to the sled.

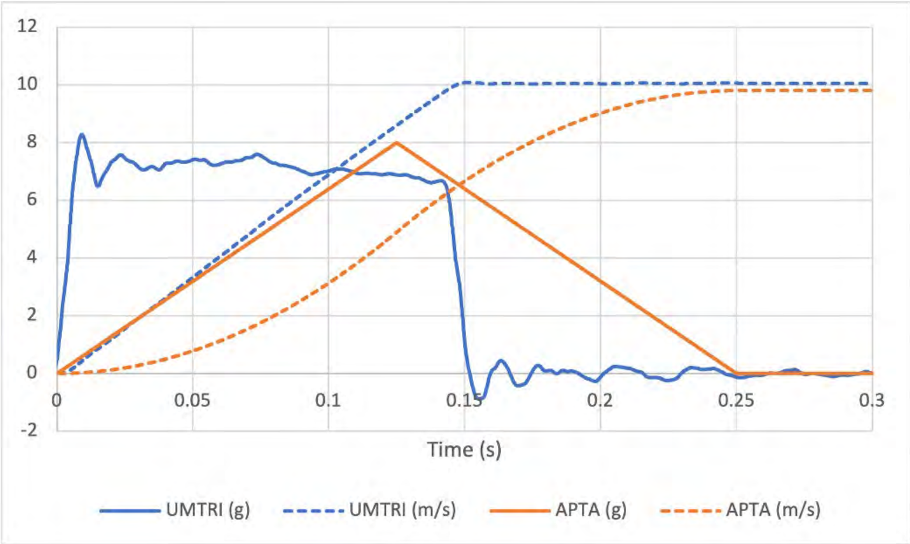

Figure 7. Comparison of UMTRI and APTA pulses

2.3 Surrogate Wheelchair

The 187-lb SWC, shown in Figure 8, represents a nominal wheelchair for evaluating WTORS, and is defined in voluntary industry standard ANSI/RESNA WC18 (RESNA, 2017). The mass, center of gravity, and basic dimensions of the SWC are defined to represent the middle of a range of typical manual or power commercial wheelchairs, either manual or power. The SWC is made of steel tubing and does not replicate the frame deformation that might be seen in a commercial wheelchair, but this non-yielding nature delivers a worst case and repeatable load to the WTORS system.

Figure 8. SWC of ANSI/RESNA WC18 and ISO 7176-19

2.4 Anthropomorphic Test Device (ATD)

National Highway Transportation Safety Administration's (NHTSA) Vehicle Research and Testing Center (VRTC) supplied a calibrated and instrumented Hybrid III 50th percentile male (H3-50M) ATD (Part 572 Subpart E) to UMTRI for the test series. This is the frontal impact

ATD used for representing a midsize adult male for testing WTORS to ANSI/RESNA WC18 (aka RESNA WC-4:2017 – Wheelchairs and Transportation Section 18: *Wheelchair Tiedown and Occupant Restraint Systems*). The ATD instrumentation included triaxial head accelerometers, triaxial chest accelerometers, a chest displacement potentiometer, a six-axis upper neck load cell, and femur load cells.

2.5 Test Matrix

Table 1 summarizes the conditions used for the three tests.

Table 1. Test Matrix

Test ID	Wheelchair Securement Method	Occupant Protection Method	Note
VP 2407	UDIG	Three-point seatbelt	
VP 2408	QLK™	Three-point seatbelt	
VP 2409	No direct securement	No direct restraint	Wheelchair with seated ATD was positioned in 59 inches/150 cm longitudinal space bounded by back of sled and back of forward passenger rail seat

2.6 Test Setup

This section provides a description of each test set-up.

2.6.1 Test #VP2407 – UDIG and Three-point Seatbelt

Figure A1 through Figure A12 of Appendix A provide detailed set up photos for test #VP2407. The team placed the SWC forward-facing on the sled platform and secured it using the heavy-duty UDIG fixture. Team members loaded the SWC with a H3-50M ATD and restrained the ATD using a surrogate vehicle-anchored three-point belt. The left side of the lap belt was anchored to the sled platform rearward of the left-rear wheelchair tiedown, while the right side of the lap belt and the lower portion of the shoulder belt formed a continuous loop through a D-ring anchored to the sled platform rearward of the right-rear tiedown of the wheelchair. A heavy-duty three-bar clip near the right hip of the ATD joined the lap belt and the lower portion of the shoulder belt. Both sides of the three-point belt were routed through the WC's armrest frame structures. The upper anchorage of the shoulder belt was bolted to a rigid fixture that simulates the geometry of a typical vehicle sidewall anchor point. The team tightened the pelvic belt to fit snugly over the ATD's pelvic region. To simulate the initial spool-out that would be present with a commercial seatbelt retractor, researchers used a 3-in block between the shoulder belt and the ATD's chest to tighten the shoulder belt snugly across the ATD's chest, in accordance with WC18. The block was removed prior to the test.

2.6.2 Test #VP2408 – Q'Straint QLK™ and Three-point Seatbelt

Figure A23 through Figure A35 of Appendix A provide detailed set up photos for test #VP2408. The team secured the SWC to the sled platform facing-forward using the Q'Straint QLK™ docking device. The QLK™ docking securement device and spacers were bolted to the steel plate on the sled and the wheelchair securement adaptor with a hardened bolt was attached to the bottom of the wheelchair. Researchers secured the wheelchair in position on the sled platform by rolling the wheelchair forward until the bolt engaged with the locking mechanism of the securement device.

Team members loaded the SWC with a H3-50M ATD and restrained the ATD with a surrogate vehicle-anchored three-point belt. The left side of the lap belt was anchored to the sled platform rearward of the left-rear wheelchair tiedown, while the right side of the lap belt and the lower portion of the shoulder belt formed a continuous loop through a D-ring anchored to the sled platform rearward of the right-rear tiedown of the wheelchair. A heavy-duty three-bar clip near the right hip of the ATD connected the lap and the lower portion of the shoulder belt. The team routed both sides of the three-point belt through the armrest of wheelchair frame structures. The upper anchorage of the shoulder belt was bolted to a rigid fixture that simulates the geometry of a typical vehicle sidewall anchor point. Like test #VP2407, UMTRI also tightened the pelvic belt to fit snugly over the ATD's pelvic region. UMTRI also tightened the shoulder belt snugly across the ATD's chest with a 3-in block between the belt and ATD. The 3-in block was removed prior to the test.

2.6.3 Test #VP2409 – No Direct Wheelchair or ATD Securement

Figure A50 through Figure A66 of Appendix A provide detailed set up photos for test #VP2409. The team positioned the SWC fully rearward on the sled plate and loaded the SWC with the H3-50M ATD. A commercial rail passenger seat was bolted to the sled plate so that the most rearward point of the commercial seat was located 59 in (150 cm) forward of the rearmost edge of the wheelchair station to simulate the level of compartmentalization on rail cars with larger accessible wheelchair space. As is typical in rail car configurations, the centerline of the two-person passenger seat was aligned with the center of the wheelchair space. A piece of aluminum flange extending upward 6 in (15 mm) blocking the rear wheels of the SWC was bolted to the rear of the sled to limit any rearward movement of the wheelchair upon sled start up. Two pieces of gaffer's tape helped maintain the initial contact between the SWC and the rear barrier. This tape tears at a very low load at the onset of the primary impact event and does not impede forward motion of the SWC.

2.7 Data Collection

The ATD transducer data and the sled acceleration data was digitized live using a TDAS™ onboard data acquisition system. All signals were filtered to the requirements of SAE J-211 (SAE, 1988). The team used the data collected to calculate head injury criteria (HIC15), 3-ms chest clip, chest maximum deflection, neck injury criteria (Nij), peak upper neck tension/compression, and peak femur loads.

The photo documentation included pre- and post-test photos as well as high-speed (1000-frames/sec) digital video of the impact event from left side, right side, right-rear side, and overhead views. These cameras were stationary. A strobe flash and simultaneous voltage pulse recorded and synchronized the onset of impact deceleration on video and transducer signals. The sideview camera video was used to determine the SWC, ATD head, and ATD knee excursions by documenting the difference in the horizontal location of the elements at the strobe flash and at the point of maximum excursion. The SWC motion was measured at "point P," a reference point located 50 mm above the seat pan and 50 mm forward of seatback that roughly corresponds to the occupant hip location, as illustrated in Figure 9. Excursion of "Point P" is the standard way that wheelchair excursion is measured in the RESNA and ISO wheelchair transportation safety standards. The knee excursion is measured at the center of rotation of the knee joint and the head excursion is measured at the leading edge of the ATD head.

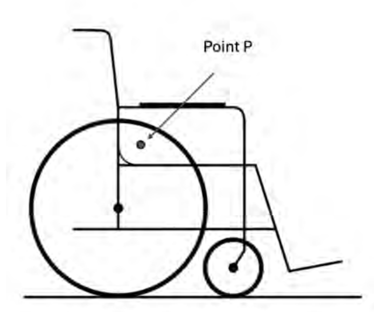

Figure 9. Diagram of Point P location

3. Results

The test results include qualitative and quantitative analysis of the wheelchair and ATD kinematics derived from the digital high-speed video, data from the ATD transducers, and observations made from post-test inspection of the tested hardware. Appendix A contains the photos and signals collected for each test.

3.1 Kinematics and Excursions

Figure 10 through Figure 15 show each sideview video frame corresponding with the peak forward ATD excursion in the three tests and the post-test sideview photo. In VP2407 and VP2408, where the wheelchair was secured and the ATD was restrained by seatbelt, the overall kinematics are very similar, with only a small amount of forward movement of the SWC and the ATD stopping early in the impact event on the seatbelts. At the end of the event, the ATD was seated in the upright SWC in approximately the same orientation as the pre-test configuration, as seen in Figure 13 and Figure 14.

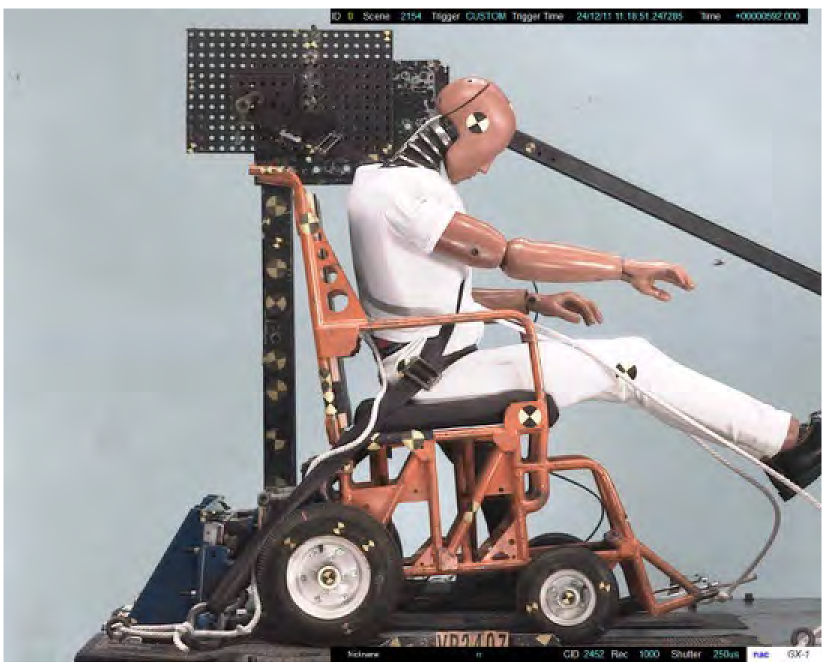

Figure 10. VP2407 still frame image of peak forward excursion

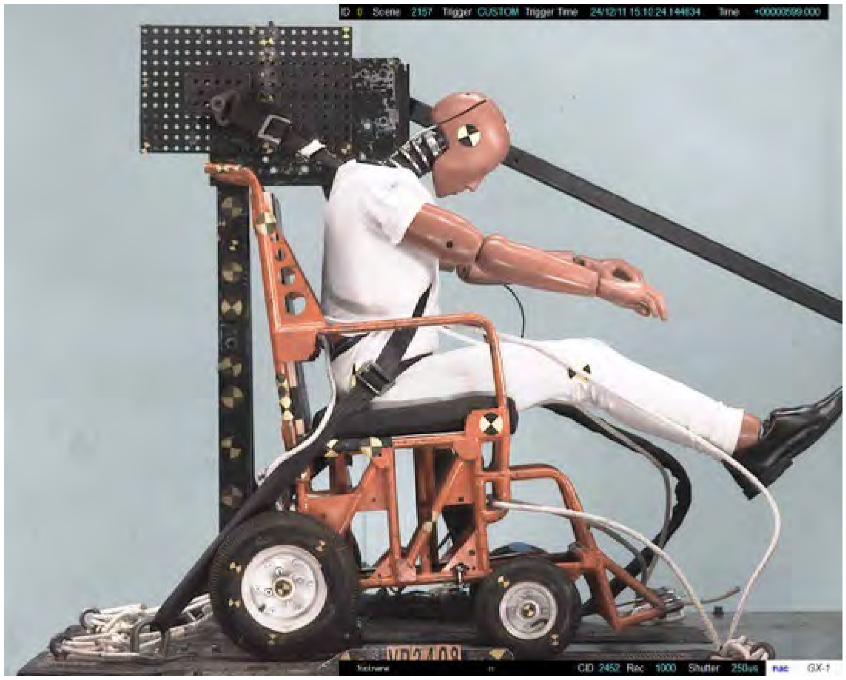

Figure 11. VP2408 still frame image of peak forward excursion

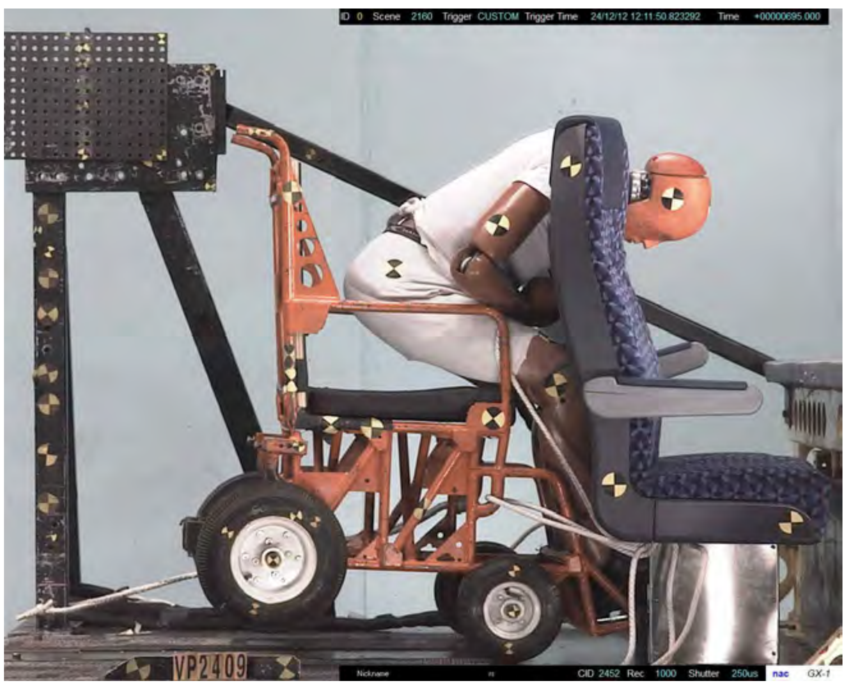

Figure 12. VP2409 still frame image of peak forward excursion

Figure 13. VP2407 post-test sideview photo

Figure 14. VP2408 post-test sideview photo

For test VP2409, the SWC and ATD moved forward until they contacted the passenger seat. The ATD lower extremities were then trapped between the SWC and the passenger seat and experienced the load of the decelerating SWC from behind while the front of the ATD pressed with the combined mass of the ATD and SWC into the passenger seat ahead. The forward motion of the upper body caused rotation at the hip, and the ATD head moved through the gap between the two forward passenger seats. The ATD forward motion was arrested through loading of the lower extremities and the tops of the shoulders. The SWC was then free to move in the wheelchair occupant space and was stopped only by the emergency tethers. The SWC moved rearward on the sled while the ATD was prevented from further motion because the head was trapped between the seats. At the end of the test (Figure 15), the ATD was in a kneeling position with the head still lodged between the impacted passenger seats, and the SWC was no longer on the sled platform.

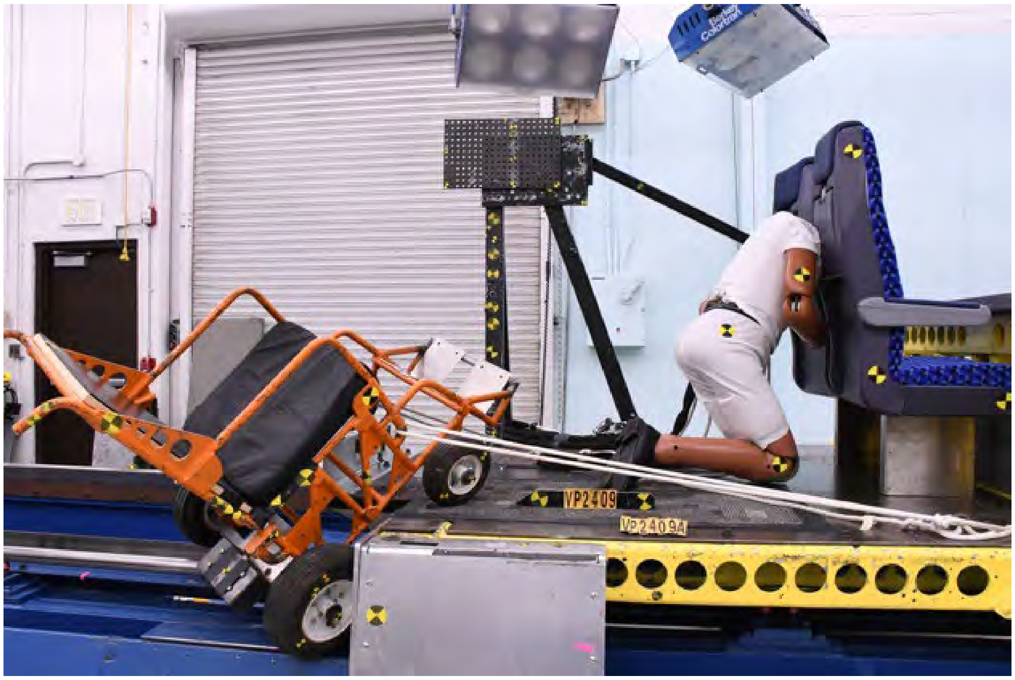

Figure 15. VP2409 post-test sideview photo

Table 2 and Figure 16 provide the SWC, ATD head, and ATD knee excursions for the three tests. These measures reflect the same trends noted from the overall kinematics, with the excursions for the no-WTORS condition far above those of the secured wheelchair and restrained ATD tests. The Appendix A photos also include a set of eight sequenced video frames that provide an overview of the recordings from each camera recording.

Table 2. SWC and ATD Excursions

Test Number/ Metric	VP2407 (UDIG)	VP2408 (QLK™)	VP2409 (None)
Point P SWC excursion, in (mm)	0.71 (18)	1.06 (27)	35.0 (889)
ATD Head excursion, in (mm)	6.30 (160)	7.56 (192)	54.57 (1386)
ATD knee excursion, in (mm)	4.29 (109)	4.06(103)	32.80 (833)

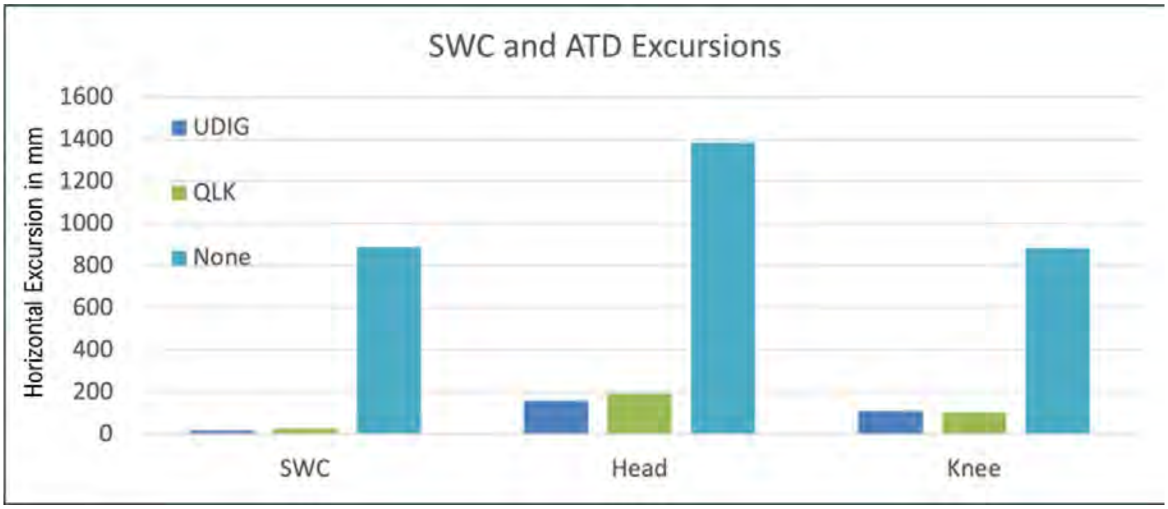

Figure 16. Comparison of Excursion Levels

3.2 ATD Injury Measures

Table 3 summarizes the ATD responses measured, as well as a ratio relative to the injury assessment reference values (IARVs). The metrics shaded in gray in the first column are performance requirements of APTA PR-CS-S-016-99 Rev 3.1 (APTA, 2023). Columns are shaded to indicate levels relative to IARVs, with red equal to or greater than IARV, orange 50-100 percent of IARV, yellow 20-50 percent of IARV, and blue less than 20 percent of IARV. The only required measure that exceeded an IARV is right femur compression load for the VP2409 "No-WTORS" condition. UMTRI compared the ATD values measured for each of the required metrics and determined that the "no-WTORS" condition recorded a higher likelihood of injury than the UDIG or QLK™ conditions for all but one measure. The increase in values for the "no-WTORS" condition over the other two tests range from 1.3 to 94 times higher than the UDIG condition. Chest deflection was the only measure where the with-WTORS conditions exceeded the no-WTORS. This was due to the shoulder belt loading the chest to limit forward motion of the ATD, but was well below the APTA performance requirement for chest deflection of 2.5 in (63 mm). On test VP2408, there is a spurious "blip" in the chest X signal trace that does not appear to reflect a physical event. Effects on the data are minimal. We expect similar chest measures between VP2507 and VP2508 due to use of the identical occupant restraint and the outputs are similar.

Table 3. ATD Injury Response Measures

Test Number/ Metric	IARV	VP2407 (UDIG) Value	VP2407 (UDIG) Ratio	VP2408 (QLK™) Value	VP2408 (QLK™) Ratio	VP2409 (No WTORS) Value	VP2409 (No WTORS) Ratio
HIC15 (700) (unitless)	700	18.1	0.026	18.1	0.026	85.2	0.12
Head Resultant (g)	--	18		18.5		34.3	
Upper Neck Force Resultant (lbf)	--	167.8		232.8		326.3	

Test Number/ Metric	IARV	VP2407 (UDIG) Value	VP2407 (UDIG) Ratio	VP2408 (QLK™) Value	VP2408 (QLK™) Ratio	VP2409 (No WTORS) Value	VP2409 (No WTORS) Ratio
Upper Neck Fz Peak Tension (lbf)	938	135.8	0.145	226.9	0.242	309.4	0.33
Upper Neck Fz Peak Compression (lbf)	899	58.7	0.065	49.5	0.055	185.4	0.21
Upper Neck Moment Resultant (lbf-ft)	--	25.4		20		55.5	
Nij NTE	1	0.17	0.170	0.17	0.170	0.59	0.59
Nij NTF	1	0.16	0.160	0.13	0.130	0.25	0.25
Nij NCE	1	0.04	0.040	0.06	0.060	0.39	0.39
Nif NCF	1	0.06	0.060	0.04	0.040	0.08	0.08
Chest 3 ms clip (g)	60	18.5	0.308	17.3	0.288	25.3	0.42
Chest Resultant (g)	--	21		21.1		30.9	
Chest Deflection (in)	2.5	0.56	0.224	0.57	0.228	0.03	0.012
Left Femur Compression (lbf)	2250	37.5	0.017	54.6	0.024	1534	0.68
Right Femur Compression (lbf)	2250	34.6	0.015	65.5	0.029	3270.0	1.45

<20% IARV, 20-50% IARV, 50-100% IARV, >IARV

4. Conclusion

Passengers in wheelchairs often ride unsecured on trains and may be at higher risk for injury than passengers seated in row-to-row seats in the event of a crash. This project compared WC and ATD kinematics along with ATD injury response measures for three WTORS scenarios: a UDIG WTORS, a QLK™ WTORS, and a no-WTORS condition. Three 8-*g* sled impact tests were conducted and showed that the use of a WTORS produced lower occupant excursions and lower injury response metrics than the no-WTORS condition. The no-WTORS condition resulted in a chaotic, uncontrolled impact, thus the results of VP2409 show one of many possible outcomes. Only the right femur compression load in the no-WTORS condition exceeded the injury assessment reference values used to evaluate passenger rail seats. These results suggest that use of WTORS has the potential to improve crash outcomes for passengers seated in wheelchairs.

The no-WTORS impact test highlighted several potential risks for occupant injury. The primary cause of passenger injury during high-*g* impact events is head strike or contact of the head with hard or sharp surfaces. The unrestrained ATD in the no-WTORS condition did not experience head strike, but also did not stay within the clear space of the wheelchair station, increasing the potential for head interaction with vehicle surfaces. Because of the uncontrolled nature of the no-WTORS condition, results could vary substantially, with potentially worse outcomes, when run with a different wheelchair, or different lateral position relative to the forward seats.

These results highlight a key benefit of seatbelt use, which allows the occupant to begin decelerating earlier in the impact and to stop over a longer amount of time. This “ride down” effect decreases the peak accelerations and forces the occupant experiences during the crash. In the first two tests, the ATD rode down the crash by stopping on the seatbelts early in the event rather than stopping more suddenly due to impact with the seatback. This is reflected in the lower acceleration values calculated by the injury response metrics for the tests with WTORS compared to the test without.

During the no-WTORS test, the ATD impacted the seatback of the forward passenger seat but was then loaded from behind by the mass of the decelerating SWC. This double load can increase injury potential for the wheelchair occupant. It should be noted that the Hybrid-III family ATDs were only designed for frontal crash impacts and were not intended for blunt impacts from behind. Real-life occupants could experience serious injuries that were not evaluated by the instrumentation in the ATD. Another concern with the unfettered movement of the wheelchair occupant and wheelchair during impact is the potential for causing injury to other passengers in the cabin.

For occupants seated in conventional passenger seats, compartmentalization occurs when they stop on the seatback forward of their seating position. The ATD head traveling in between the two forward seats in the no-WTORS test meant that, in this case, the wheelchair occupant did not experience the intended method of compartmentalization. This is due to both the center of the wheelchair station being aligned with the point where the two forward seats meet, but it was also aggravated by the higher seated position of the wheelchair occupant.

This test series illustrates some potential safety benefits associated with the use of WTORS on trains. A viable WTORS that can provide this added safety while allowing for independent use by people in many types of wheelchairs does not yet exist. Several recent studies have evaluated the crashworthiness and usability of prototype UDIG hardware to allow safe and independent use of wheelchairs in AVs (Klinich et al. 2022), which could also be used in other transportation modes such as railroads. NHTSA has sponsored two Small Business Innovation Research (SBIR) projects to support development of commercially available UDIG anchors and attachments. The previous work also assessed the usability of prototype automatic seatbelt donning systems that could be paired with UDIG wheelchair securement and be used as a model for automated seatbelt donning on trains. However, additional development would be needed to achieve commercial seatbelt donning products.

5. References

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Appendix A.
Impact Test Photos

This appendix includes pre-test and post-test photos for all three sled impact tests.

VP2407 Pre-test

Figure A1. VP2407 Pre-test Front View

Figure A2. VP2407 Pre-test Right Front Oblique View

Figure A3. VP2407 Pre-test Right Side View

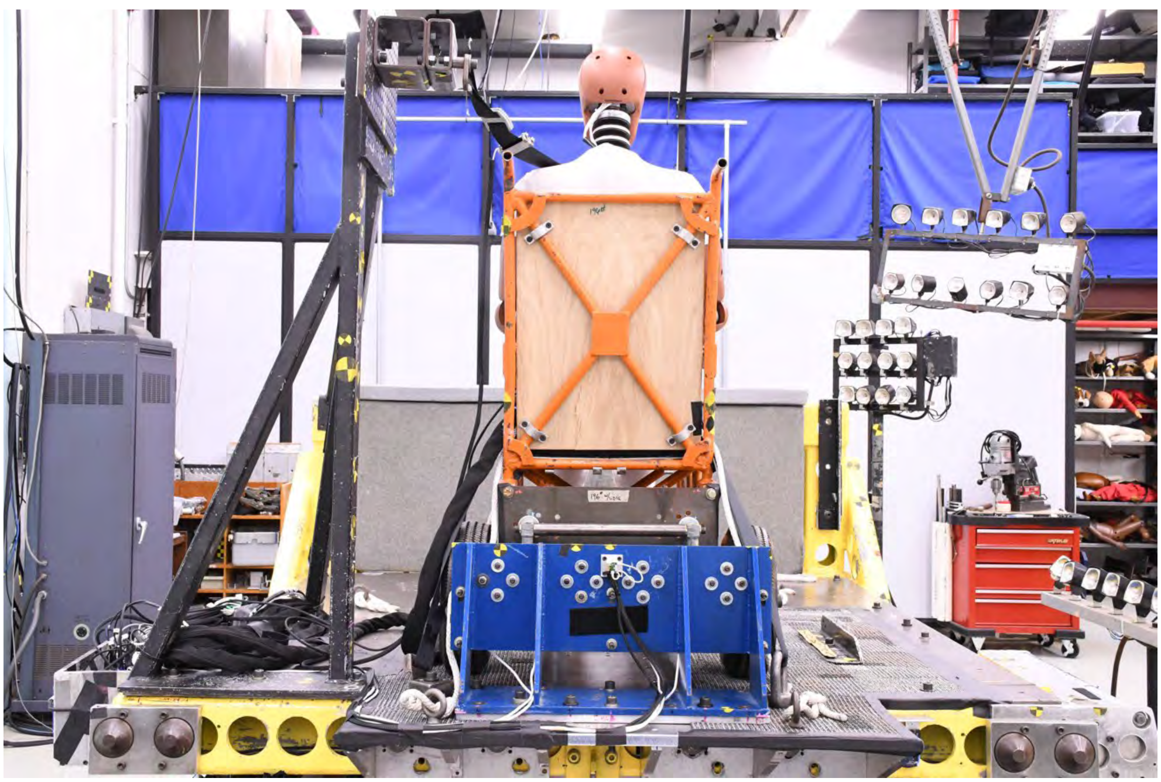

Figure A4. FVP2407 Pre-test Rear View

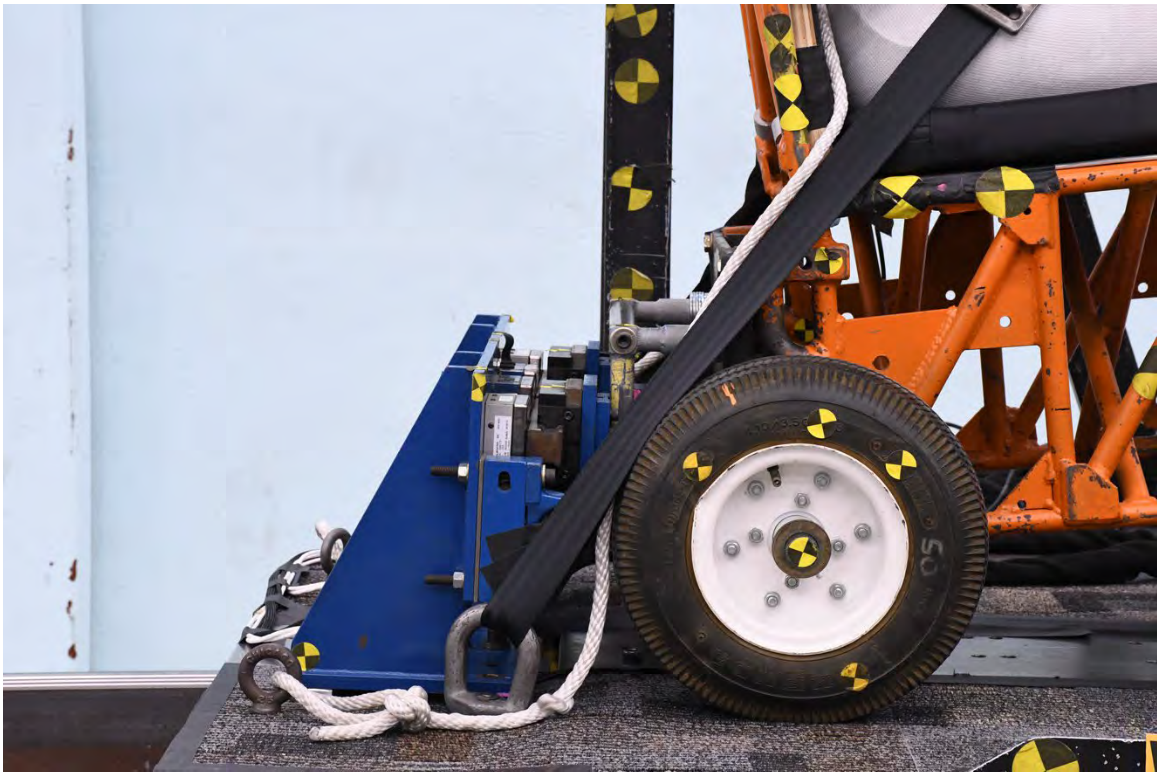

Figure A5. VP2407 Pre-test UDIG Side View

Figure A6. VP2407 Pre-test UDIG Rear Oblique View

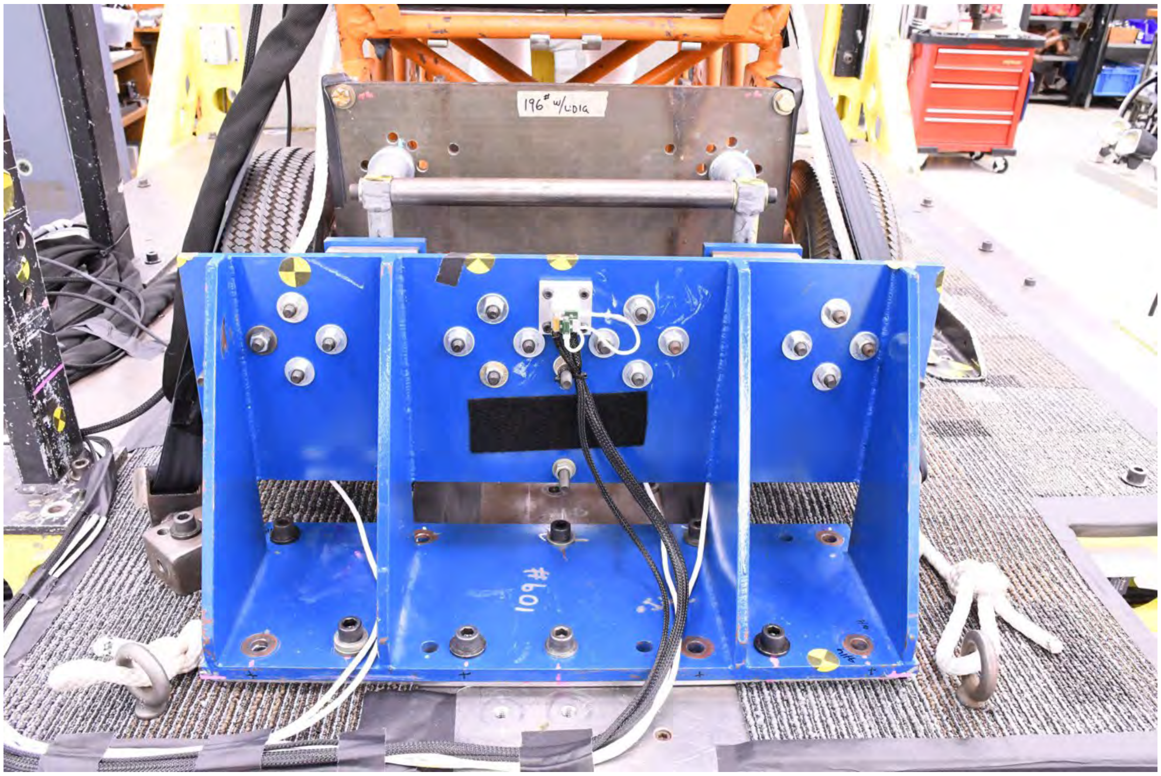

Figure A7. VP2407 Pre-test UDIG Rear View

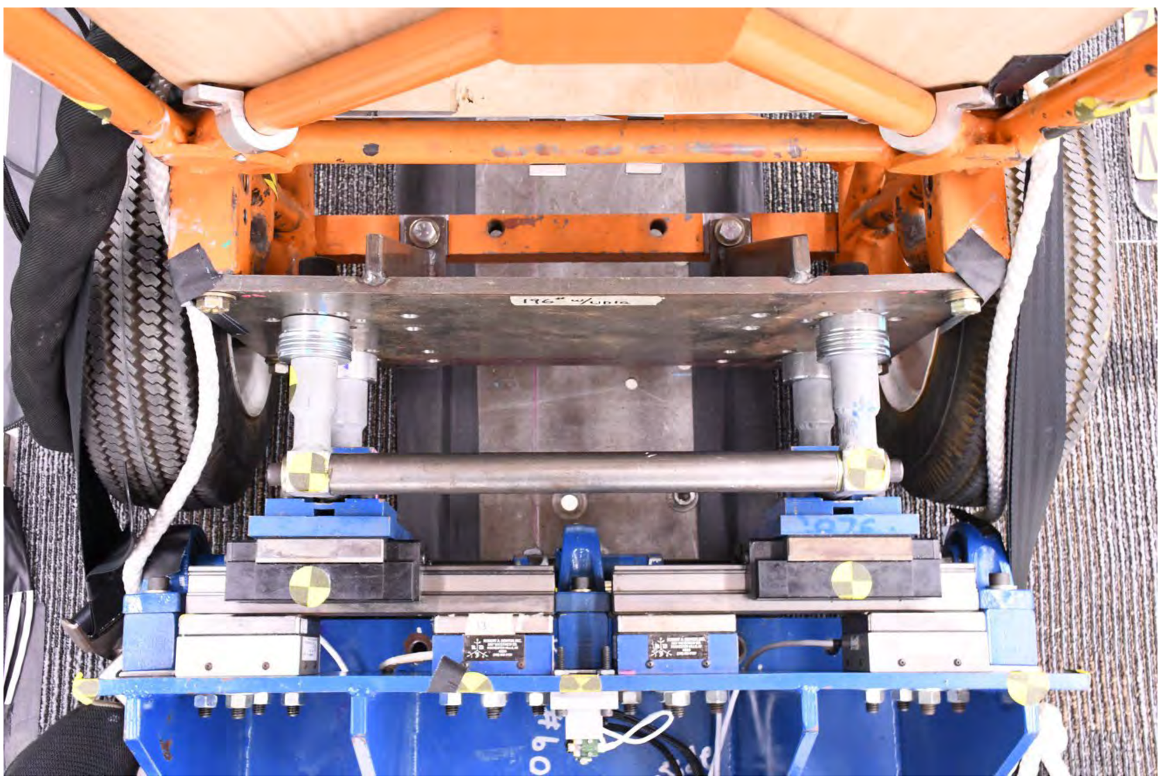

Figure A8. VP2407 Pre-test UDIG Overhead View

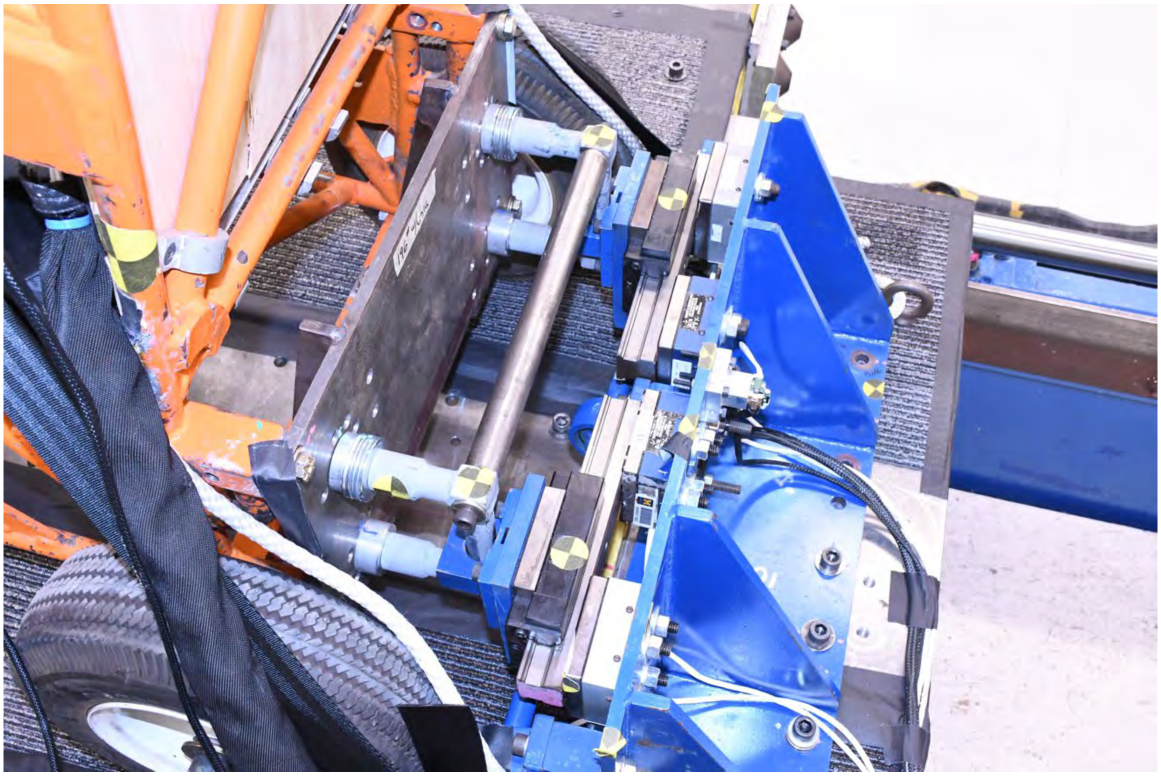

Figure A9. VP2407 Pre-test UDIG Overhead Oblique View

Figure A10. VP2407 Pre-test UDIG Left Side Rear Wheel

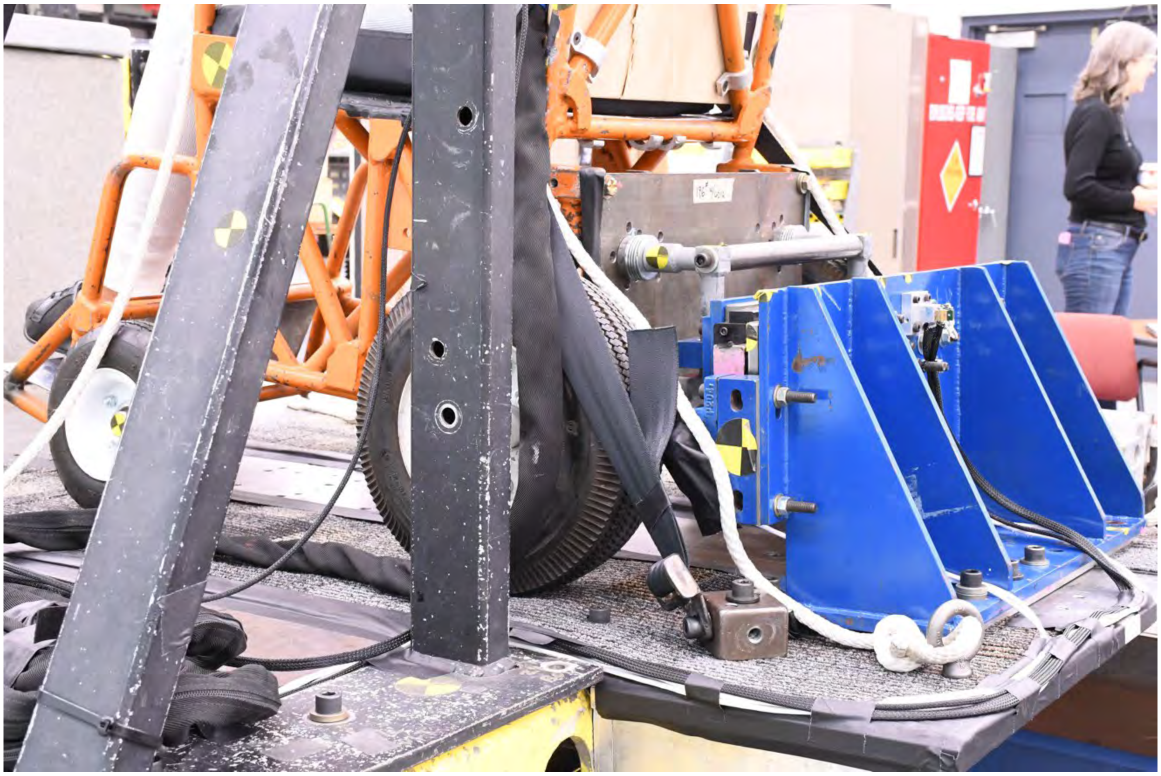

Figure A11. VP2407 Pre-test UDIG Left Side Lower View

Figure A12. VP2407 Pre-test UDIG Left Front Oblique View

VP2407 Post-test

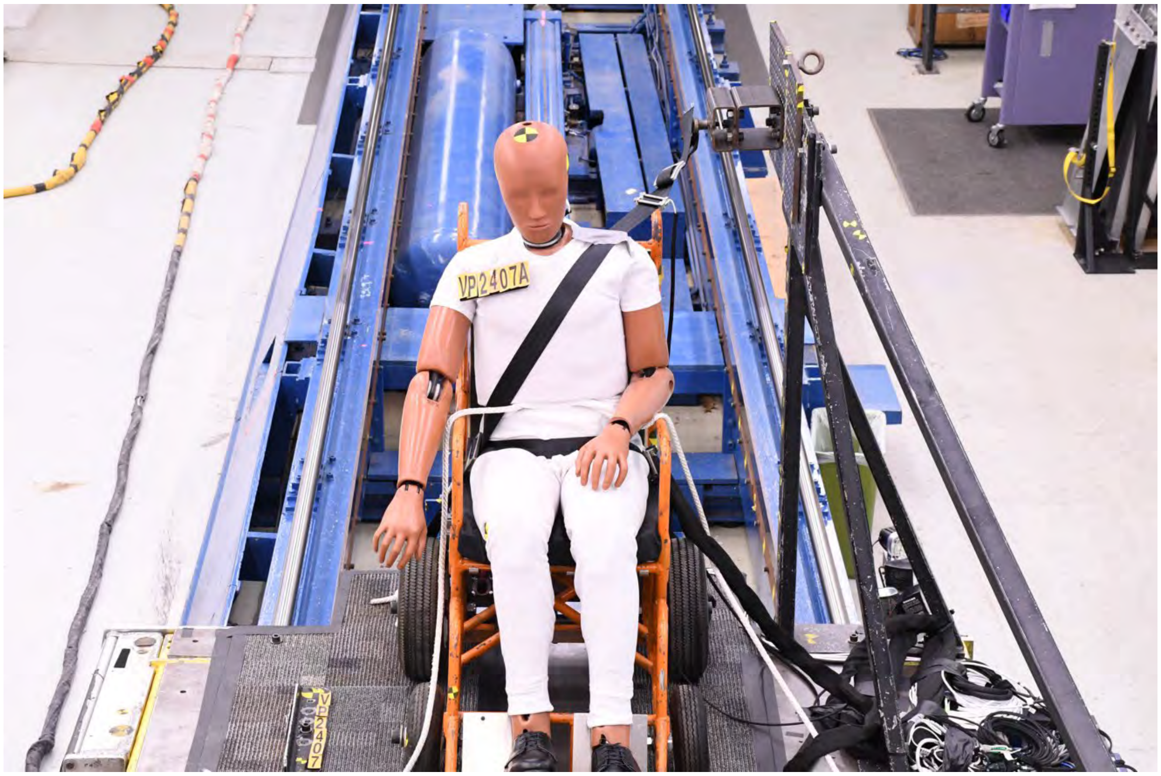

Figure A13. VP2407 Post-test Front View

Figure A14. VP2407 Post-test Front Right Oblique View

Figure A15. VP2407 Post-test Right Side View

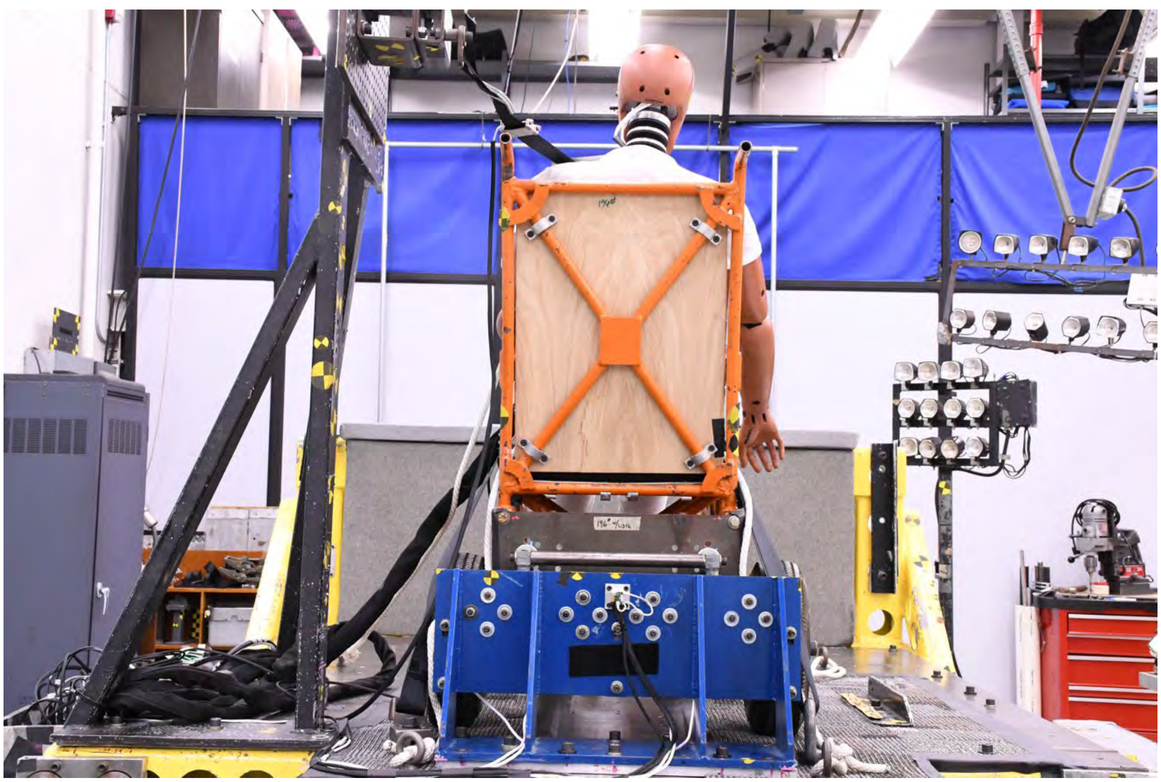

Figure A16. VP2407 Post-test Rear View

Figure A17. VP2407 Post-test Right Rear Oblique View

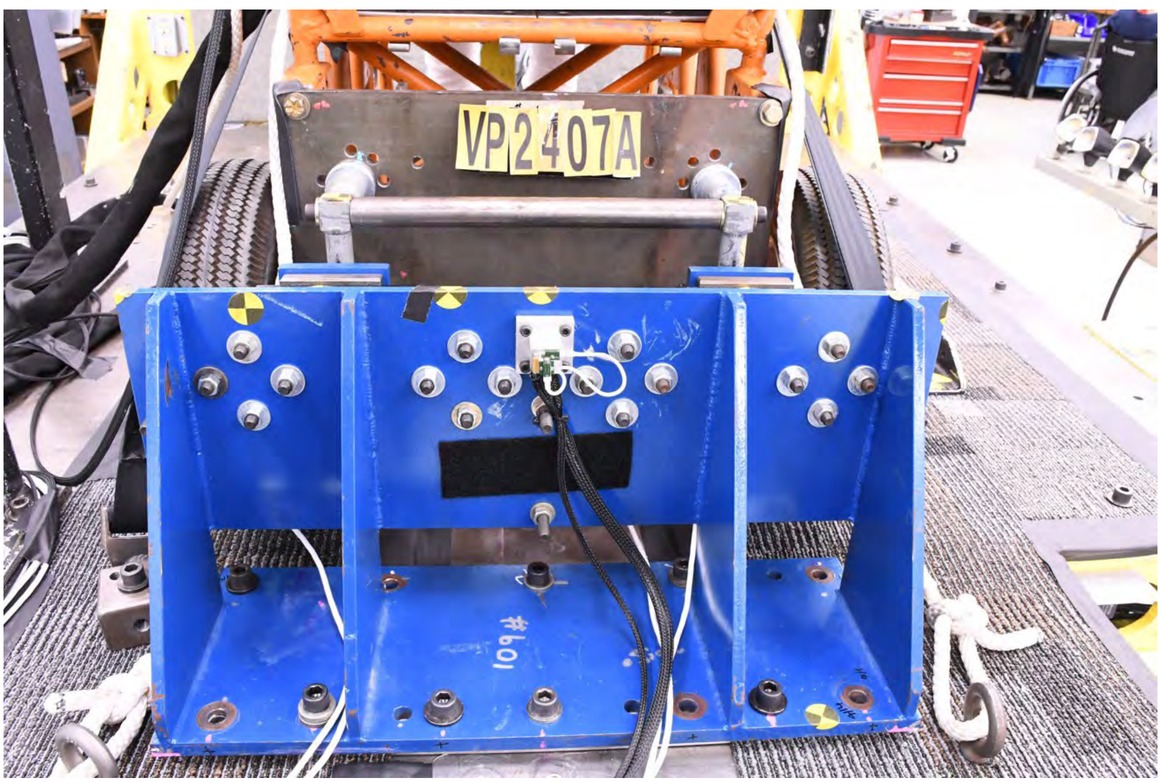

Figure A18. VP2407 Post-test UDIG Rear View

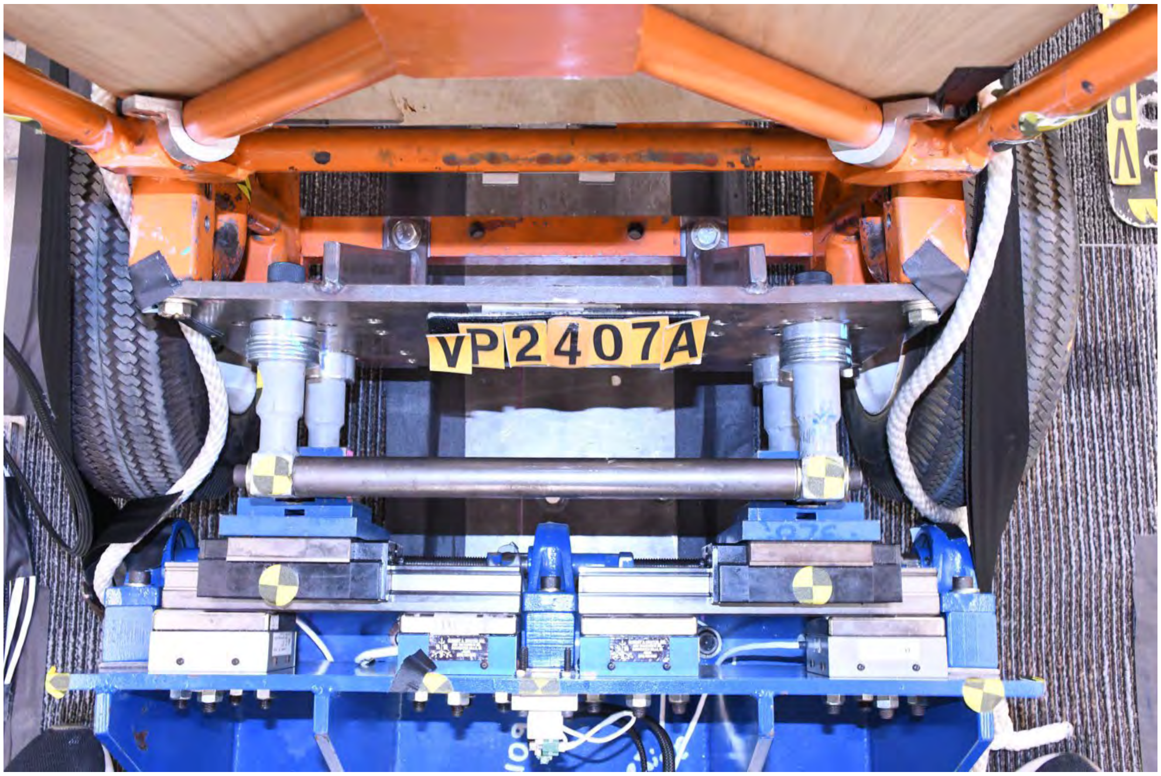

Figure A19. VP2407 Post-test UDIG Overhead View

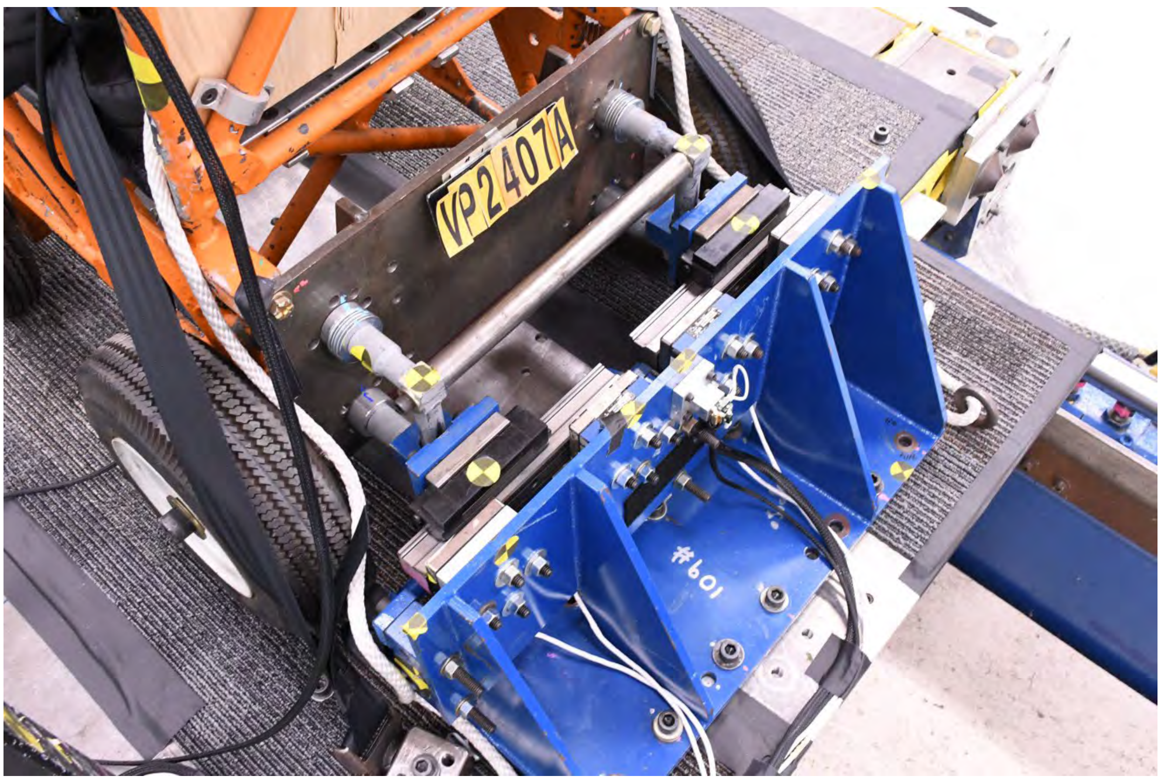

Figure A20. VP2407 Post-test UDIG Left Overhead Oblique View

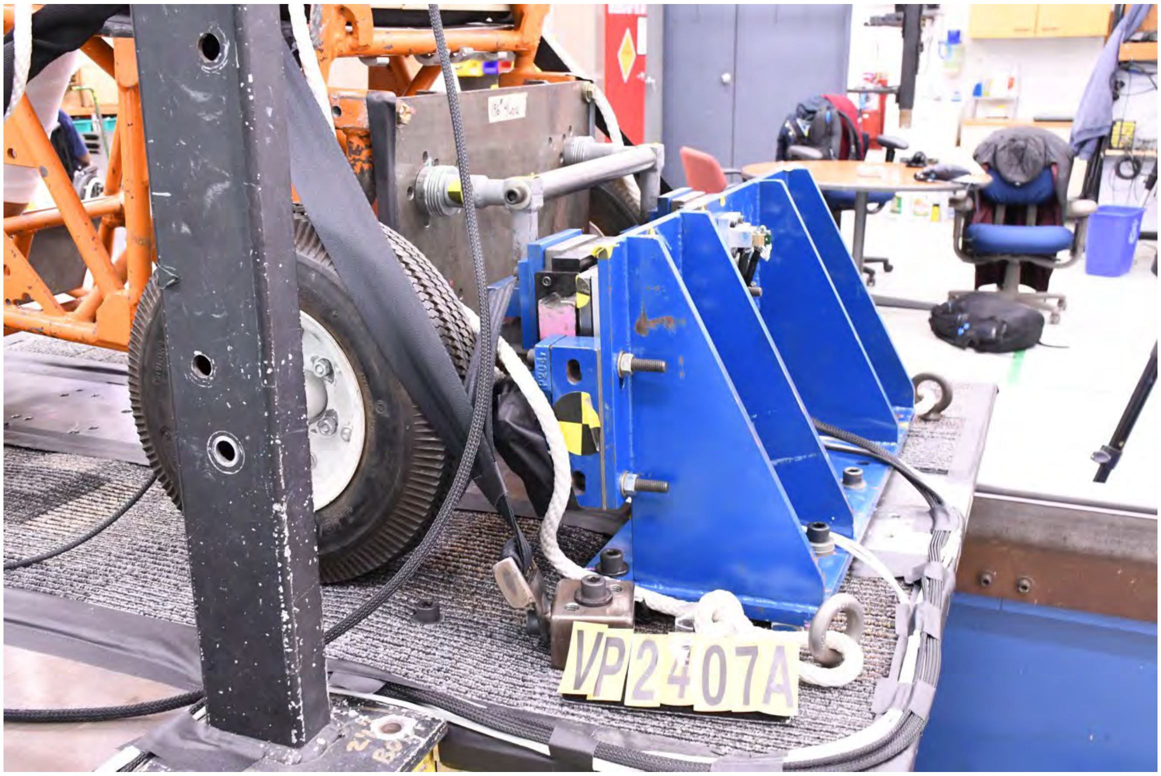

Figure A21. VP2407 Post-test UDIG Left Side View

Figure A22. VP2407 Post-test Left Front Oblique View

VP2408 Pre-test

Figure A23. VP2408 Pre-test Front View

Figure A24. VP2408 Pre-test Right Front Oblique View

Figure A25. VP2408 Pre-test Right Side View

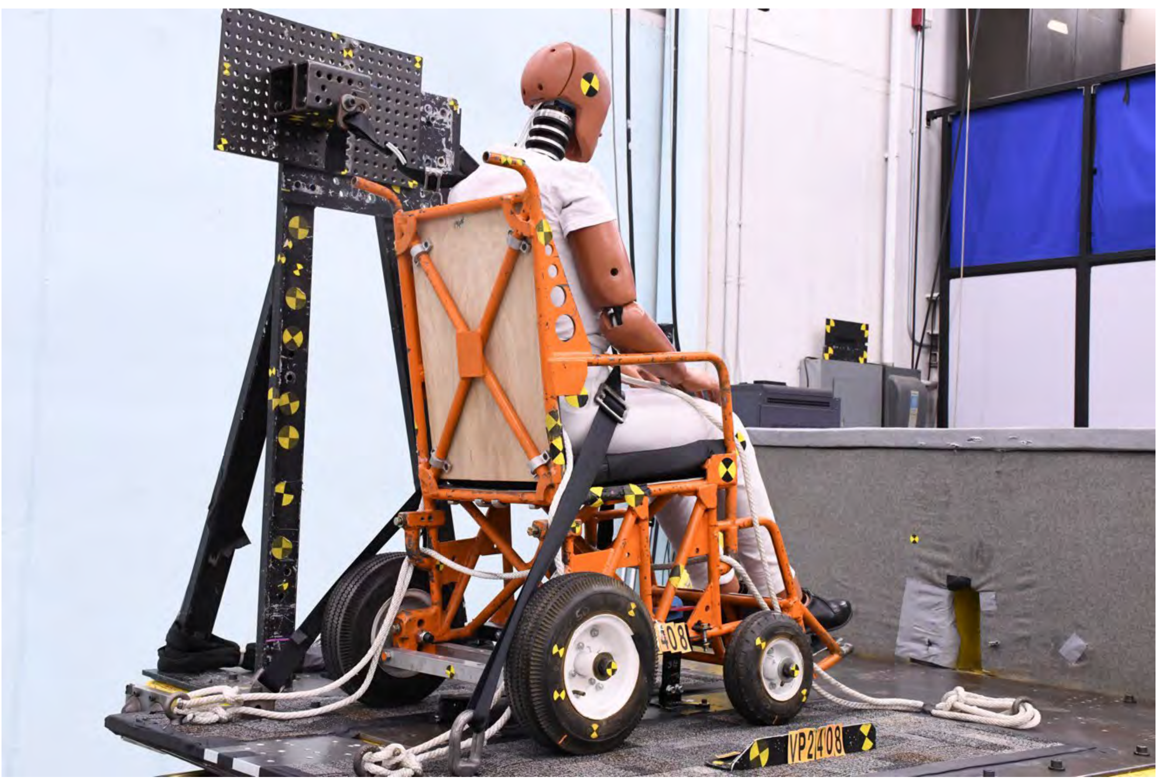

Figure A26. VP2408 Pre-test Right Rear Oblique View

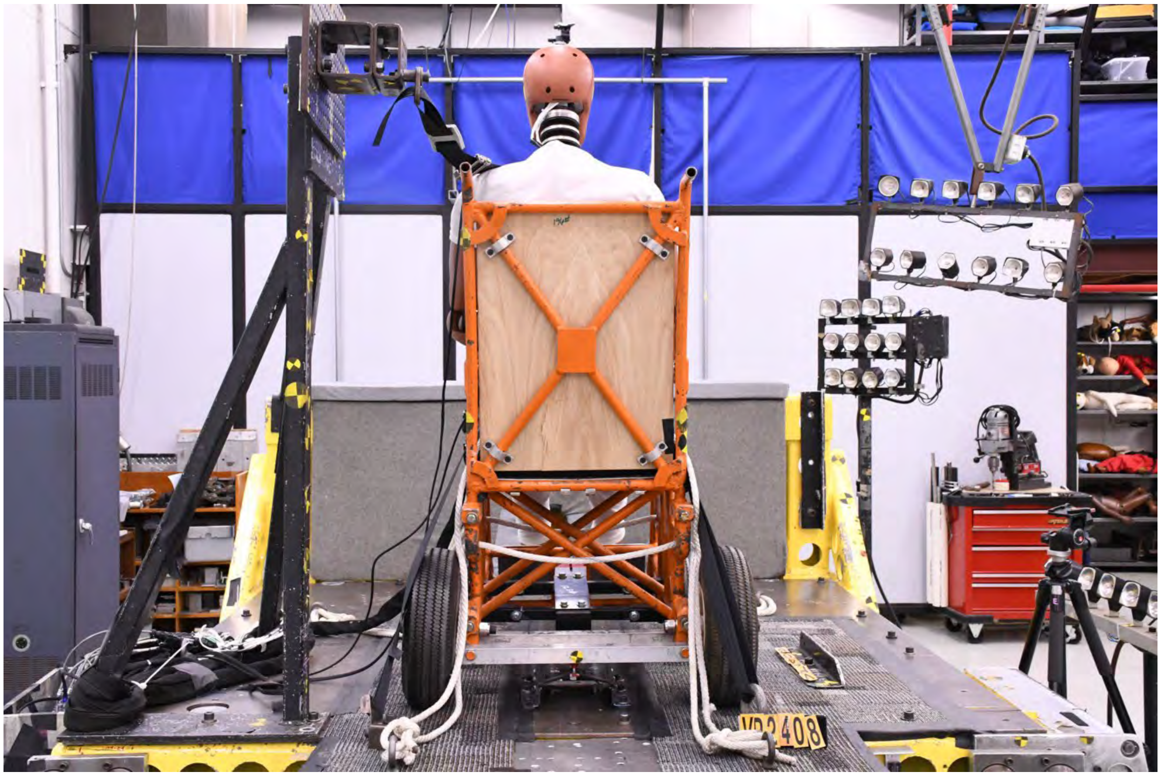

Figure A27. VP2408 Pre-test Rear View

Figure A28. VP2408 QLK™ Stabilizer Bracket

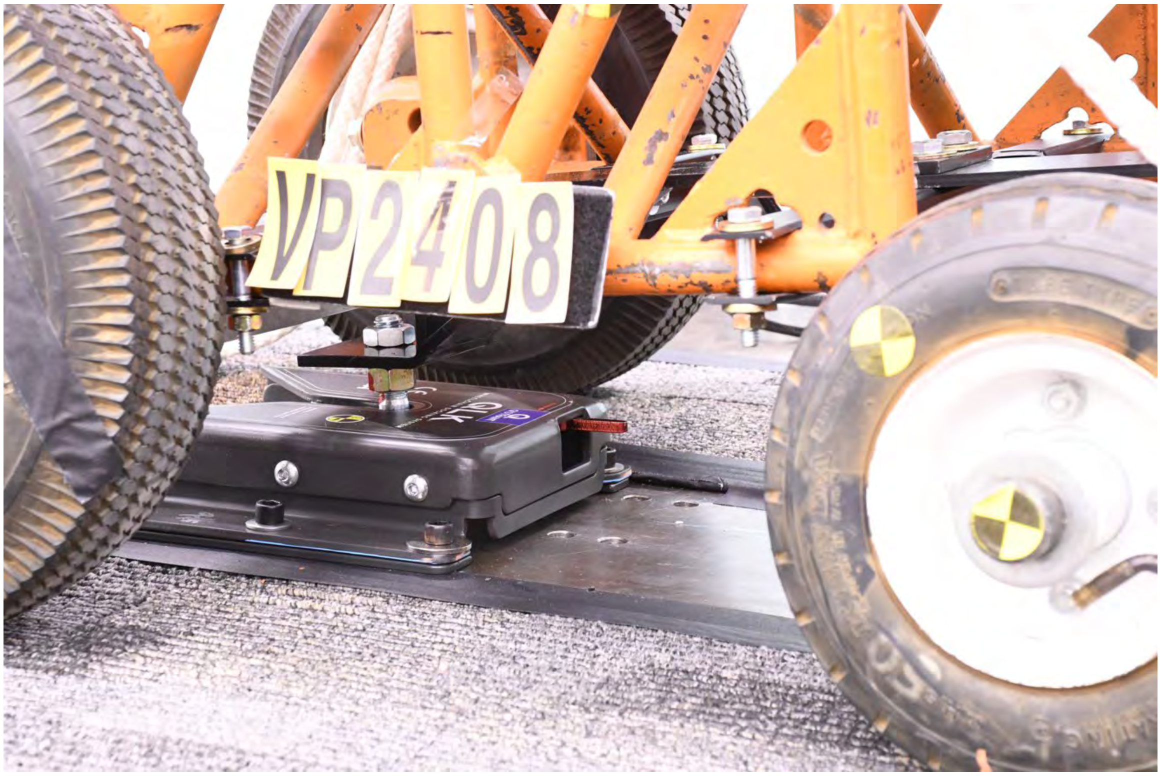

Figure A29. VP2408 Pre-test QLK™ Docking Unit

Figure A30. VP2408 Pre-test QLK™ Docking Unit and Stabilizer Bracket

Figure A31. VP2408 Pre-test Rear View of QLK™ Dock and Stabilizer Bracket

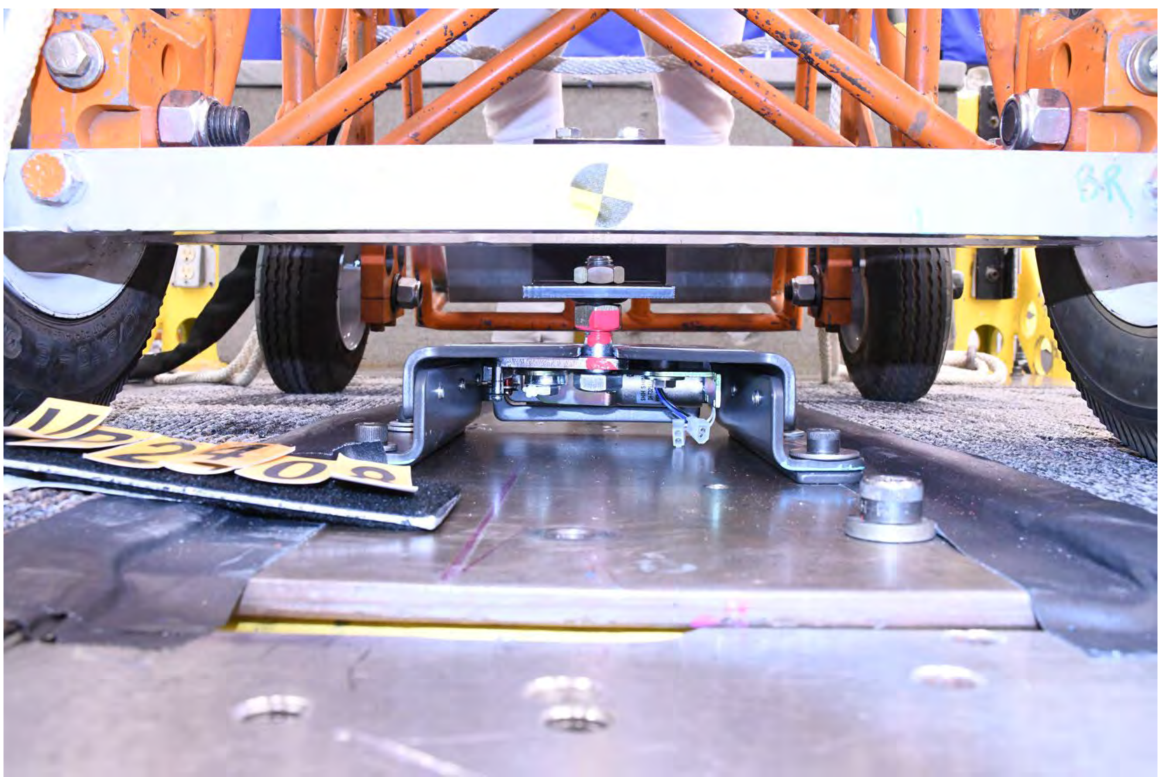

Figure A32. VP2408 Pre-test Rear Closeup View of QLK™ Dock

Figure A33. VP2408 Pre-test Left Rear Oblique View of QLK™ Dock

Figure A34. VP2408 Pre-test Left side View of QLK™ Dock and Stabilizer Bracket

Figure A35. VP2408 Pre-test Front Left Oblique View

VP2408 Post-test

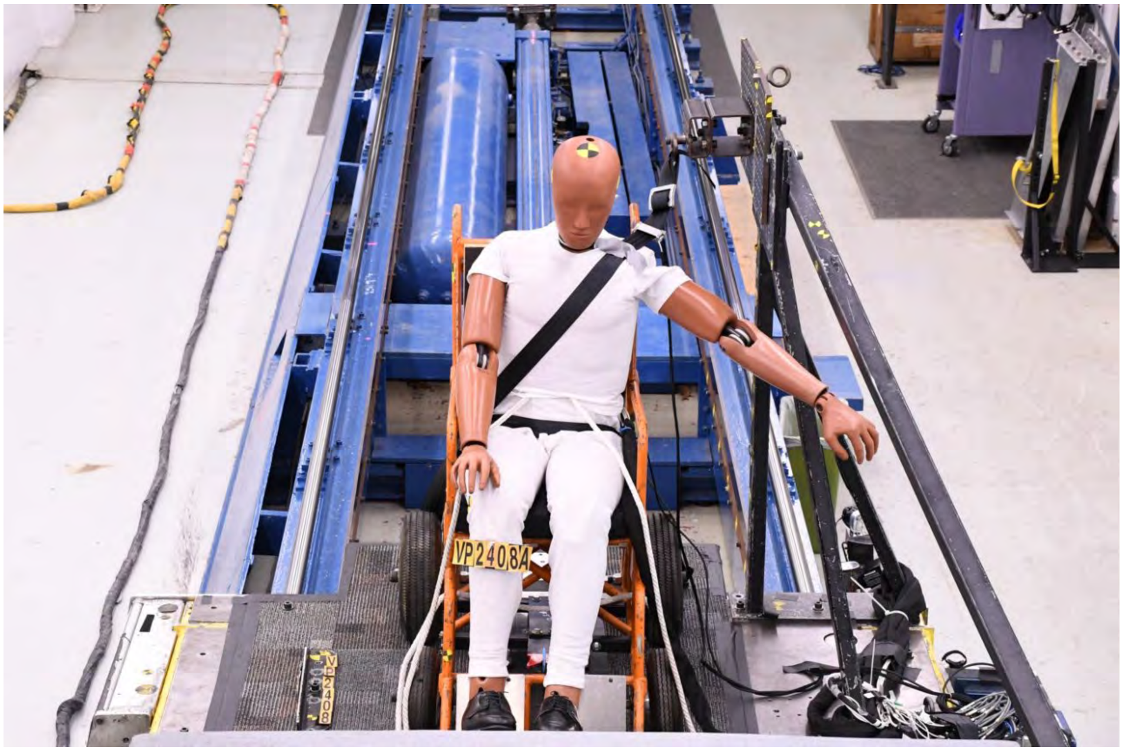

Figure A36. VP2408 Post-test Front View

Figure A37. VP2408 Post-test Right Front Oblique View

Figure A38. VP2408 Post-test Side View

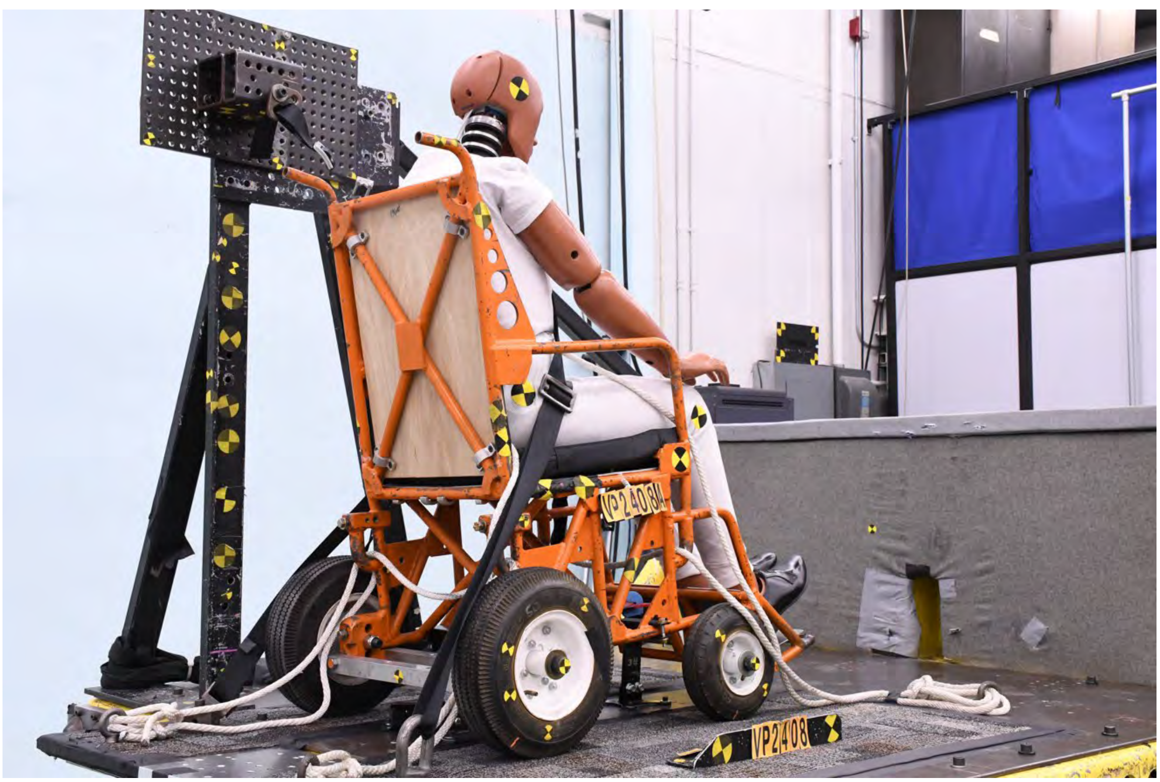

Figure A39. VP2408 Post-test Right Rear Oblique View

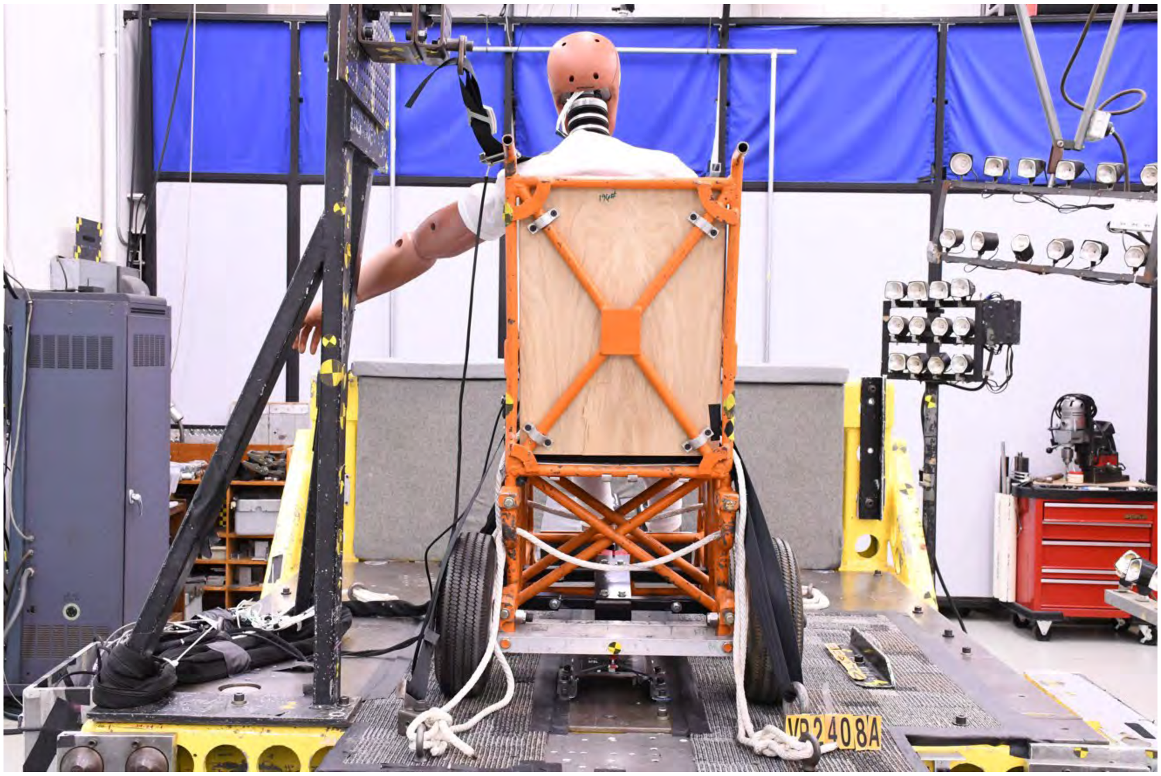

Figure A40. VP2408 Post-test Rear View

Figure A41. VP2408 Post-test Side View of QLK™ Dock and Stabilizer Bracket

Figure A42. VP2408 Post-test Right Rear Oblique View of QLK™ Stabilizer Bracket

Figure A43. VP2408 Post-test Right Front Oblique View of QLK™ Dock

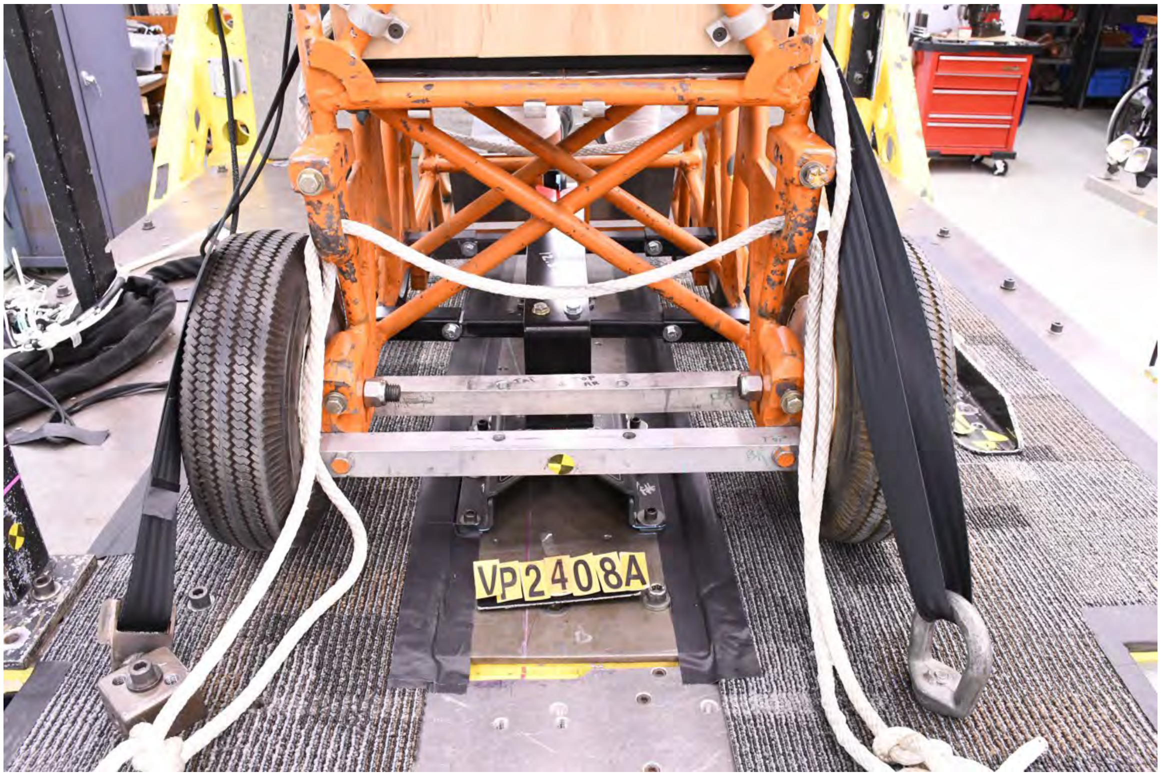

Figure A44. VP2408 Post-test Rear View of QLK™ Dock and Stabilizer Bracket

Figure A45. VP2408 Post-test Rear Closeup View of QLK™ Dock and Stabilizer Bracket

Figure A46. VP2408 Post-test Rear Close View of QLK™ Dock

Figure A47. VP2408 Post-test Left Rear Oblique View

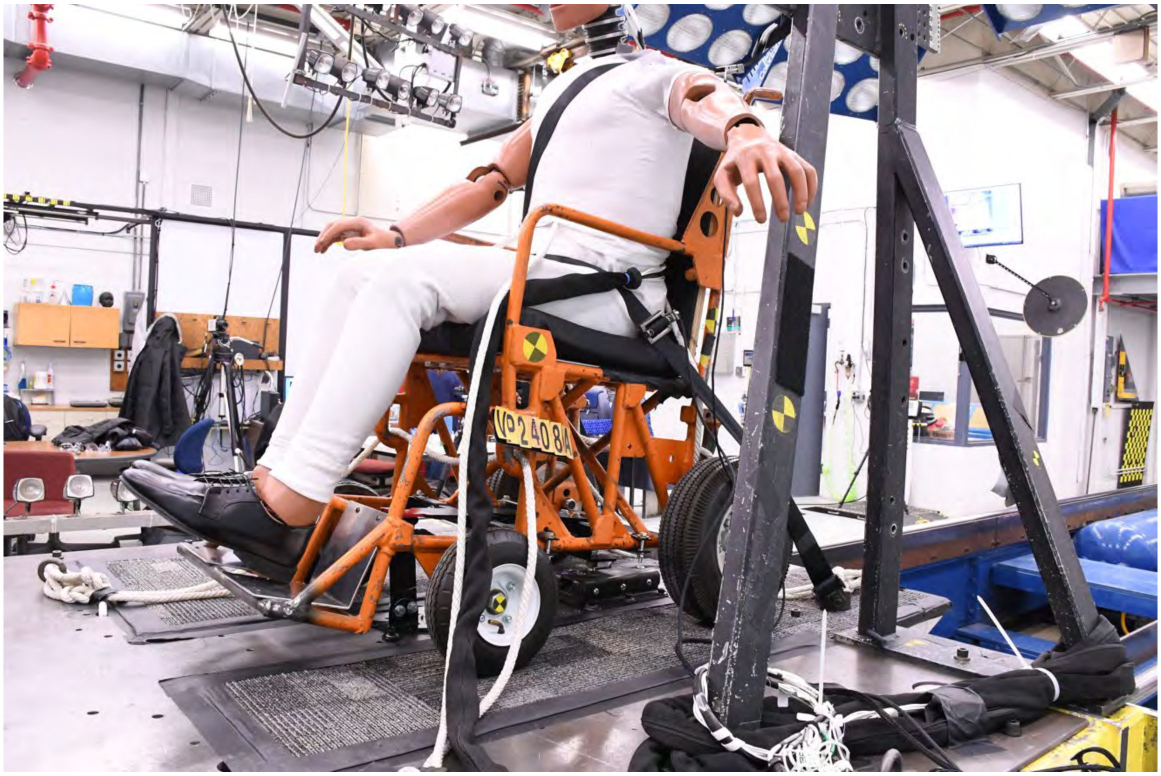

Figure A48. VP2408 Post-test Left Front Oblique View

Figure A49. VP2408 Post-test Closeup Left Front Oblique View

VP2409 Pre-test

Figure A50. VP2409 Pre-test Side View

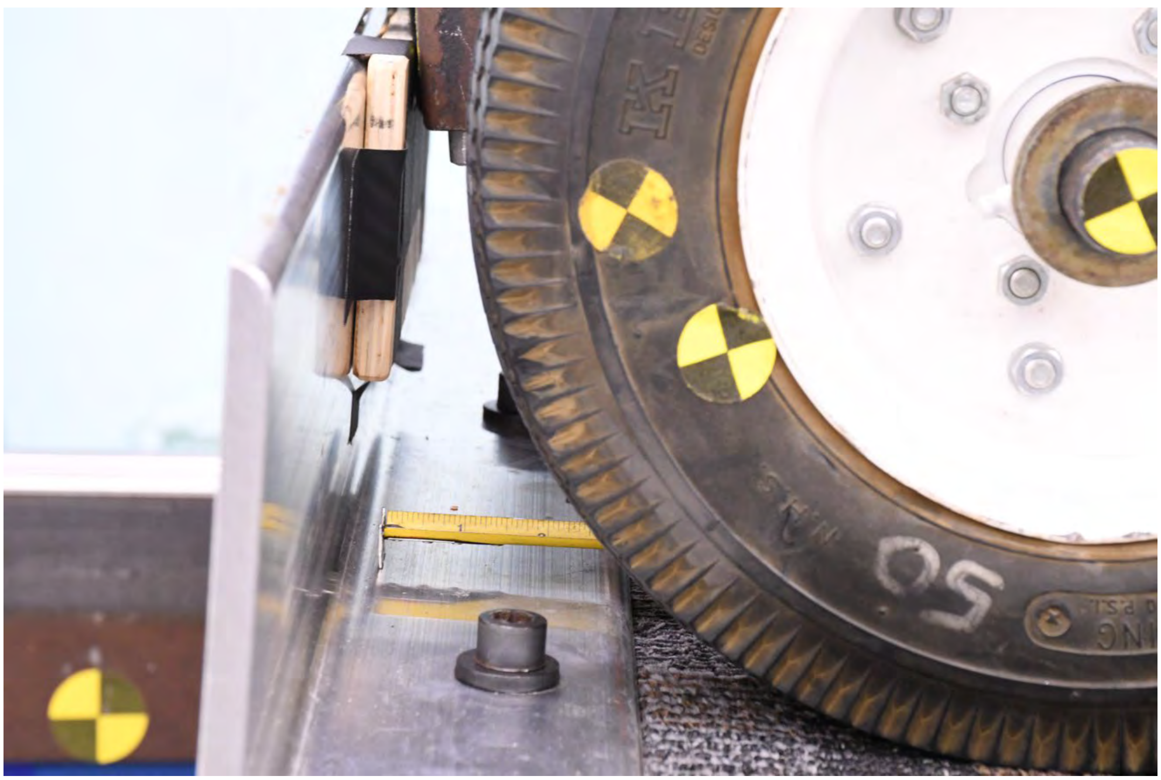

Figure A51. VP2409 Pre-test Side View of WC Station Back Stop

Figure A52. VP2409 Pre-test View of Plumb bob Set Up

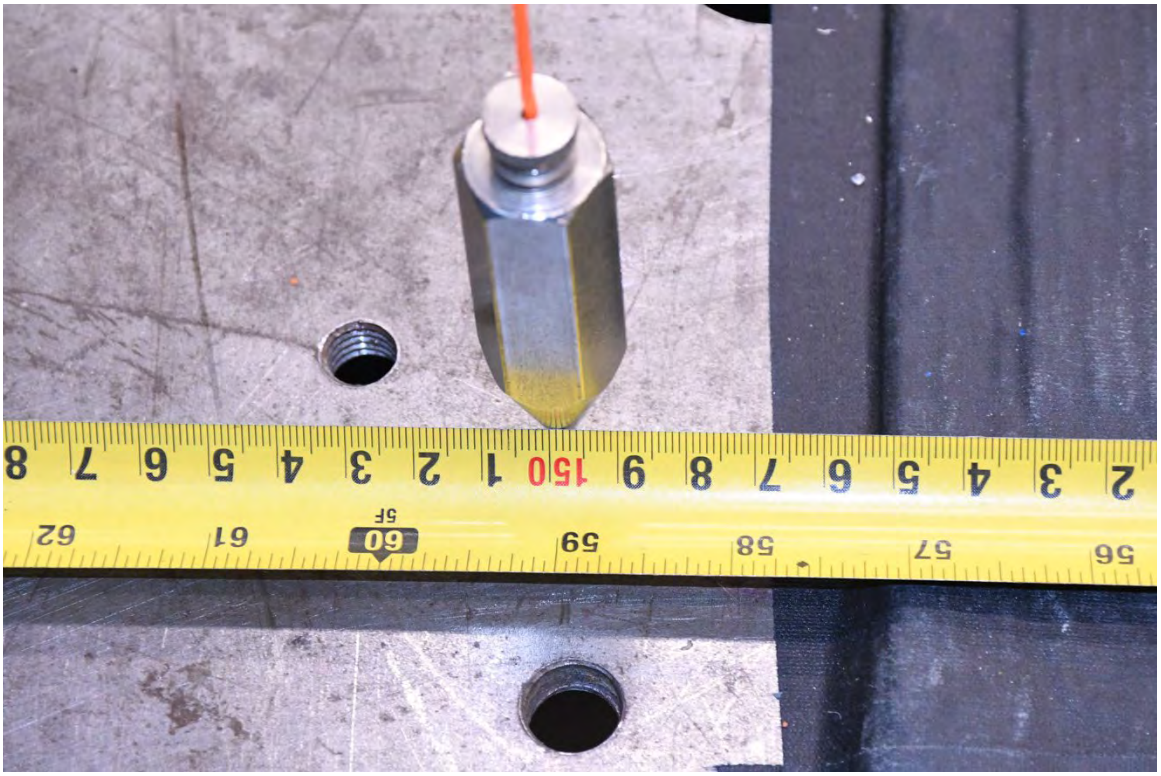

Figure A53. VP2409 Pre-test View of Plumb bob Measurement

Figure A54. VP2409 Pre-test Right Rear View of Station Measurement

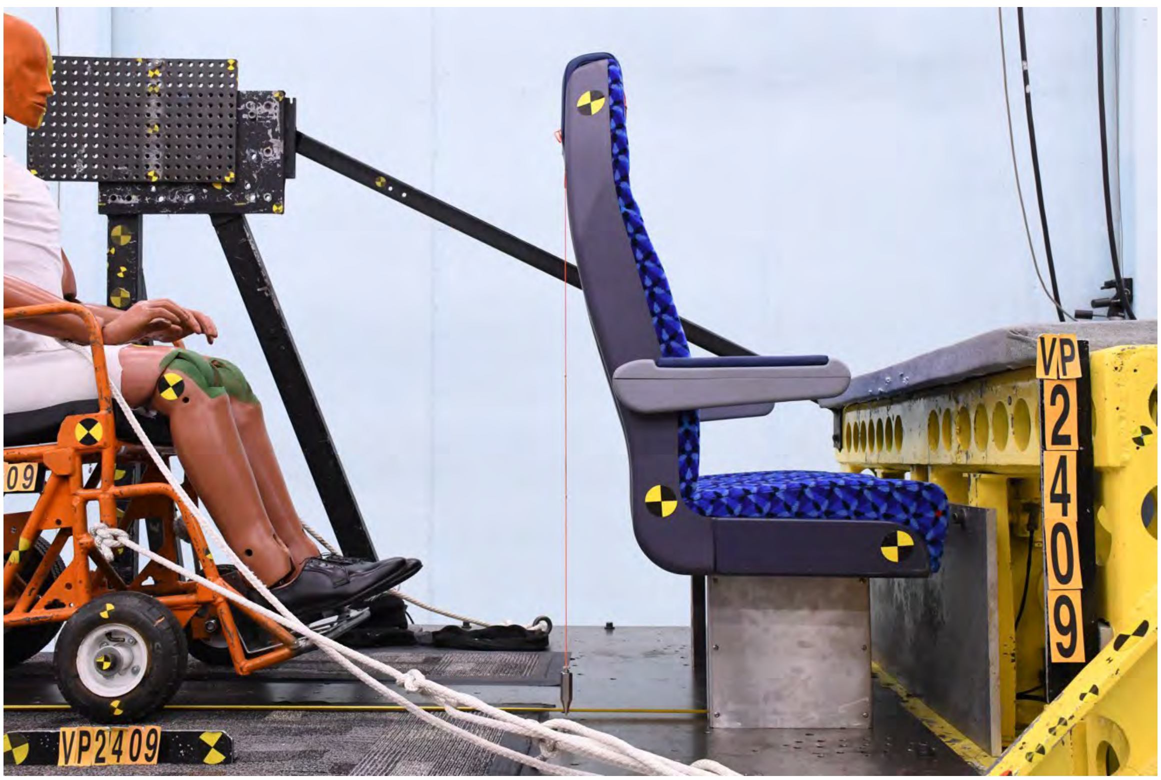

Figure A55. VP2409 Pre-test Right Side View of Station Measurement

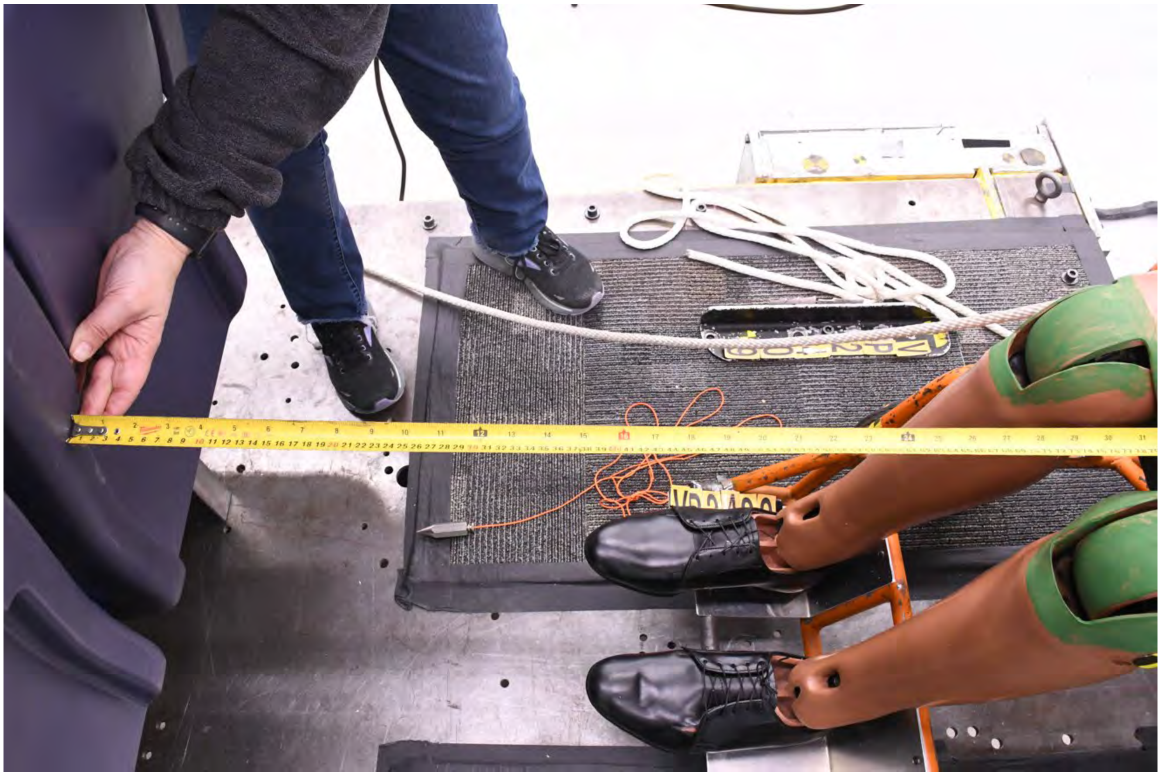

Figure A56. VP2409 Pre-test Overhead View of Station Measurement

Figure A57. VP2409 Pre-test Overhead Closeup View of Station Measurement

Figure A58. VP2409 Pre-test Right Front Oblique View

Figure A59. VP2409 Pre-test Side View

Figure A60. VP2409 Pre-test Right Rear Oblique View of Commuter Rail Seat

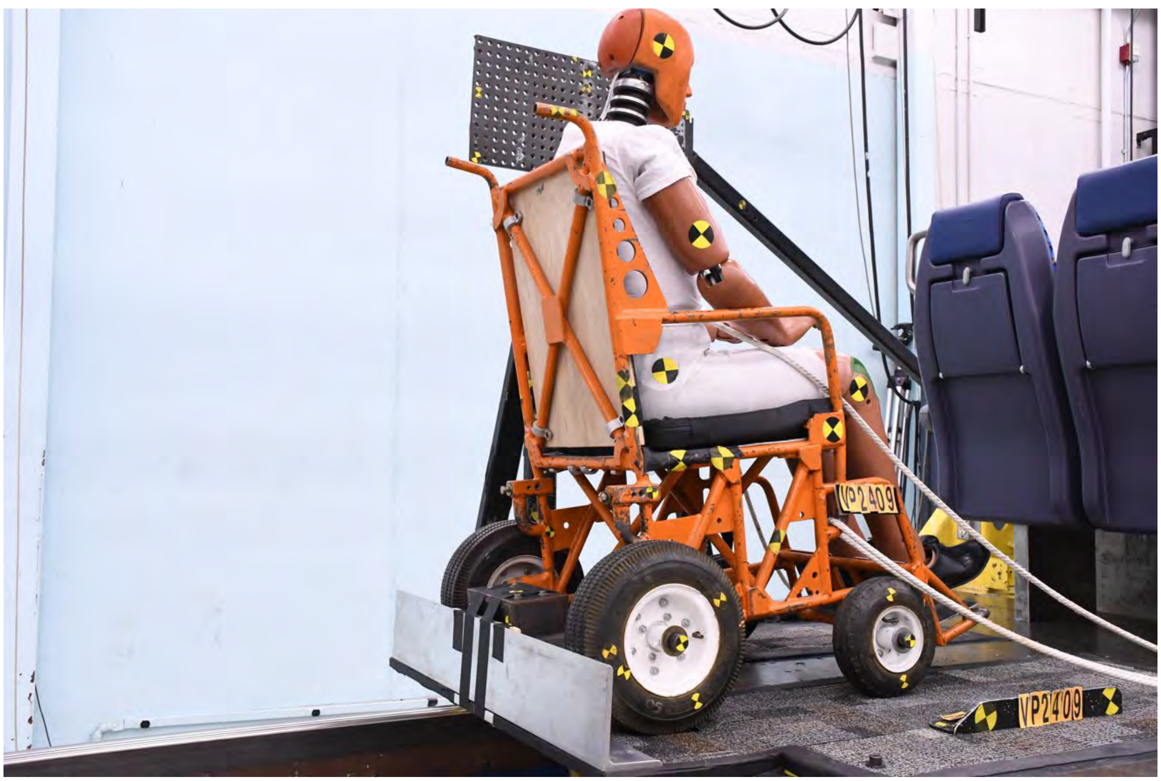

Figure A61. VP2409 Pre-test Right Rear Oblique View of Wheelchair

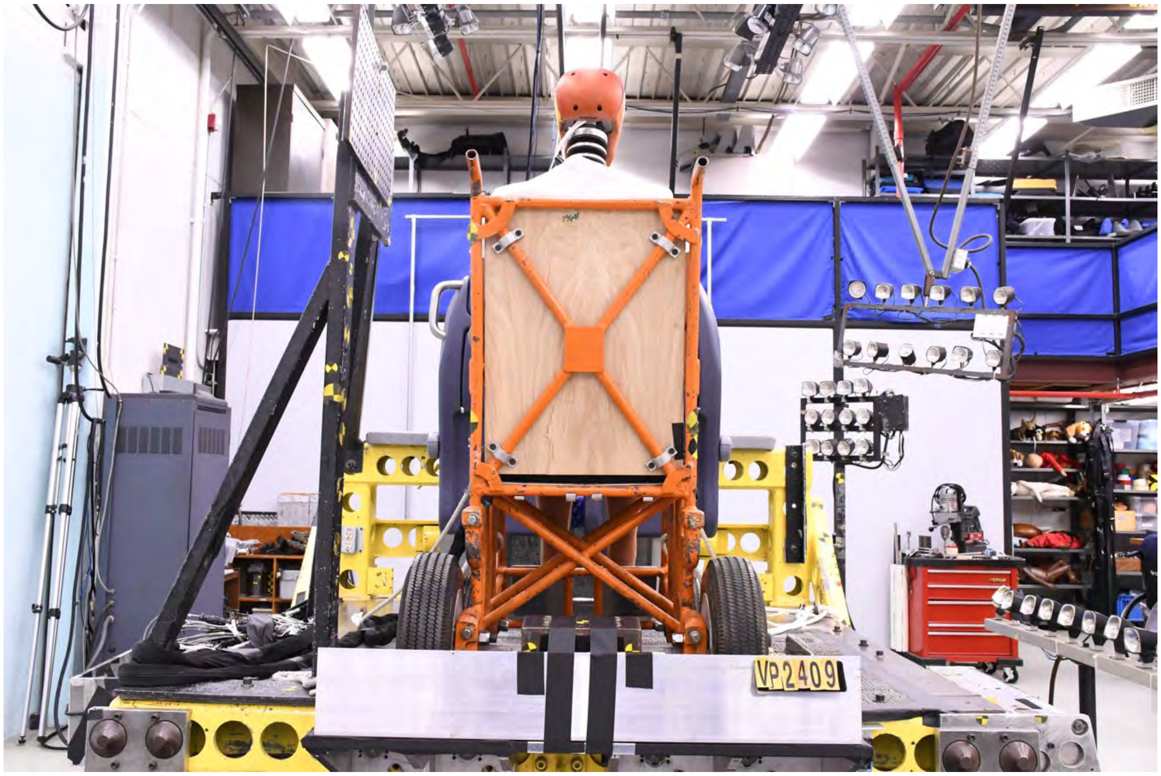

Figure A62. VP2409 Pre-test Rear View of Wheelchair

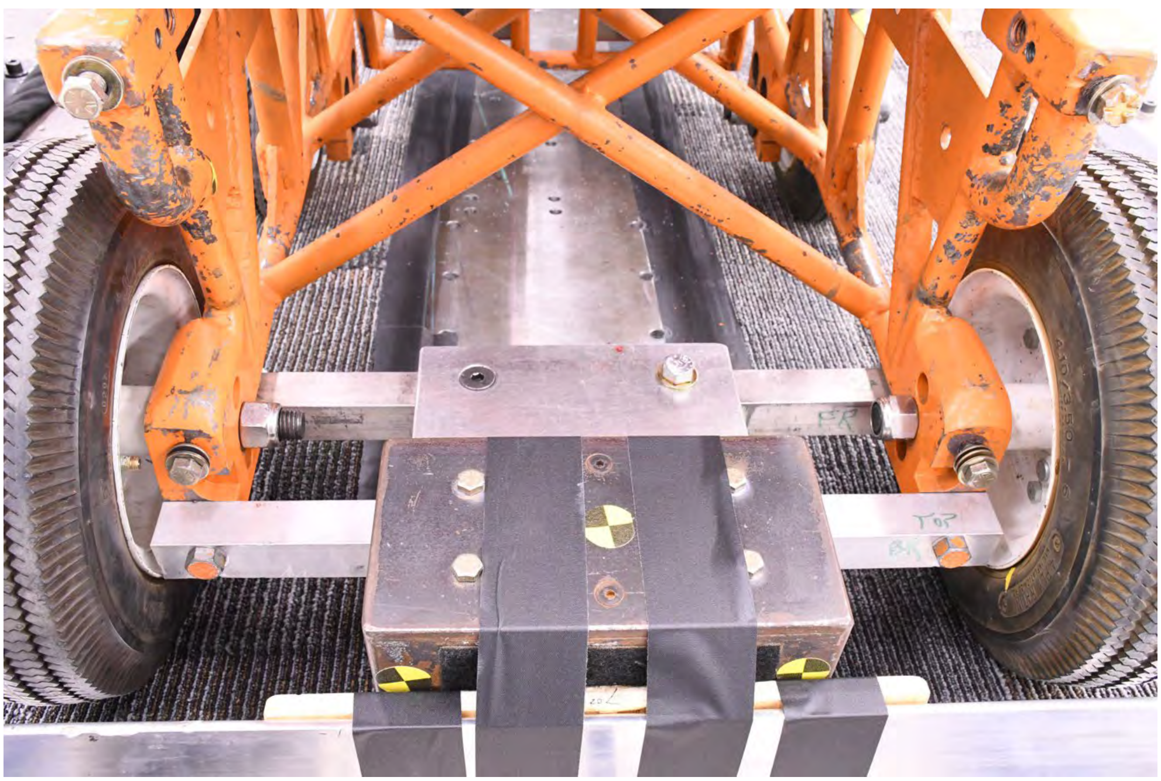

Figure A63. VP2409 Pre-test Rear Closeup View of Wheelchair Gaffer Tape

Figure A64. VP2409 Pre-test Left Side View of Wheelchair

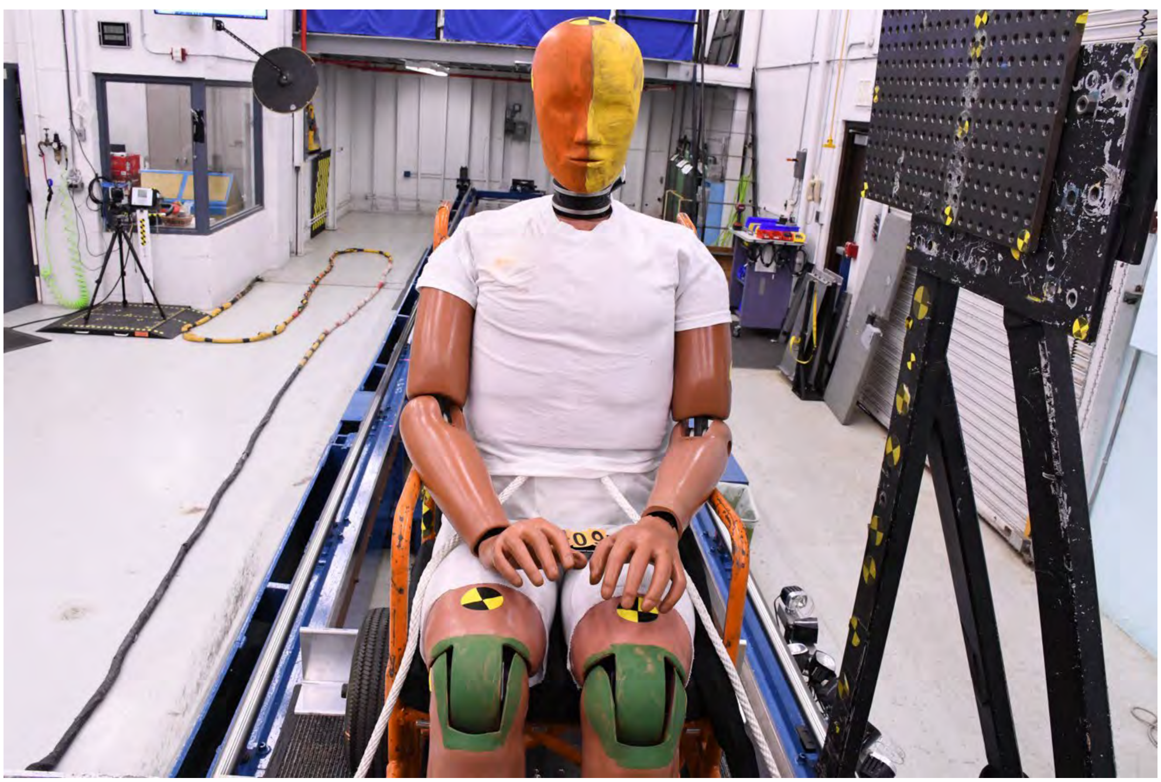

Figure A65. VP2409 Pre-test Front View of Wheelchair

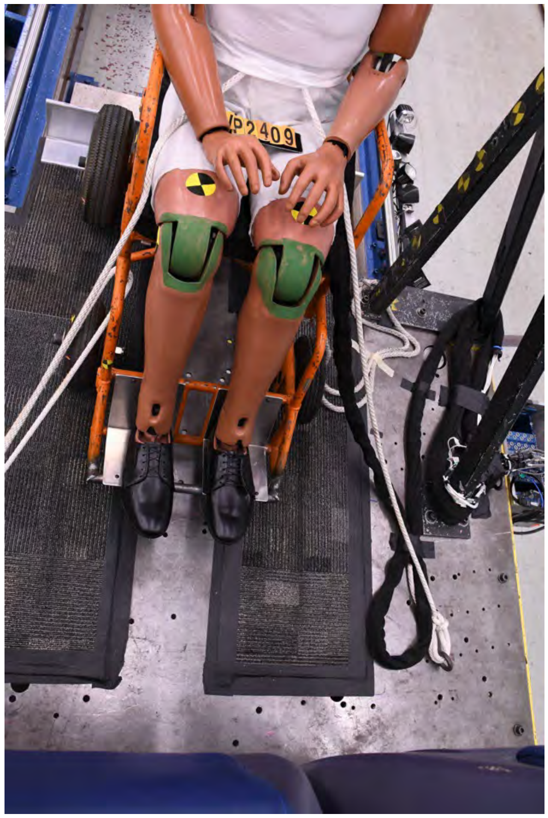

Figure A66. VP2409 Pre-test Overhead View of ATD Knees

VP2408 Post-test

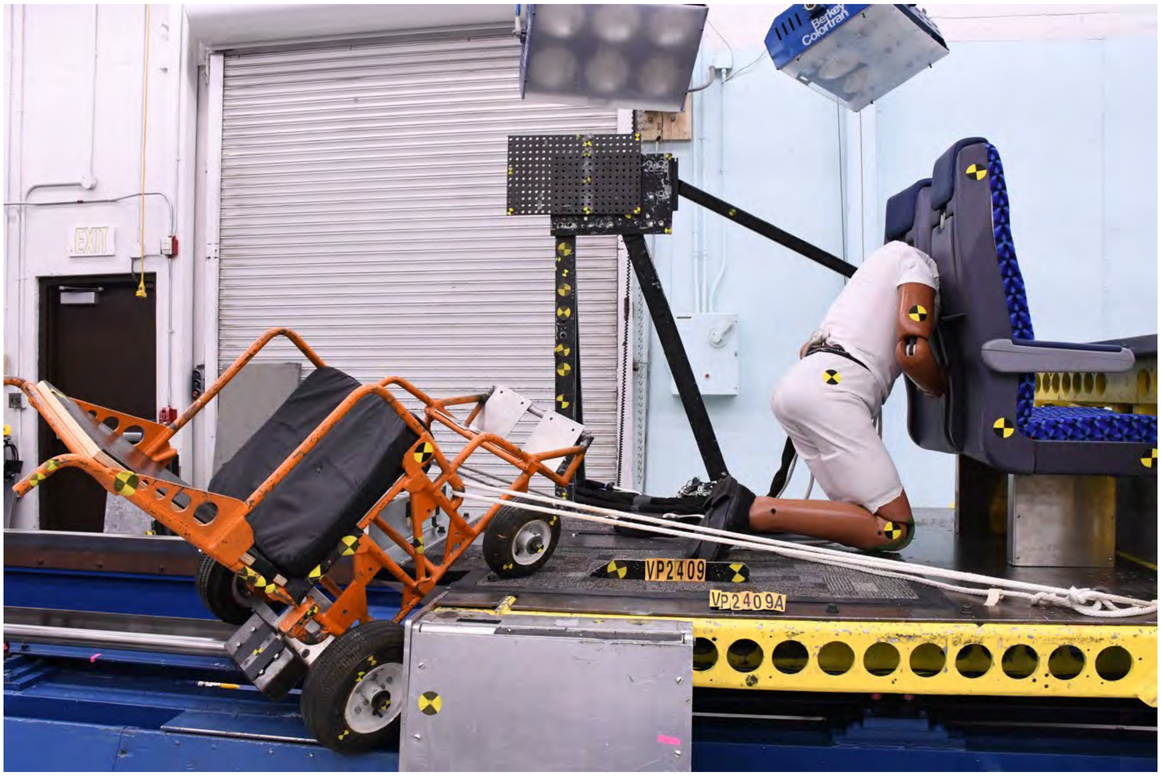

Figure A67. VP2409 Post-test Side View

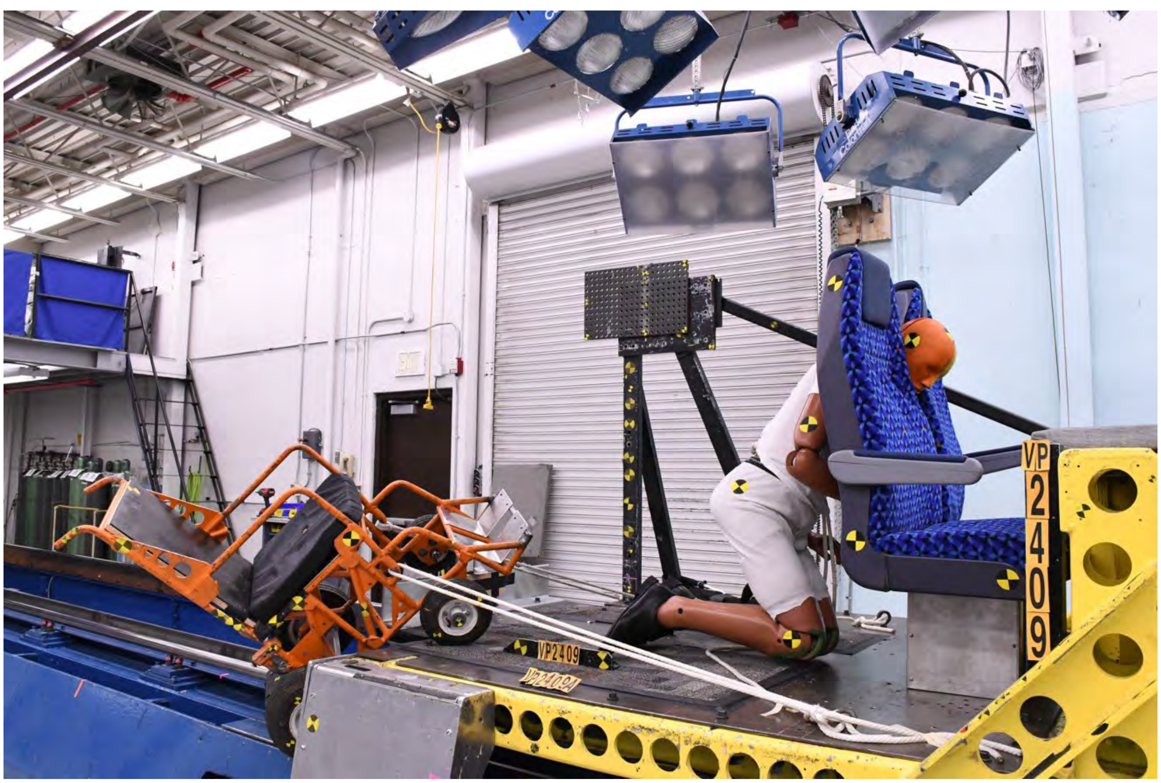

Figure A68. VP2409 Post-test Right Front Oblique View

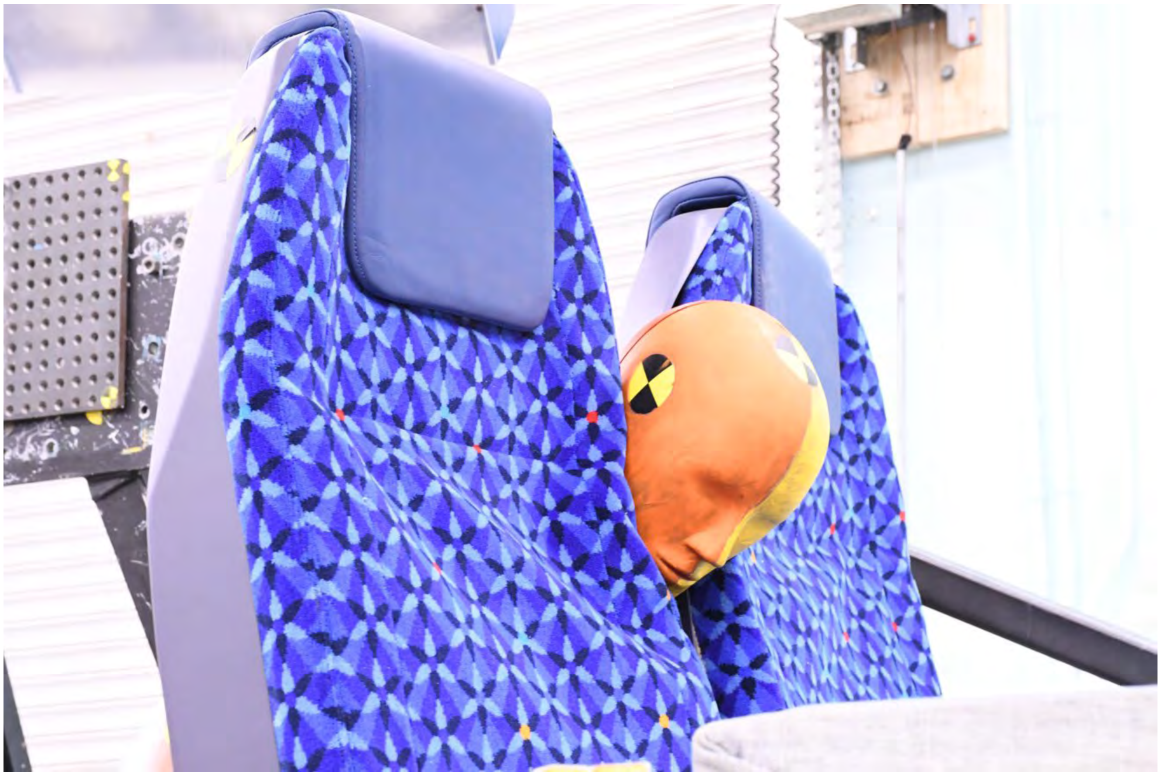

Figure A69. VP2409 Post-test Right Front Oblique View of ATD Head

Figure A70. VP2409 Post-test Right Rear Oblique View

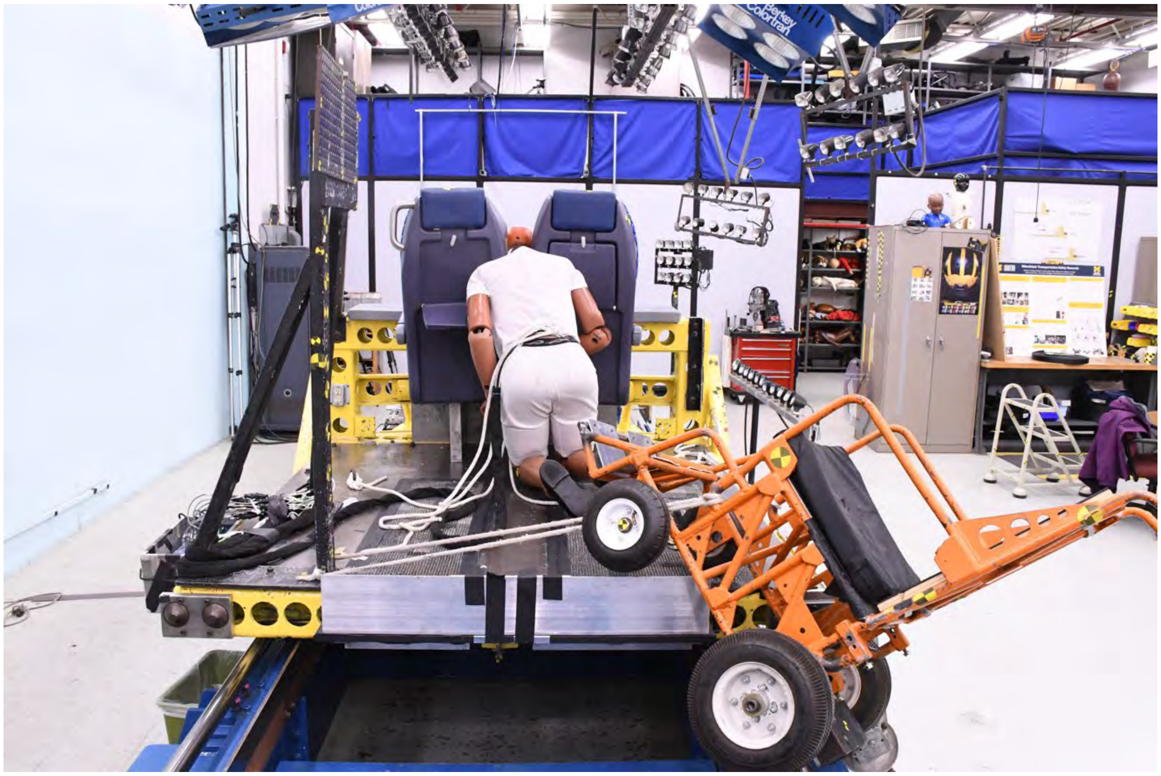

Figure A71. VP2409 Post-test Rear View

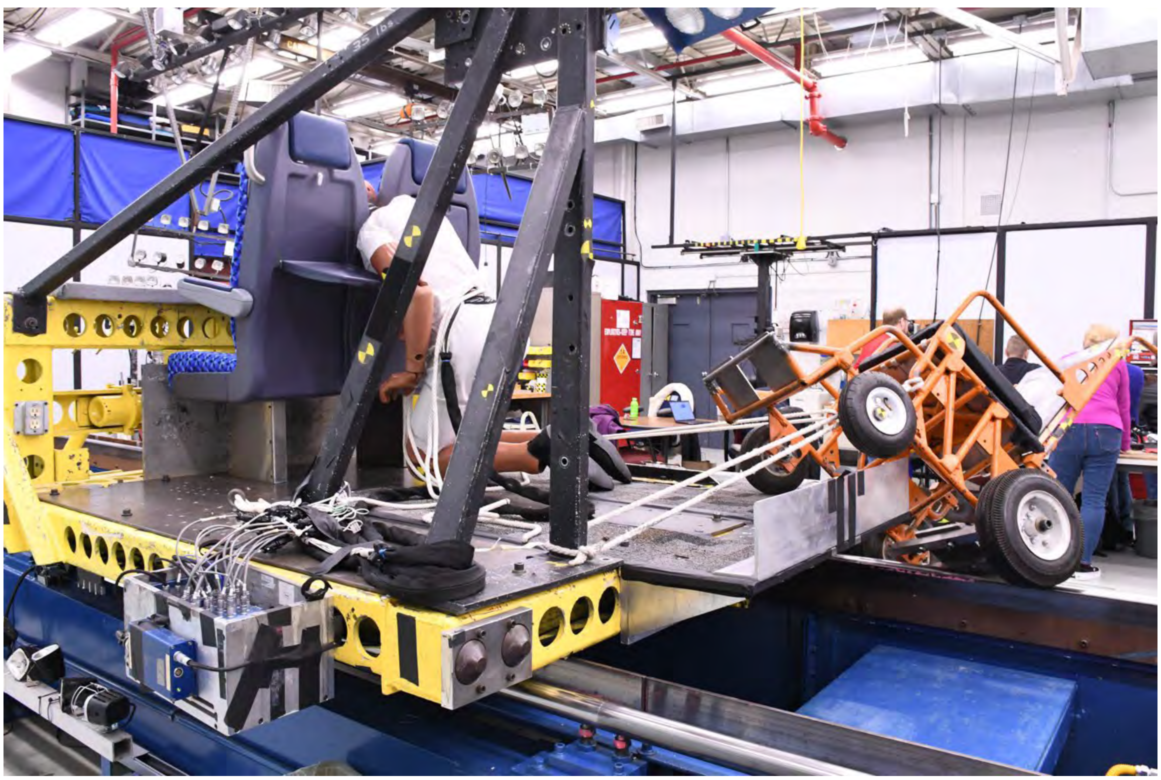

Figure A72. VP2409 Post-test Left Rear Oblique View

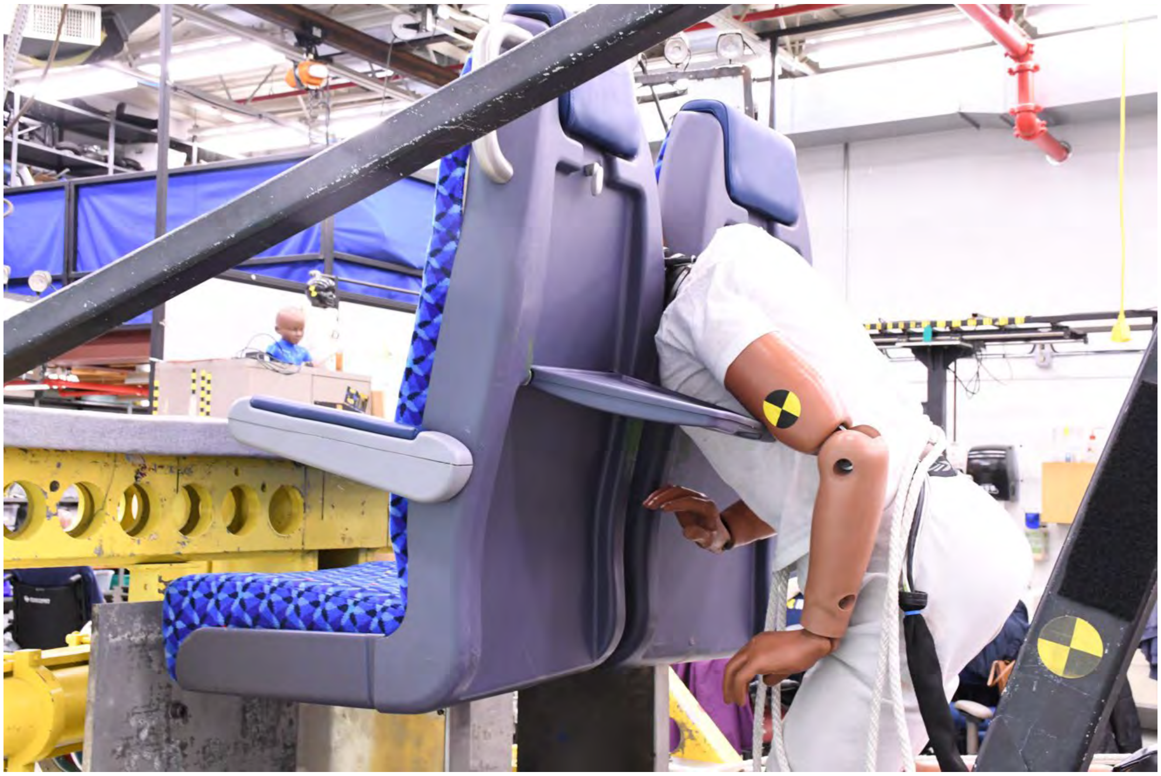

Figure A73. VP2409 Post-test Left Rear Oblique View of Commuter Rail Seat

Figure A74. VP2409 Post-test Left Side View of Commuter Rail Seat

Figure A75. VP2409 Post-test Left Side View of Wheelchair

Figure A76. VP2409 Post-test Knee Contact Point on Back of Commuter Rail Seat

Figure A77. VP2409 Post-test Left Rear Oblique View of Commuter Rail Seat and Tray

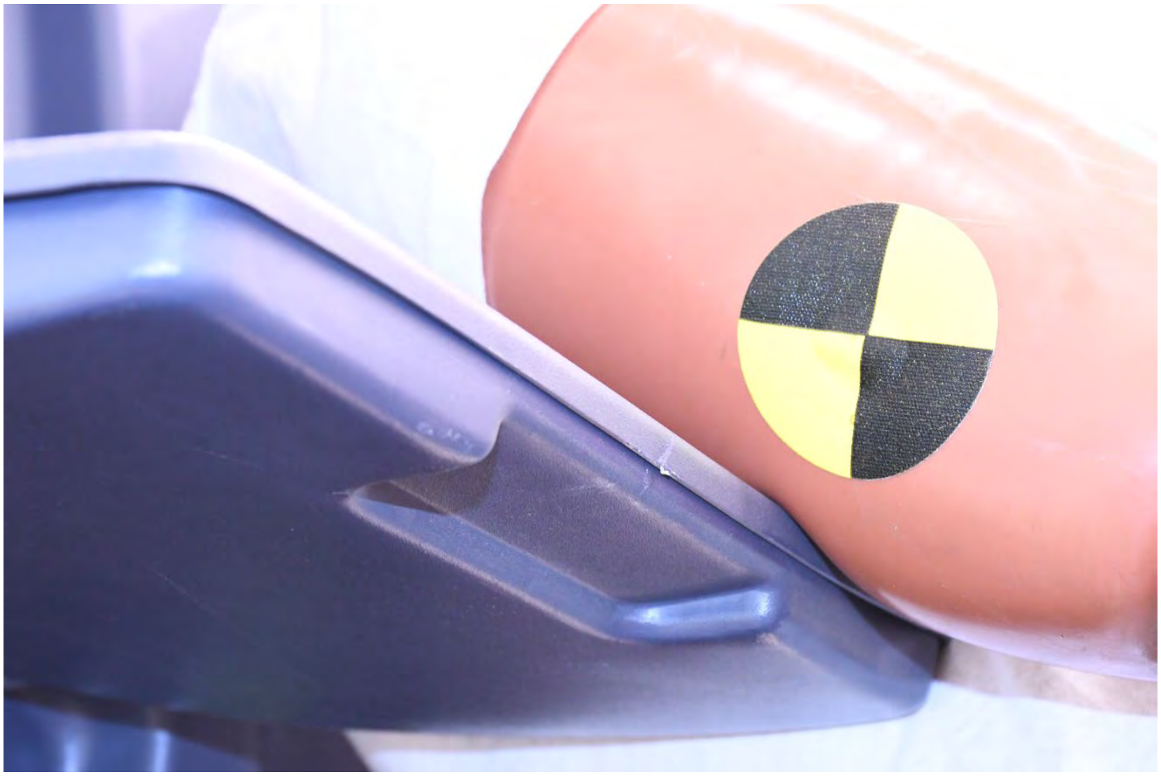

Figure A78. VP2409 Post-test Closeup of ATD Arm Contact with Commuter Rail Seat Tray

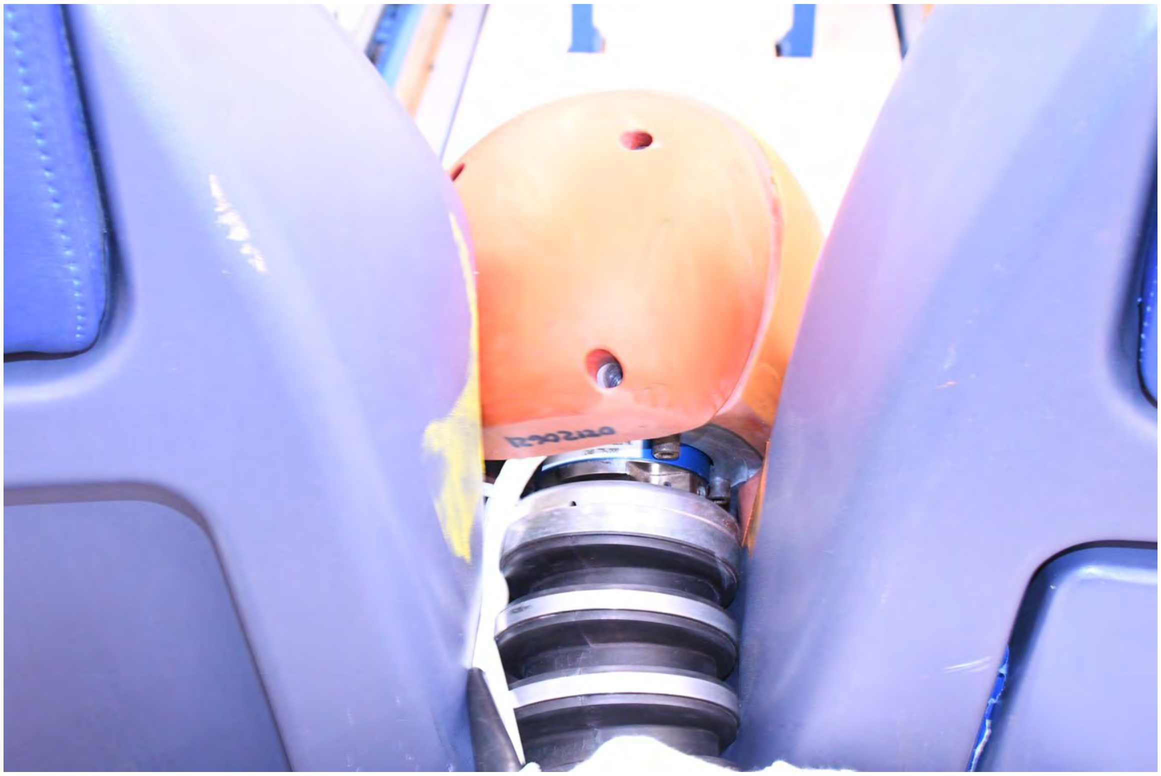

Figure A79. VP2409 Post-test Rear Closeup View of ATD Head

Figure A80. VP2409 Post-test Rear View of ATD Head

Appendix B.
Impact Signal Outputs

This appendix contains the signal data from each channel plotted versus time for the three sled impact tests.

VP2407 Signals

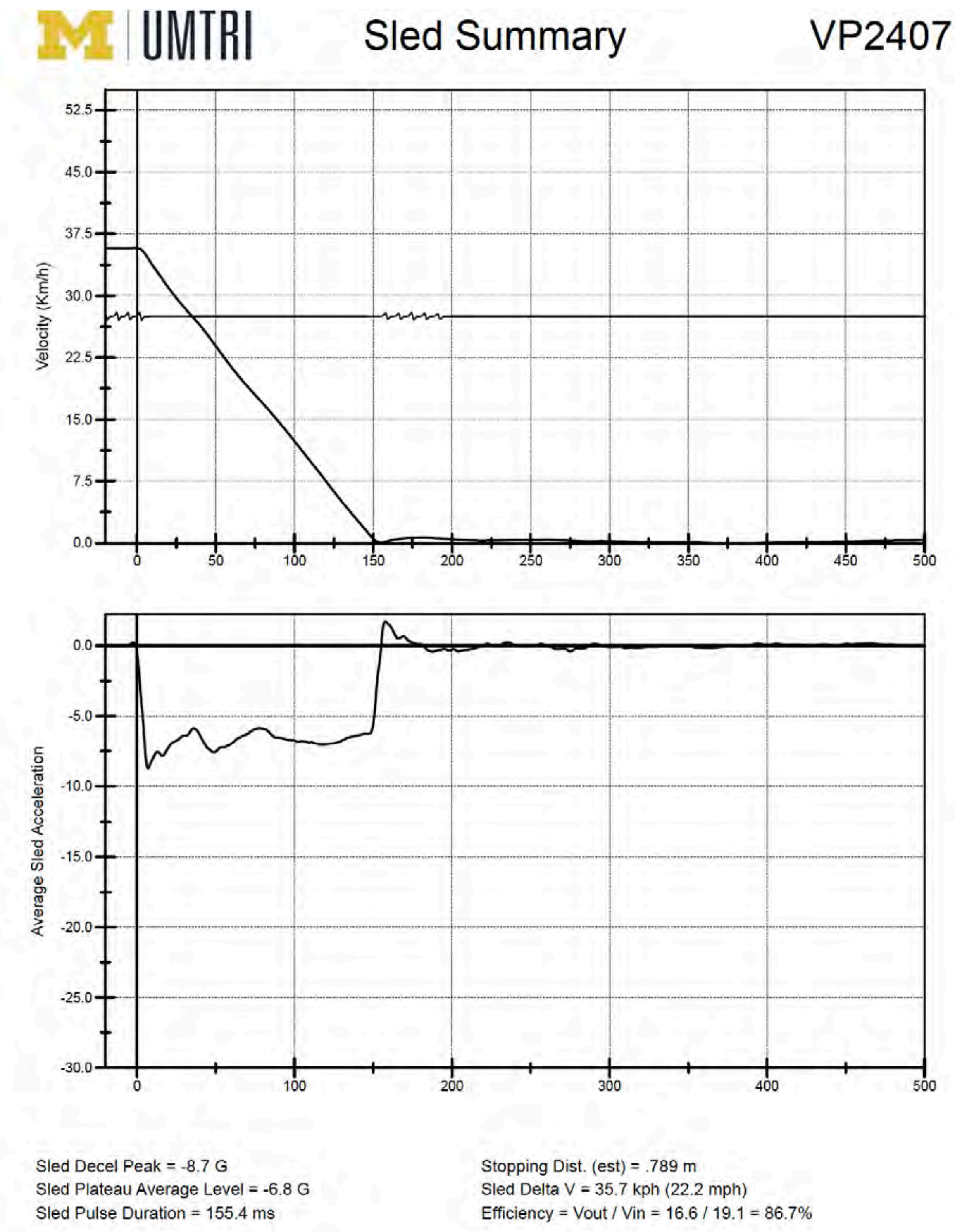

Figure B1. VP2407 Sled Pulse and Velocity

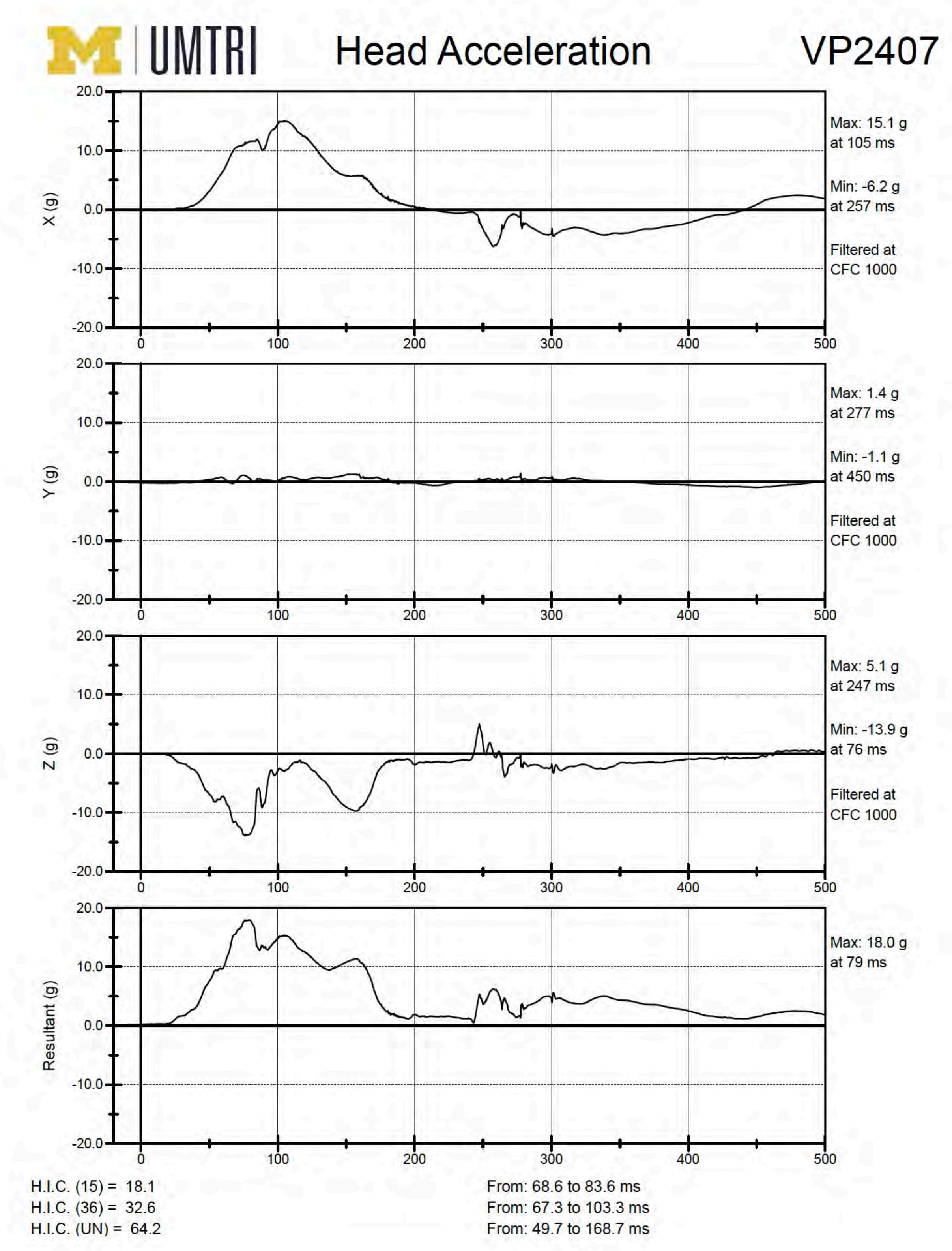

Figure B2. VP2407 Head Acceleration

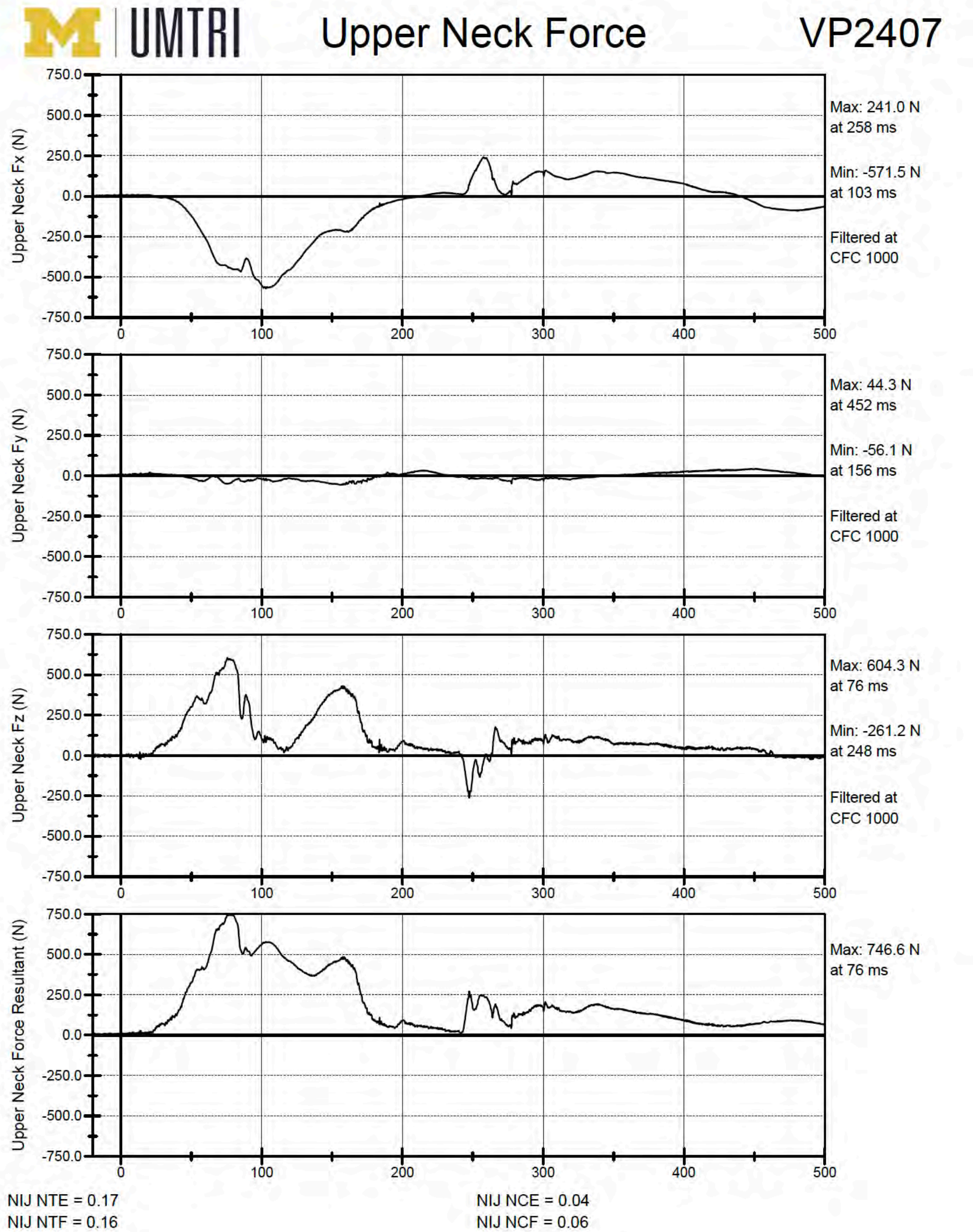

Figure B3. VP2407 Upper Neck Force

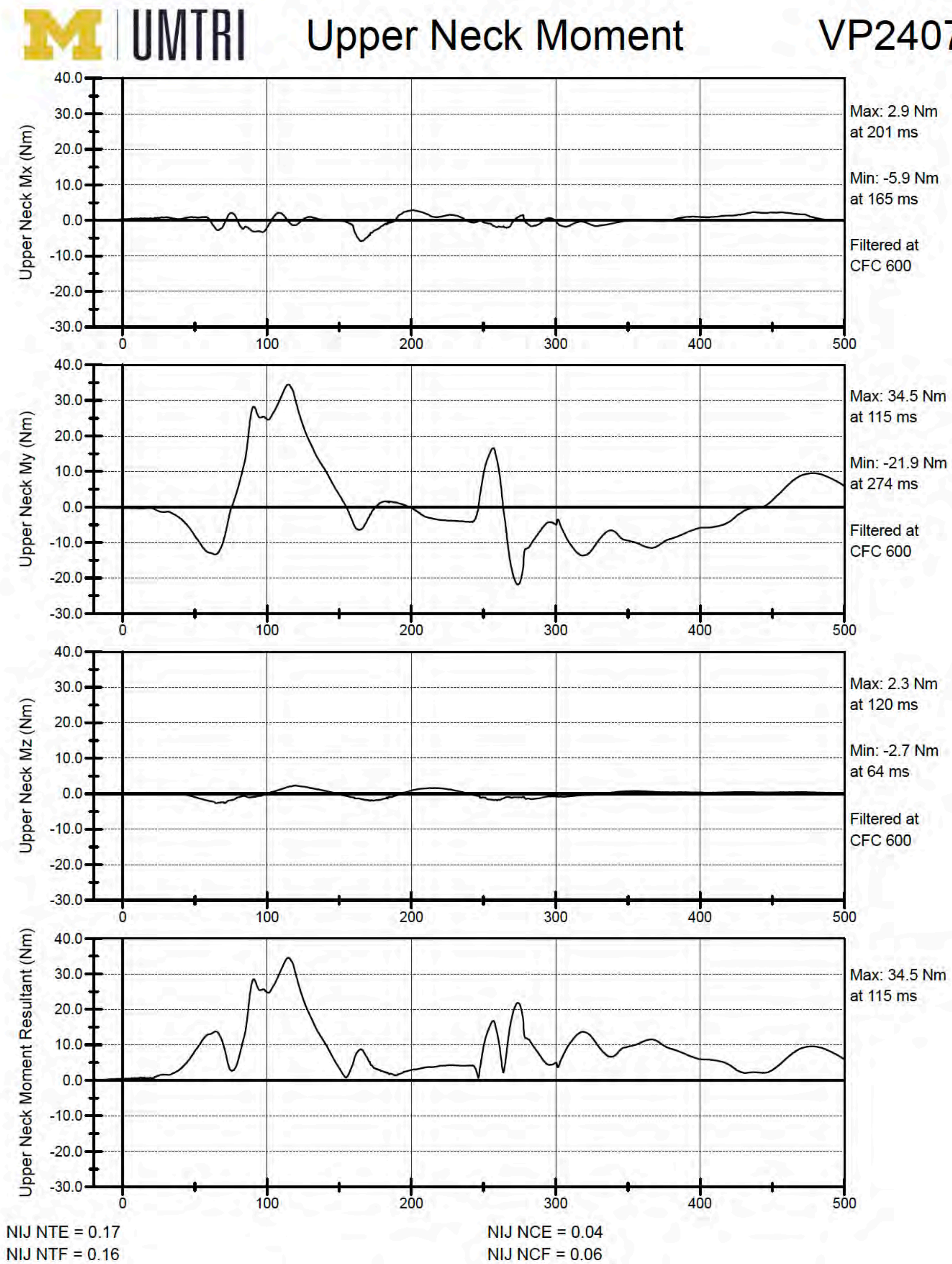

Figure B4. VP2407 Upper Neck Moments

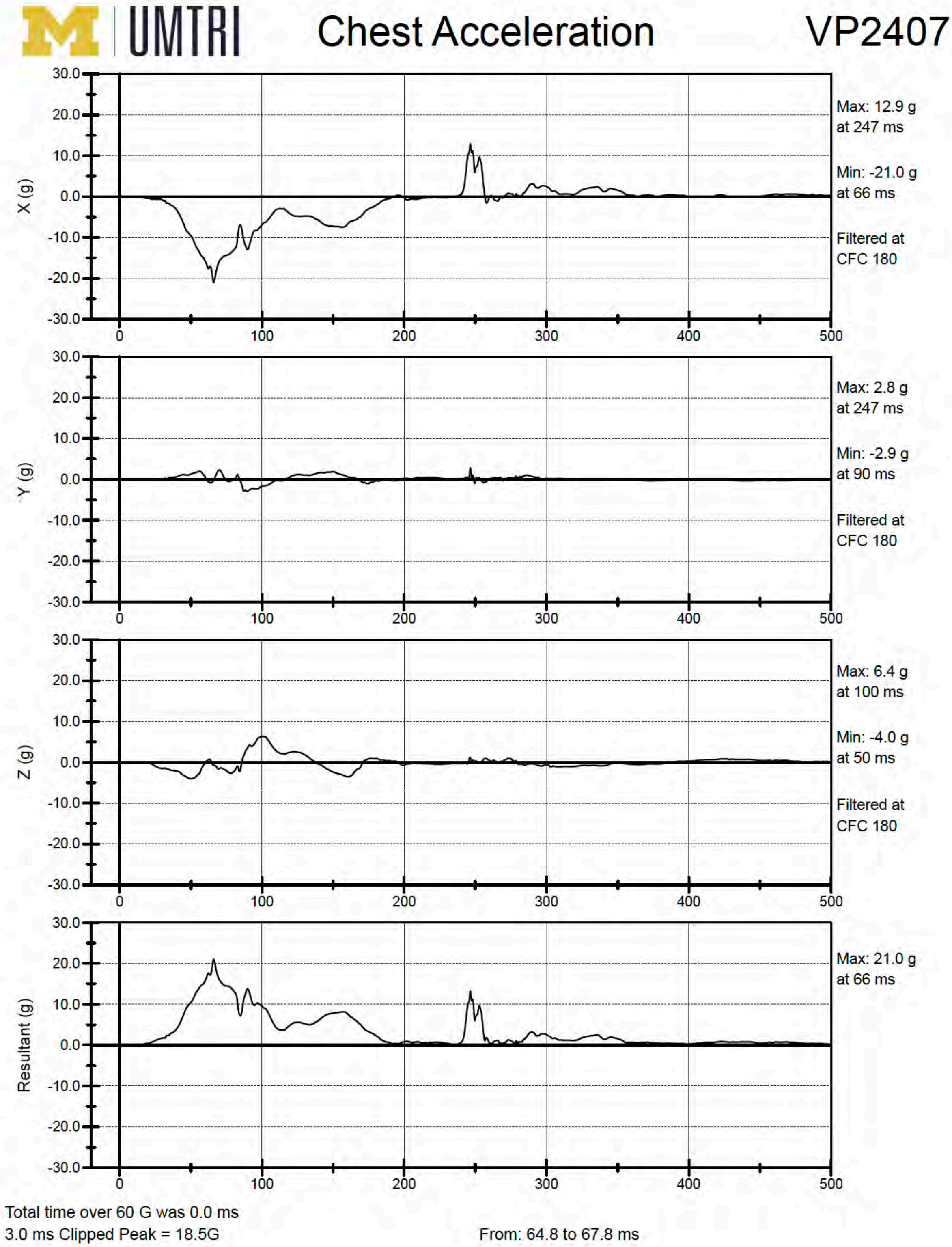

Figure B5. VP2407 Chest Acceleration

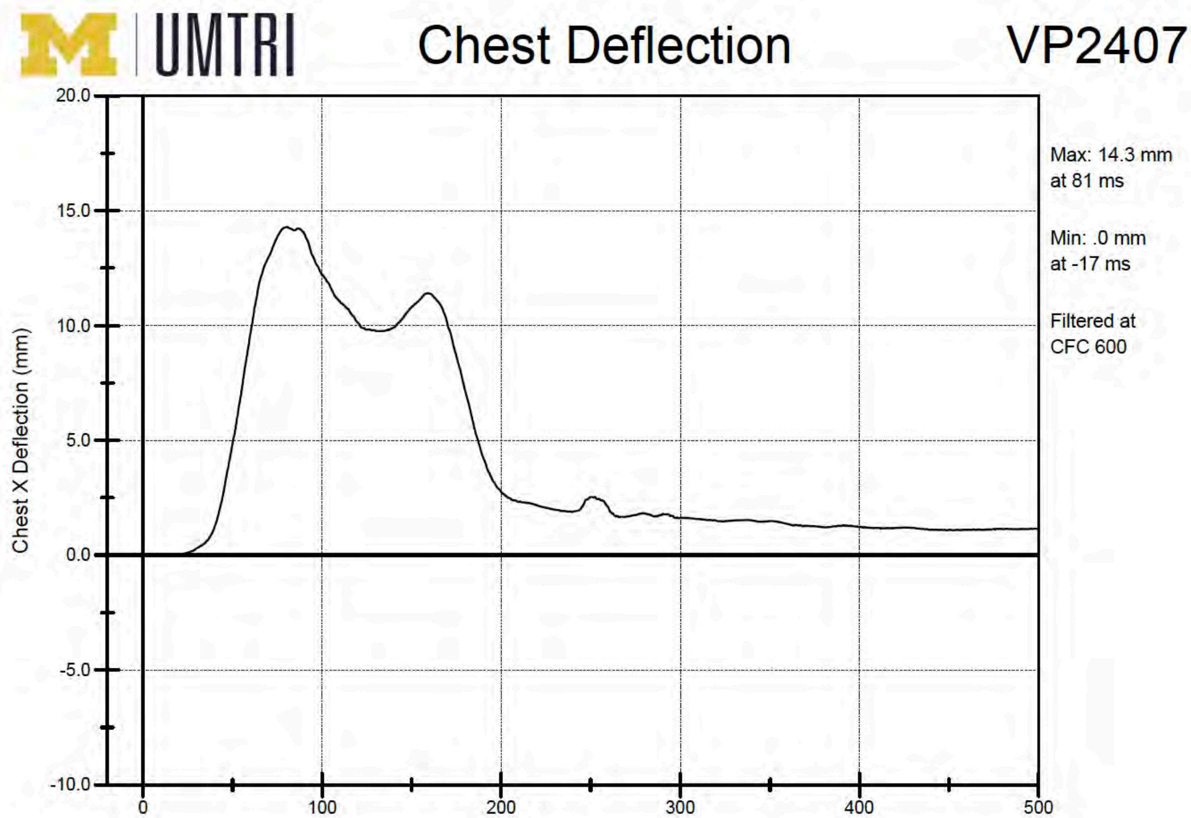

Figure B6. VP2407 Chest Deflection

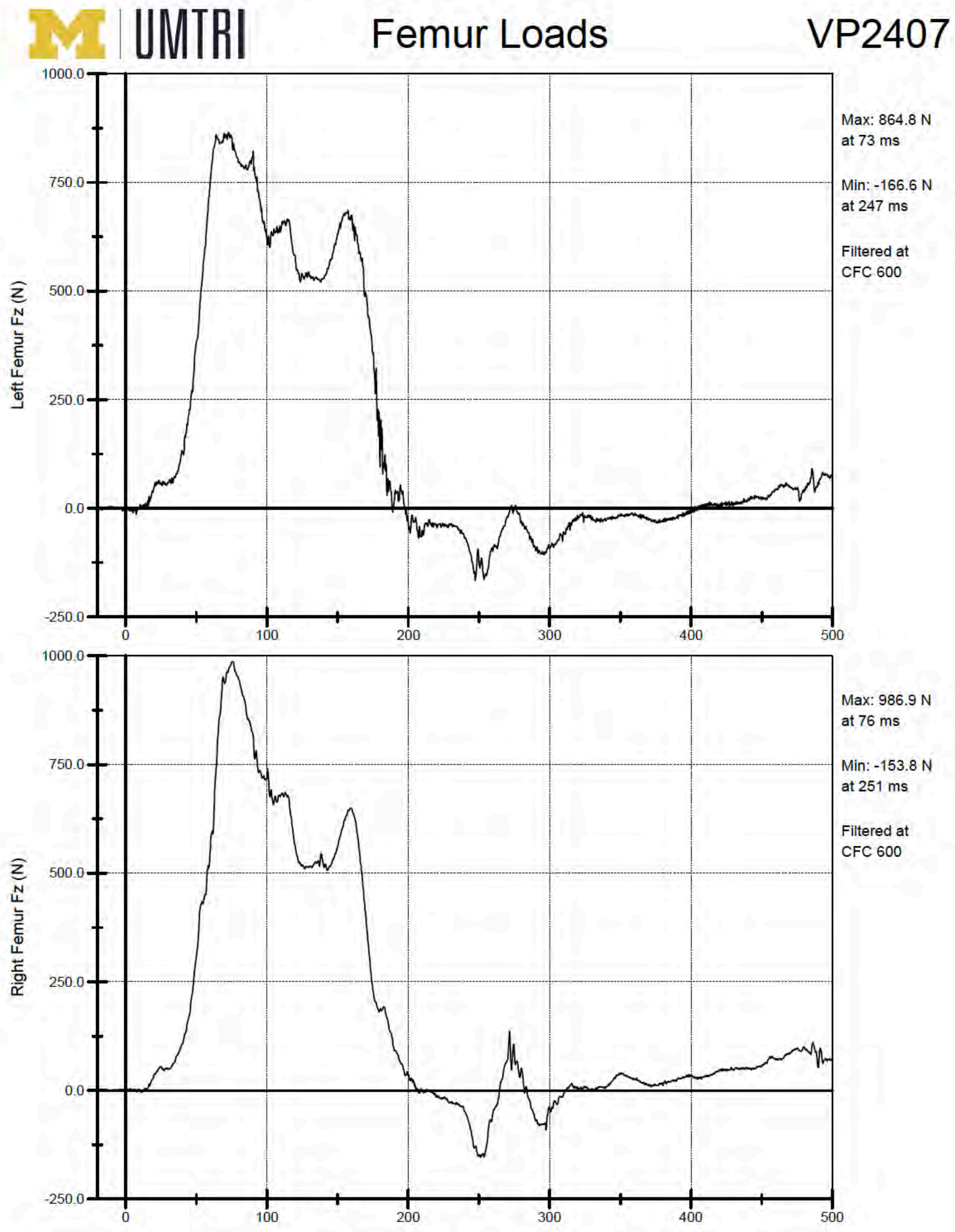

Figure B7. VP2407 Femur Loads

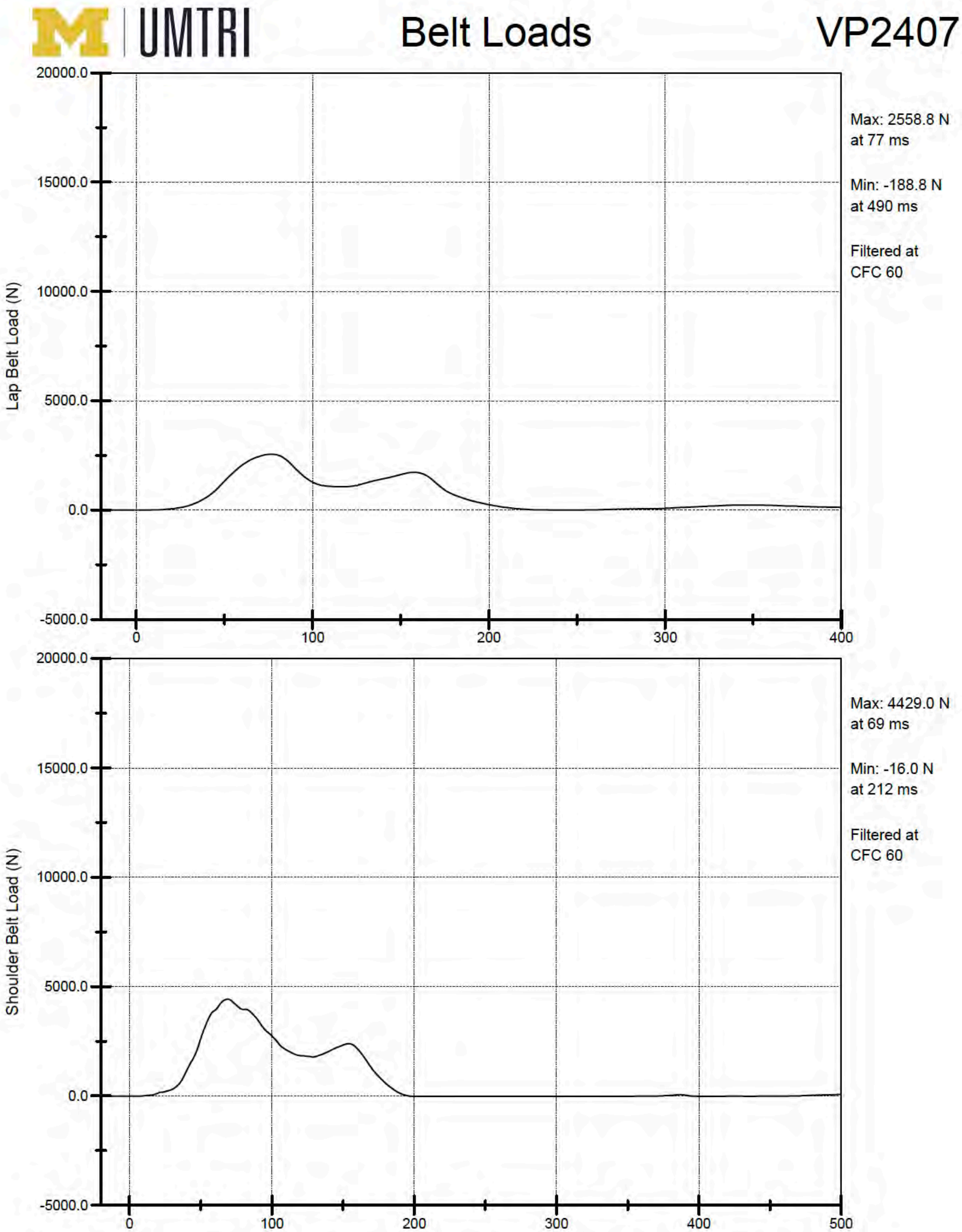

Figure B8. VP2407 Belt Loads

VP2408 Signals

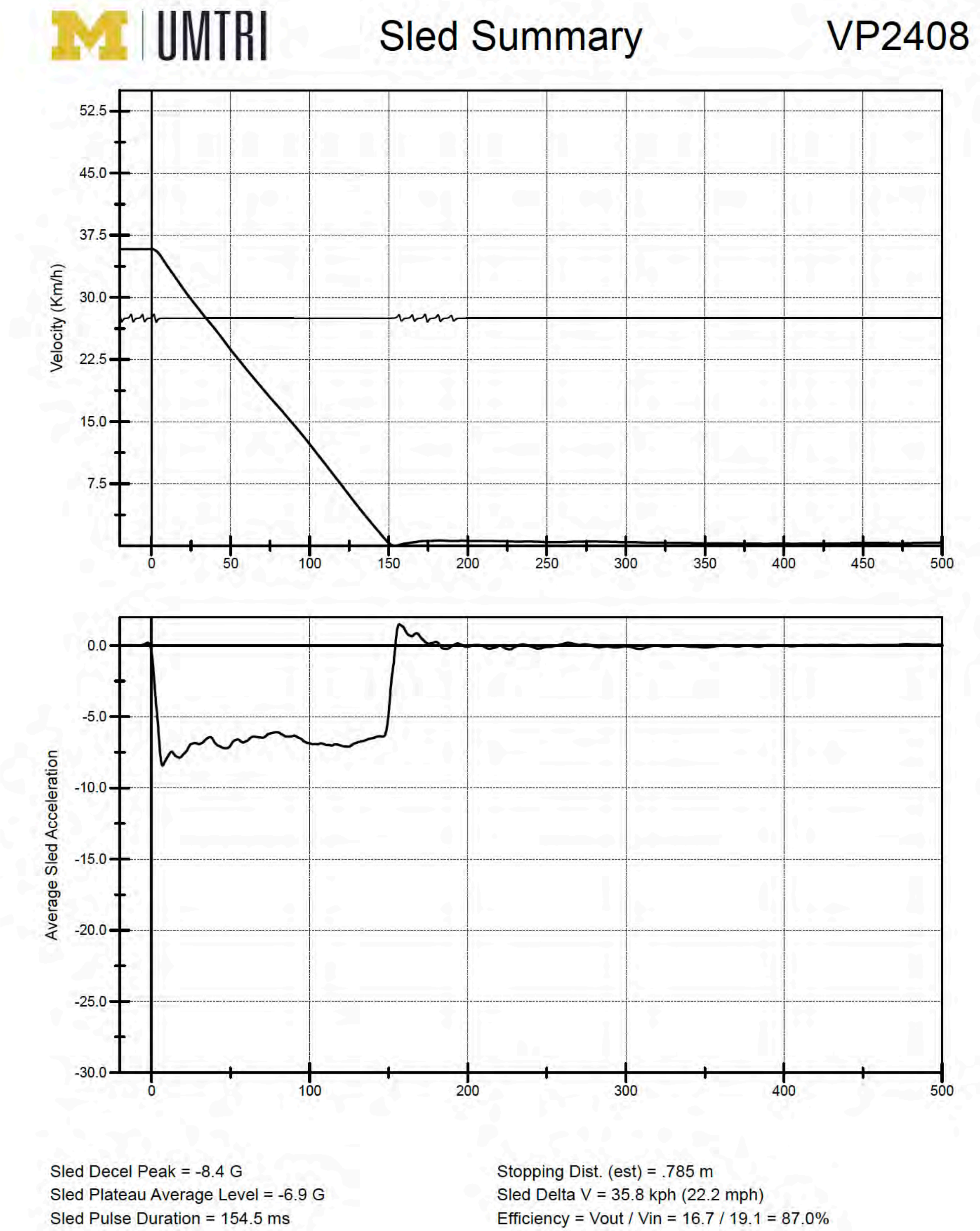

Figure B9. VP2408 Sled Pulse and Velocity

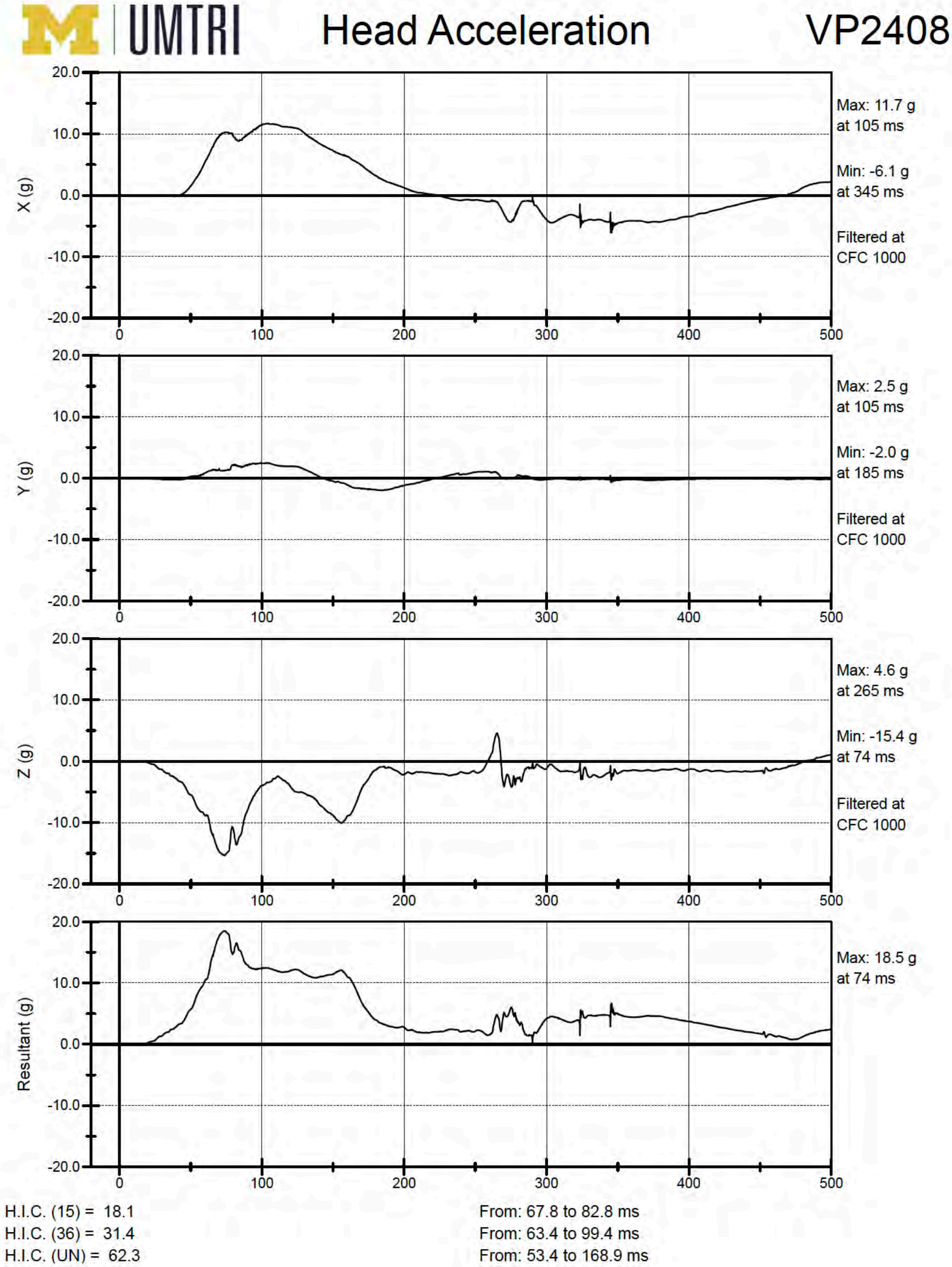

Figure B10. VP2408 Head Acceleration

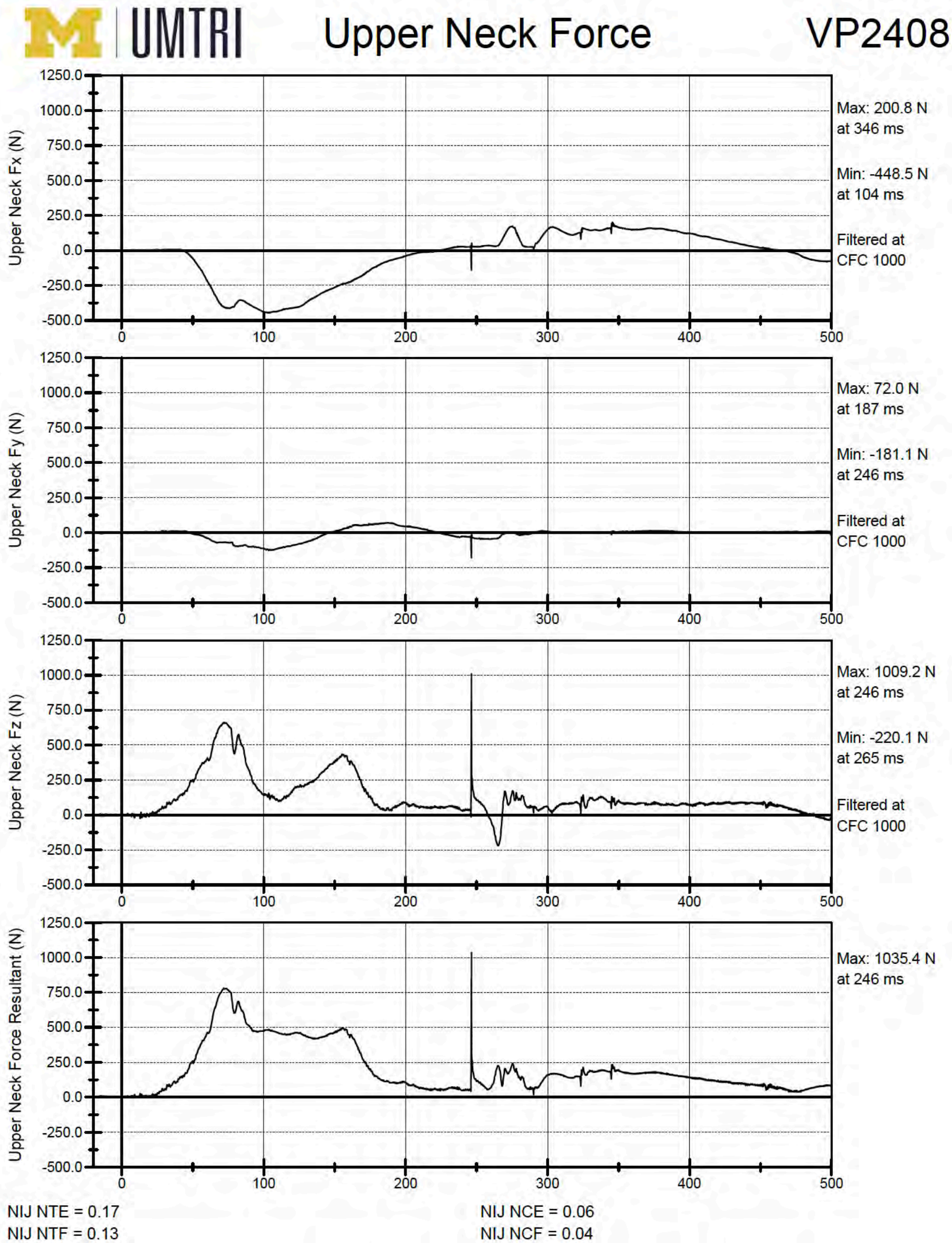

Figure B11. VP2408 Upper Neck Forces

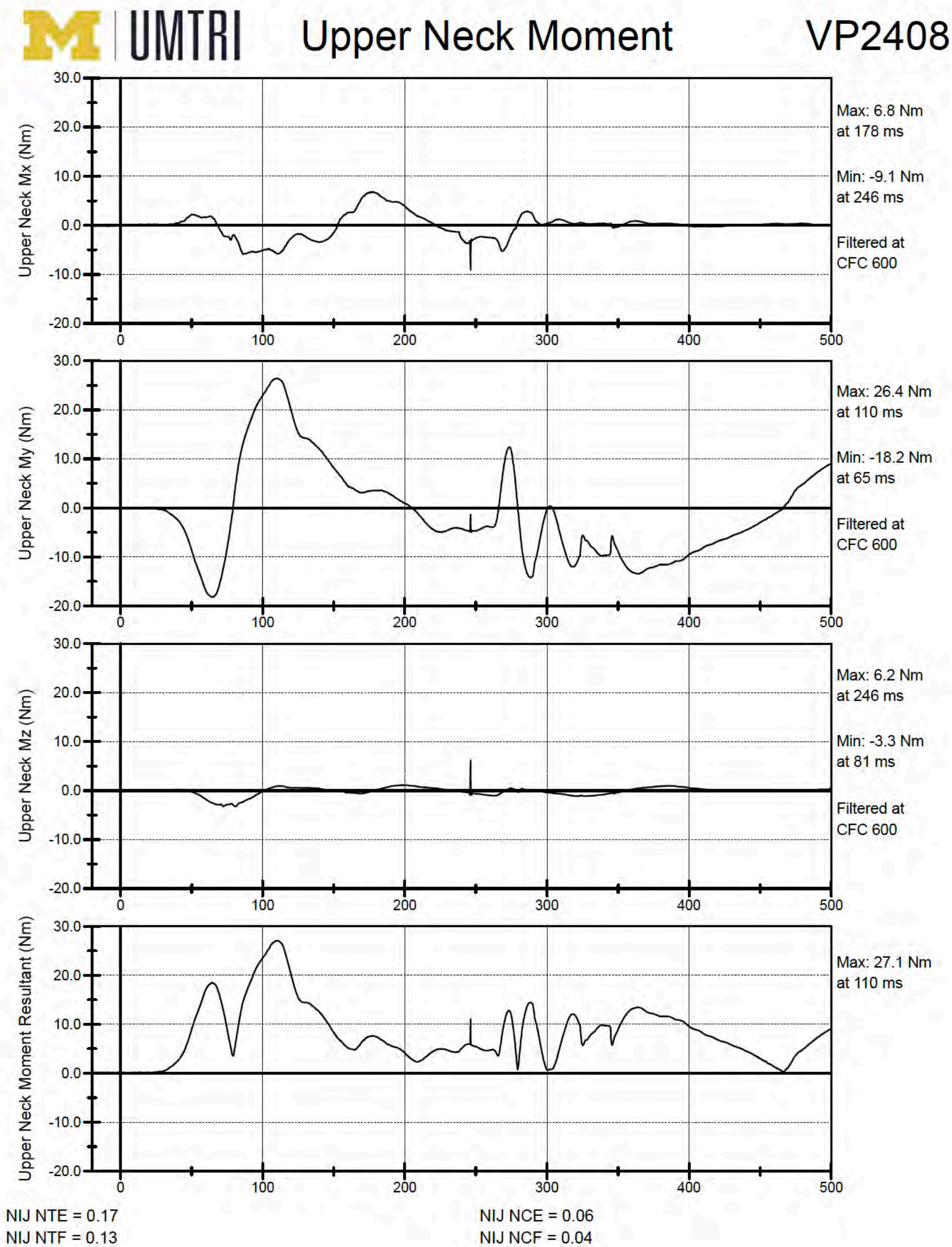

Figure B12. VP2408 Upper Neck Moments

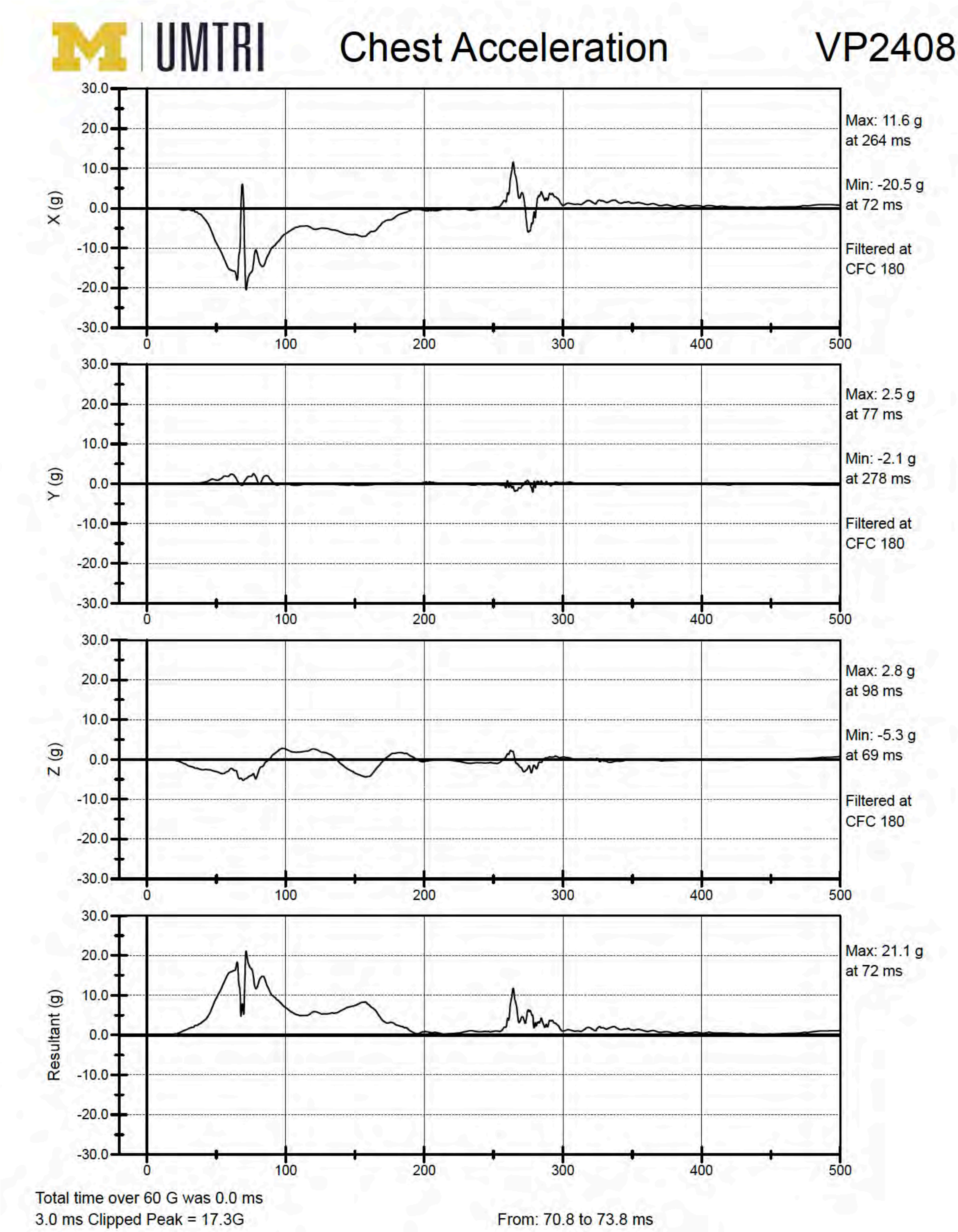

Figure B13. VP2408 Chest Acceleration

(note: spurious "blip" on Chest X signal at about t=65 ms)

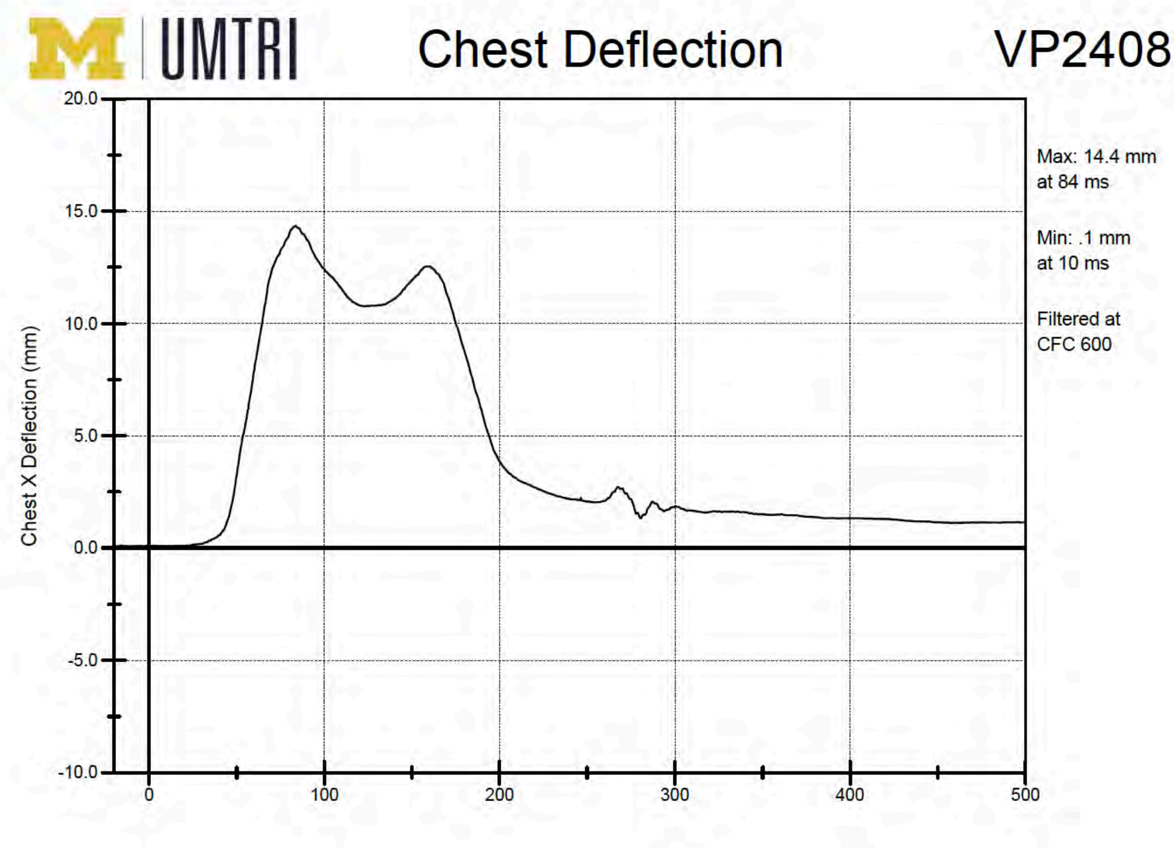

Figure B14. VP2408 Belt Loads

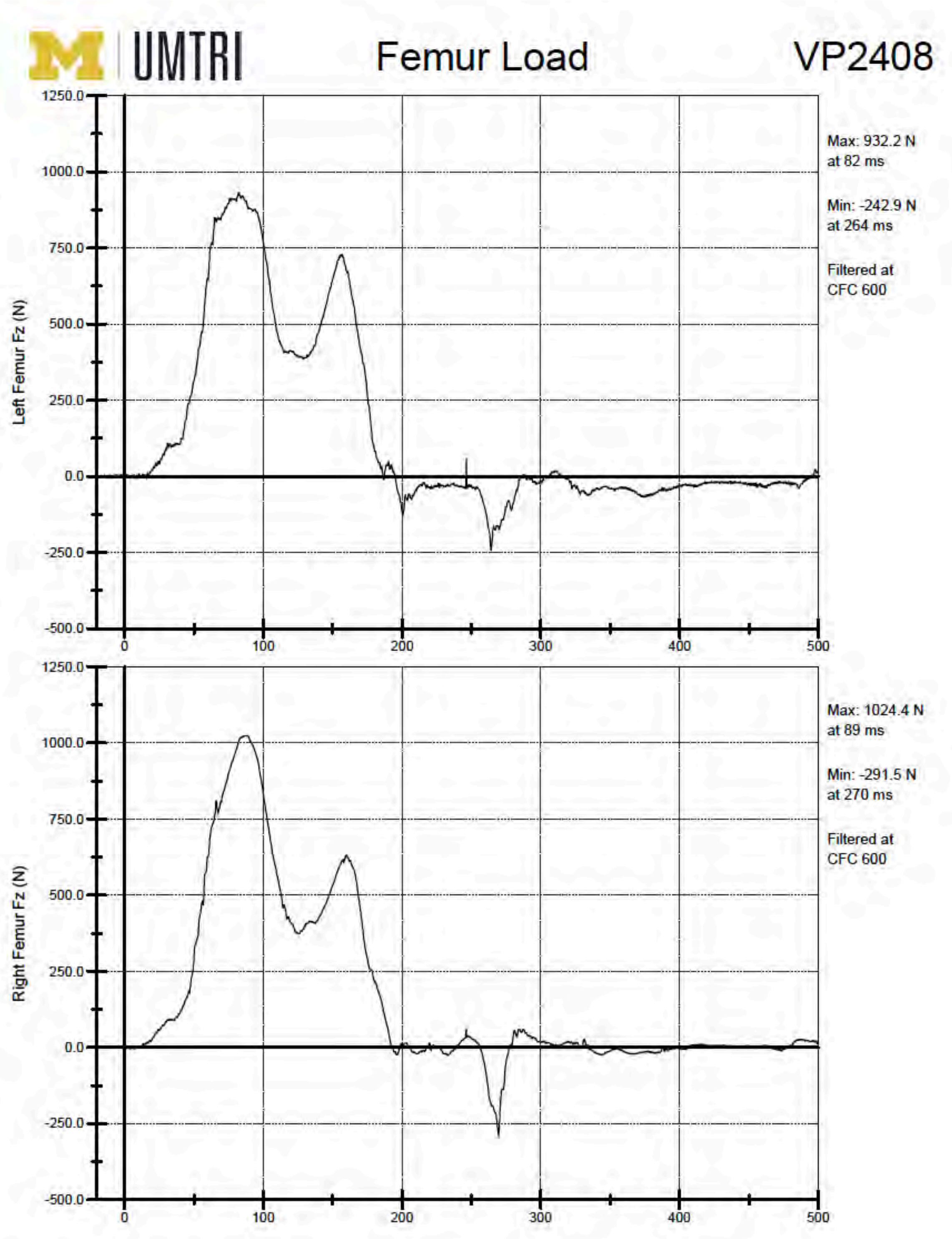

Figure B15. VP2408 Femur Loads

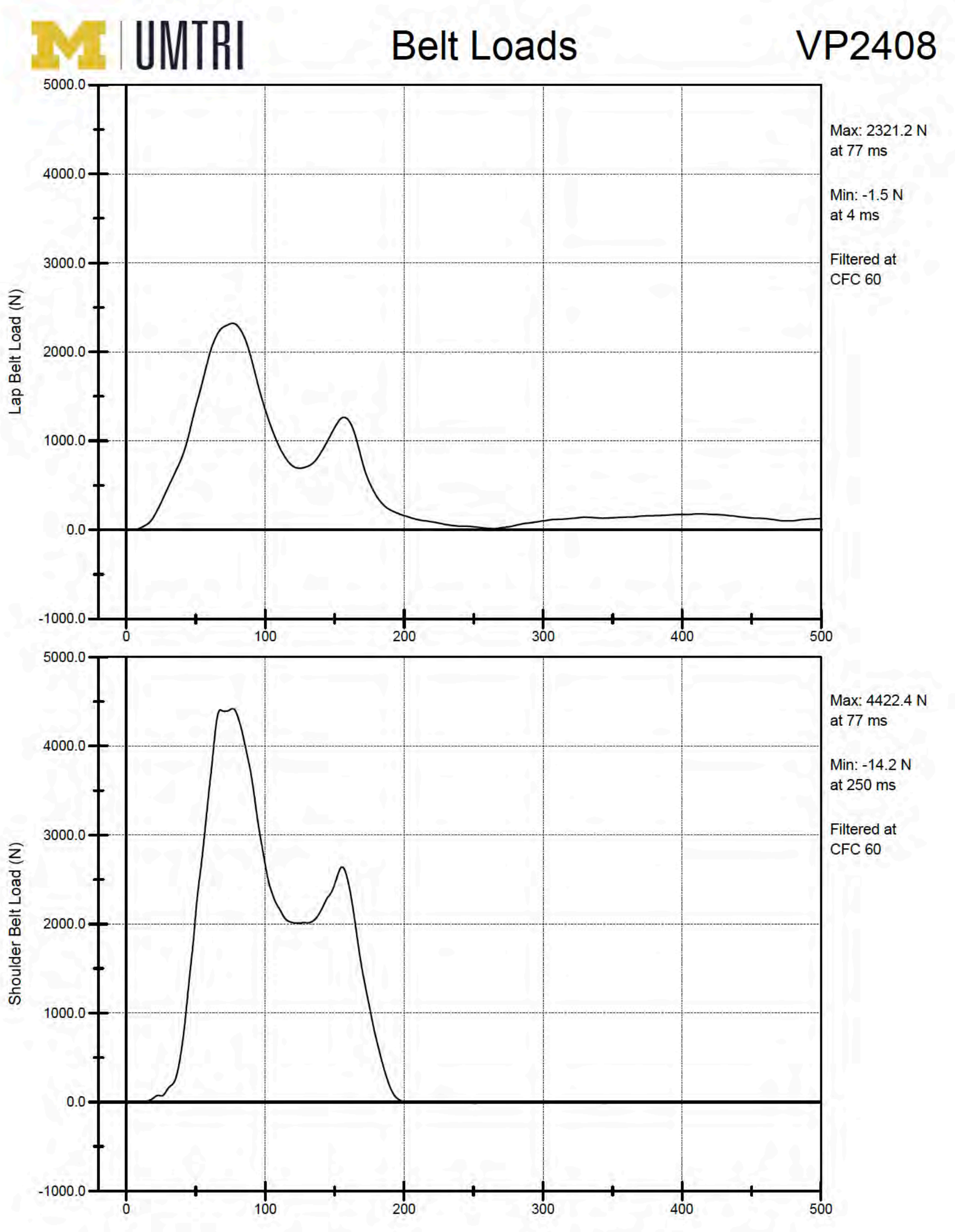

Figure B16. VP2408 Belt Loads

VP2409 Signals

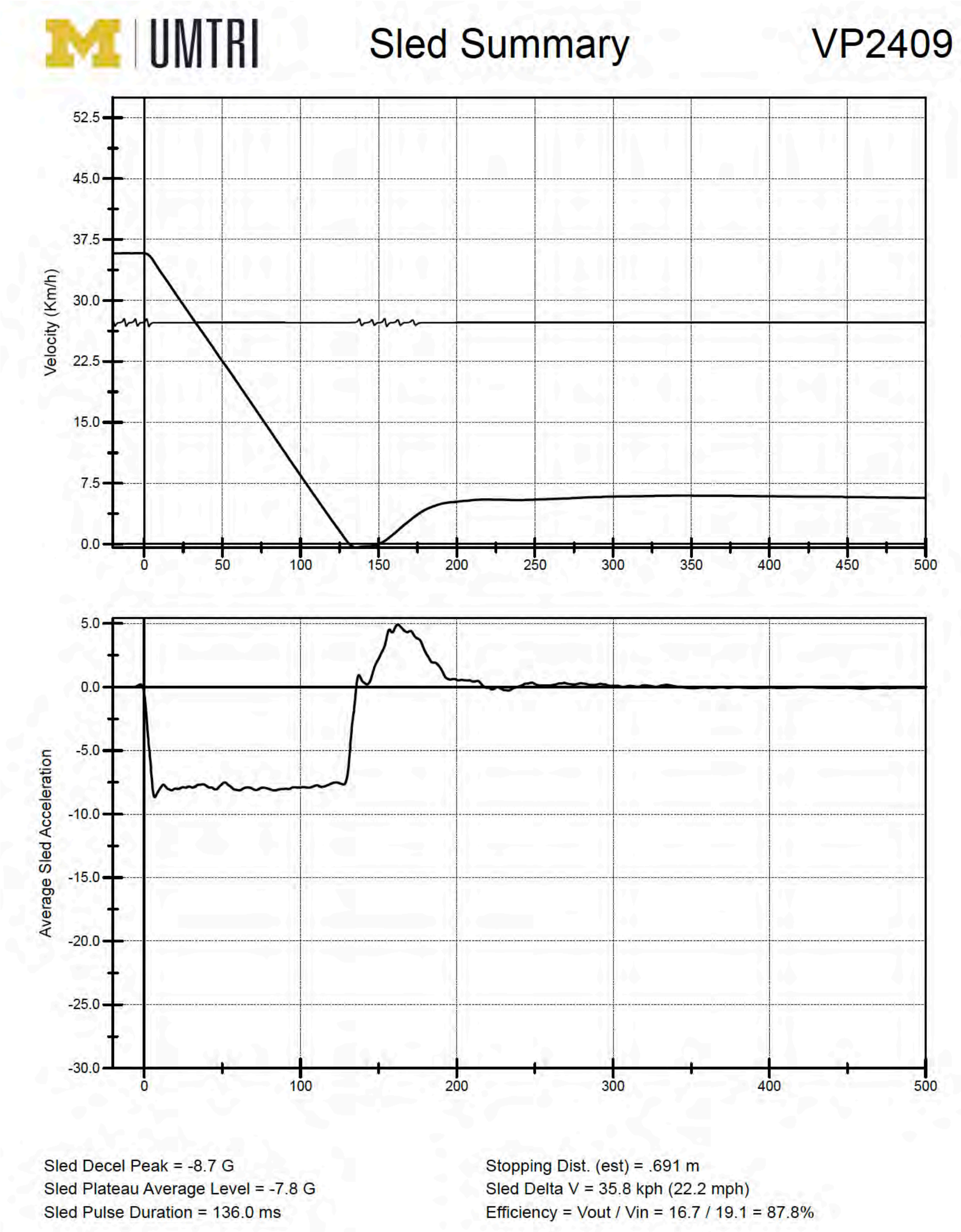

Figure B17. VP2409 Sled Pulse and Velocity

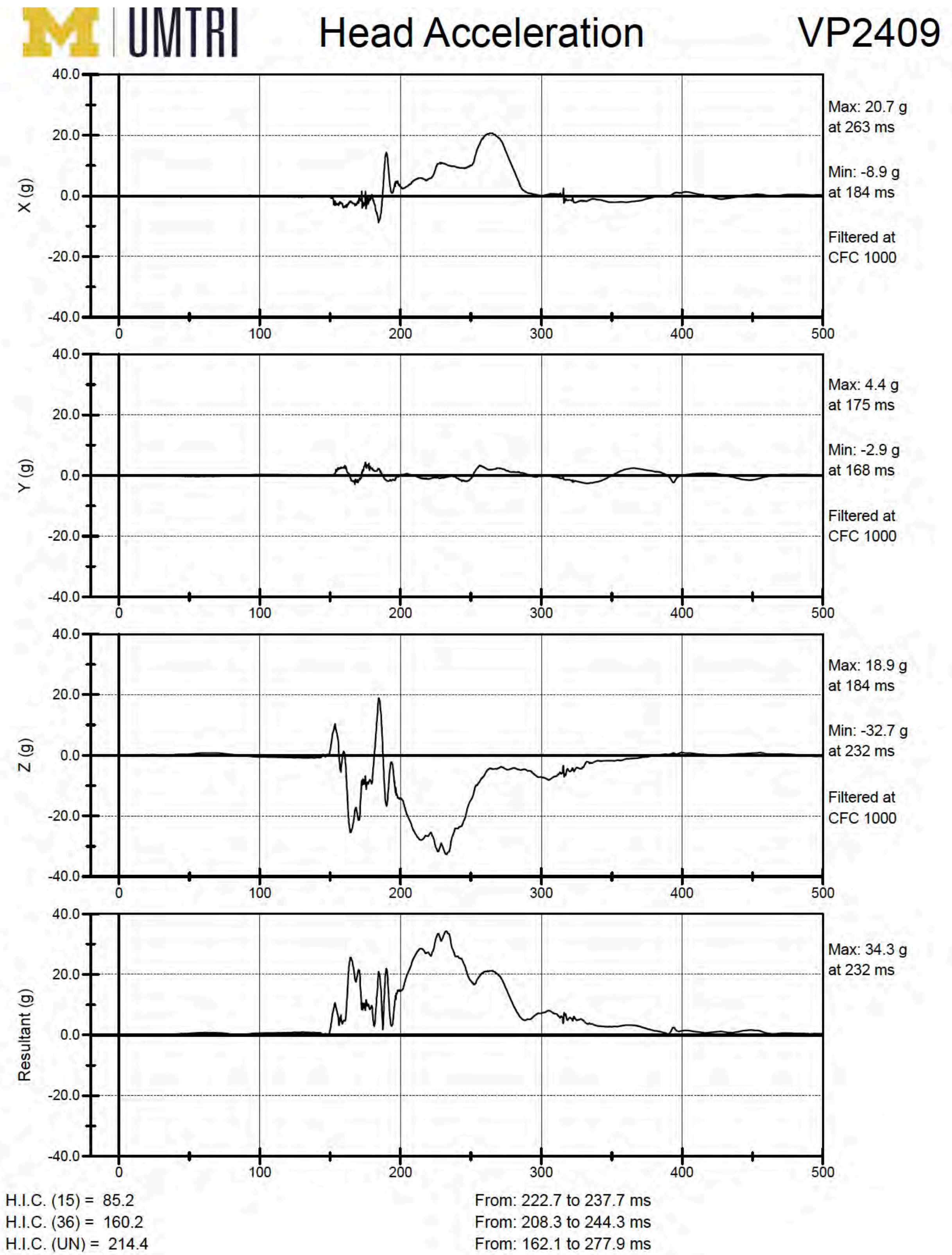

Figure B18. VP2409 Head Acceleration

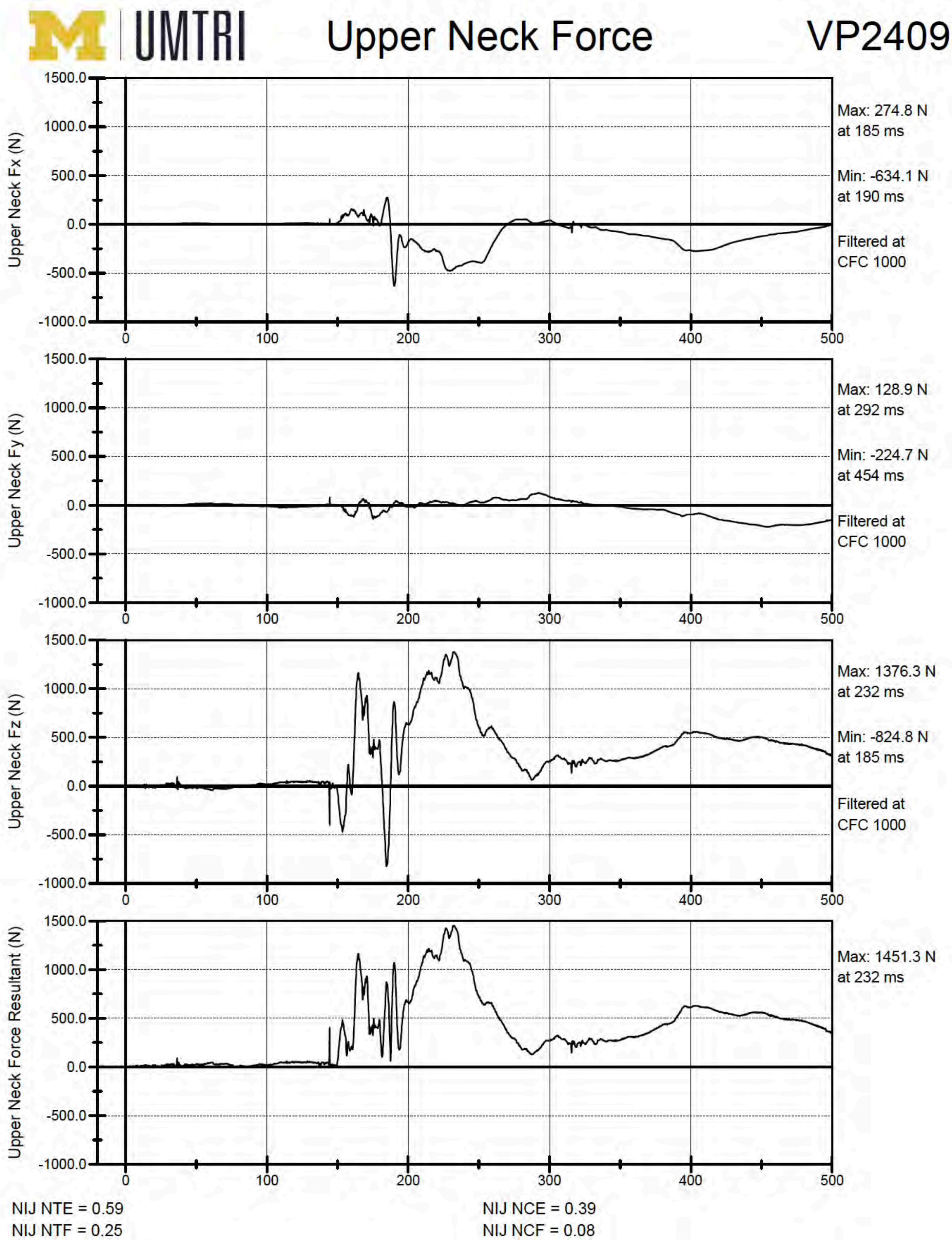

Figure B19. VP2409 Upper Neck Force

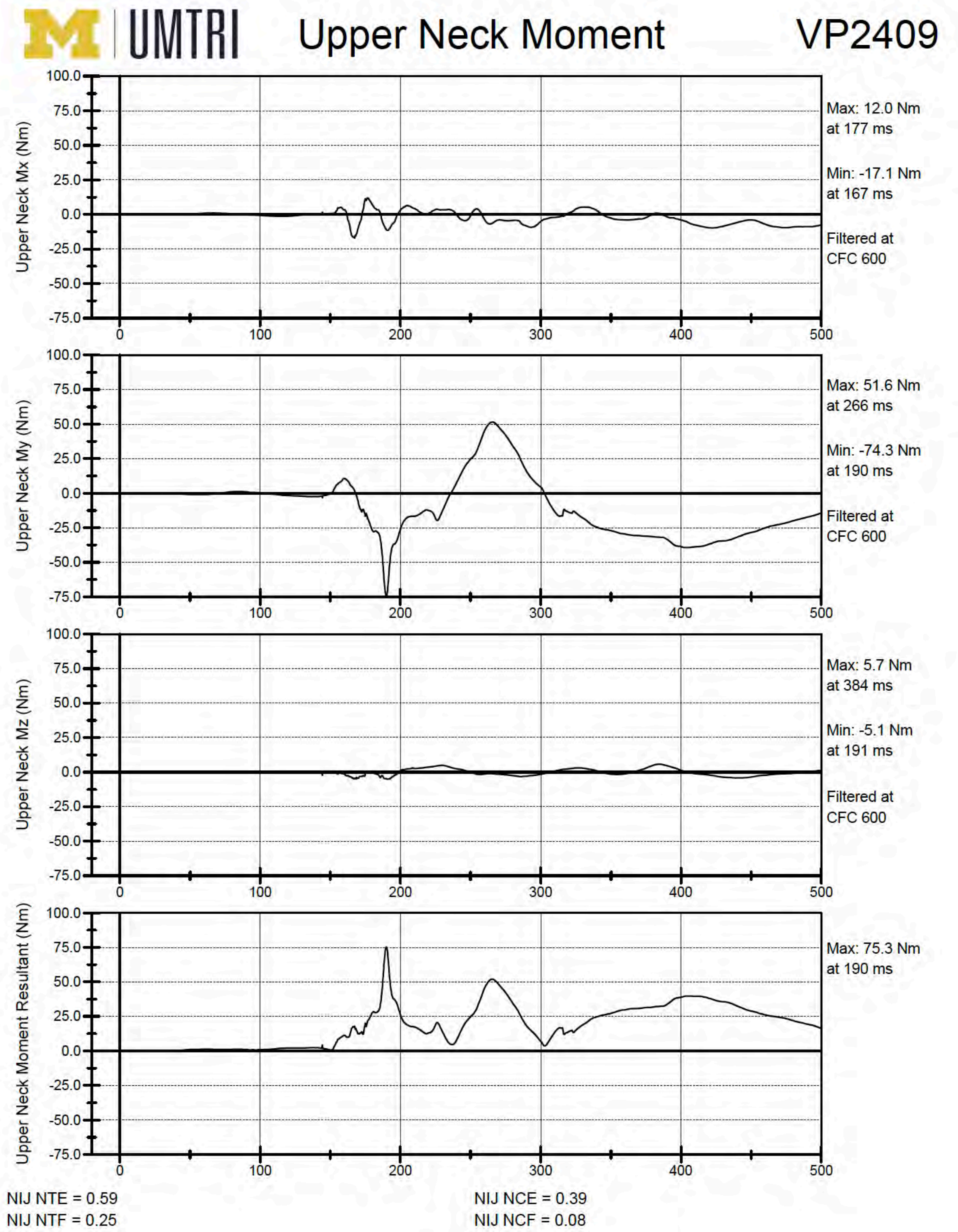

Figure B20. VP2409 Upper Neck Moment

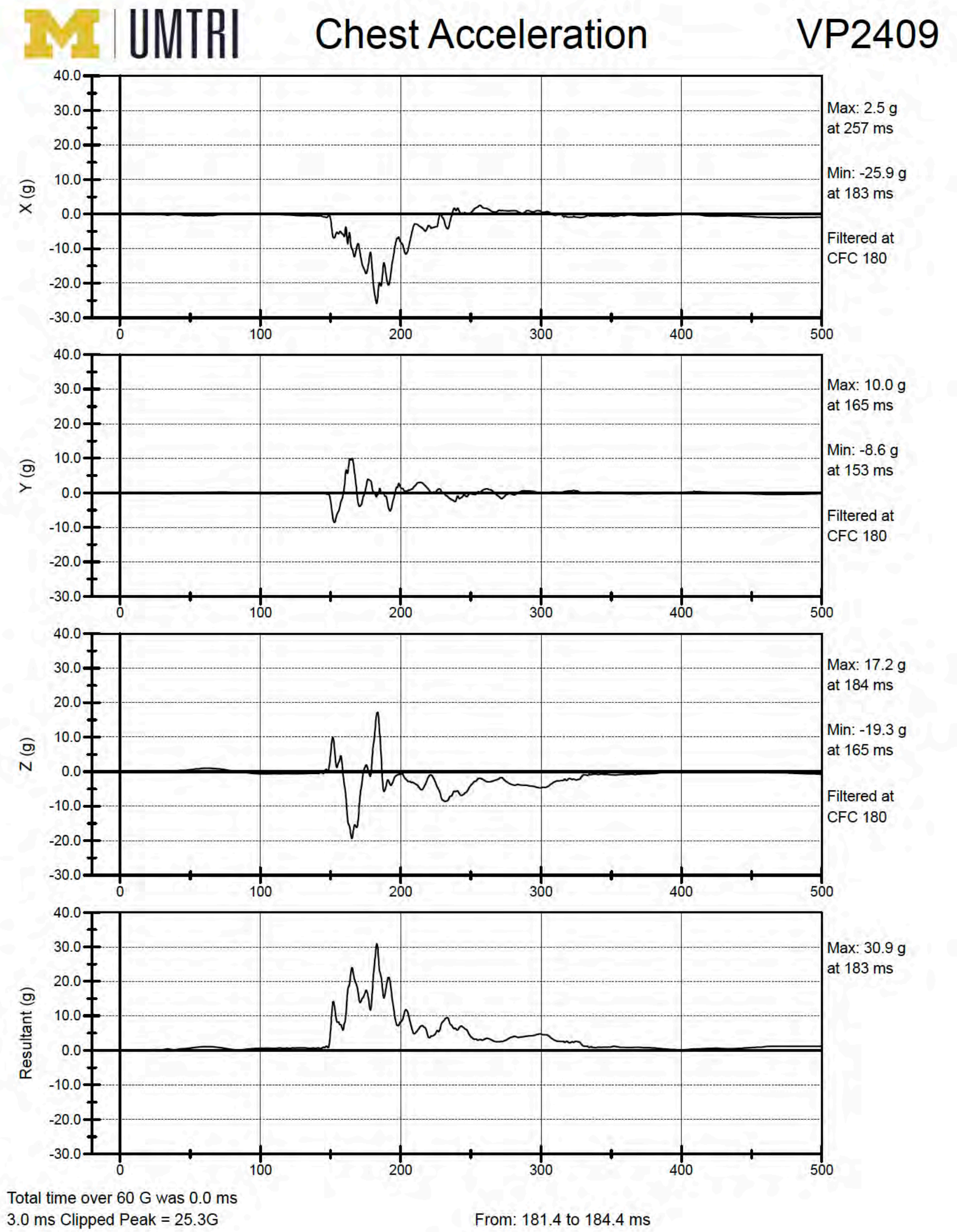

Figure B21. VP2409 Chest Acceleration

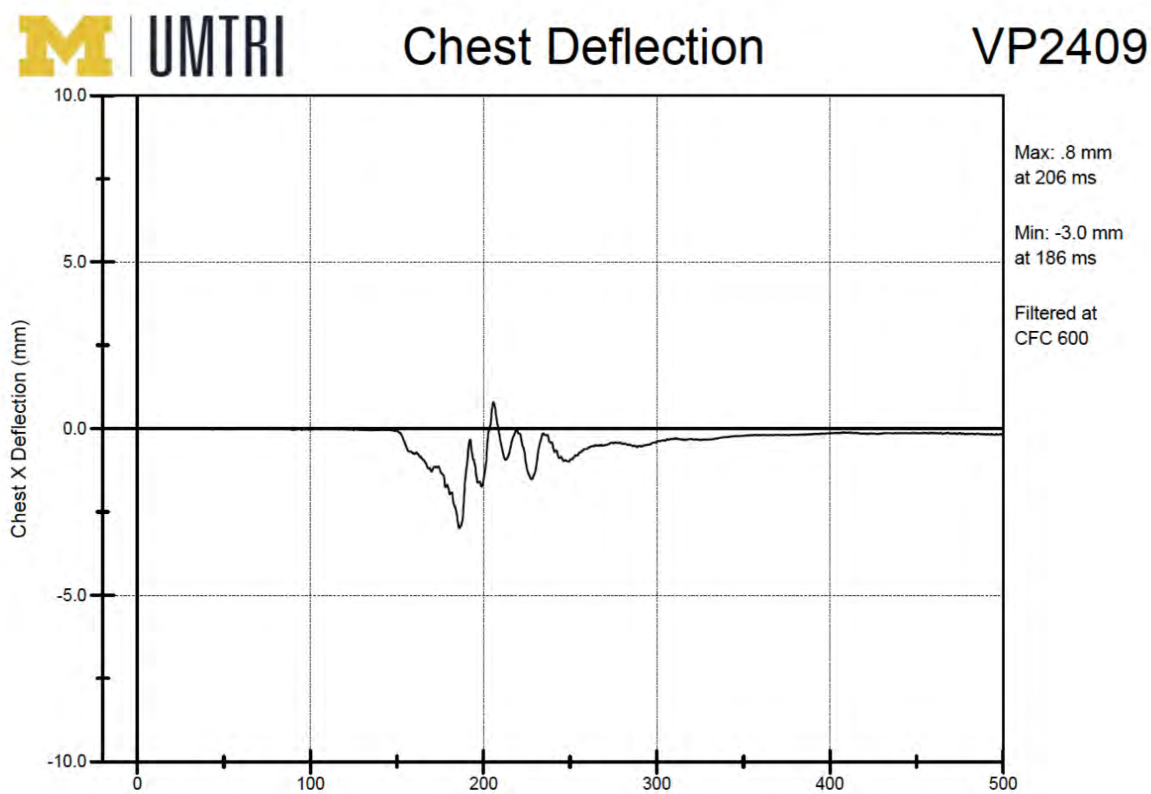

Figure B22. VP2409 Chest Deflection

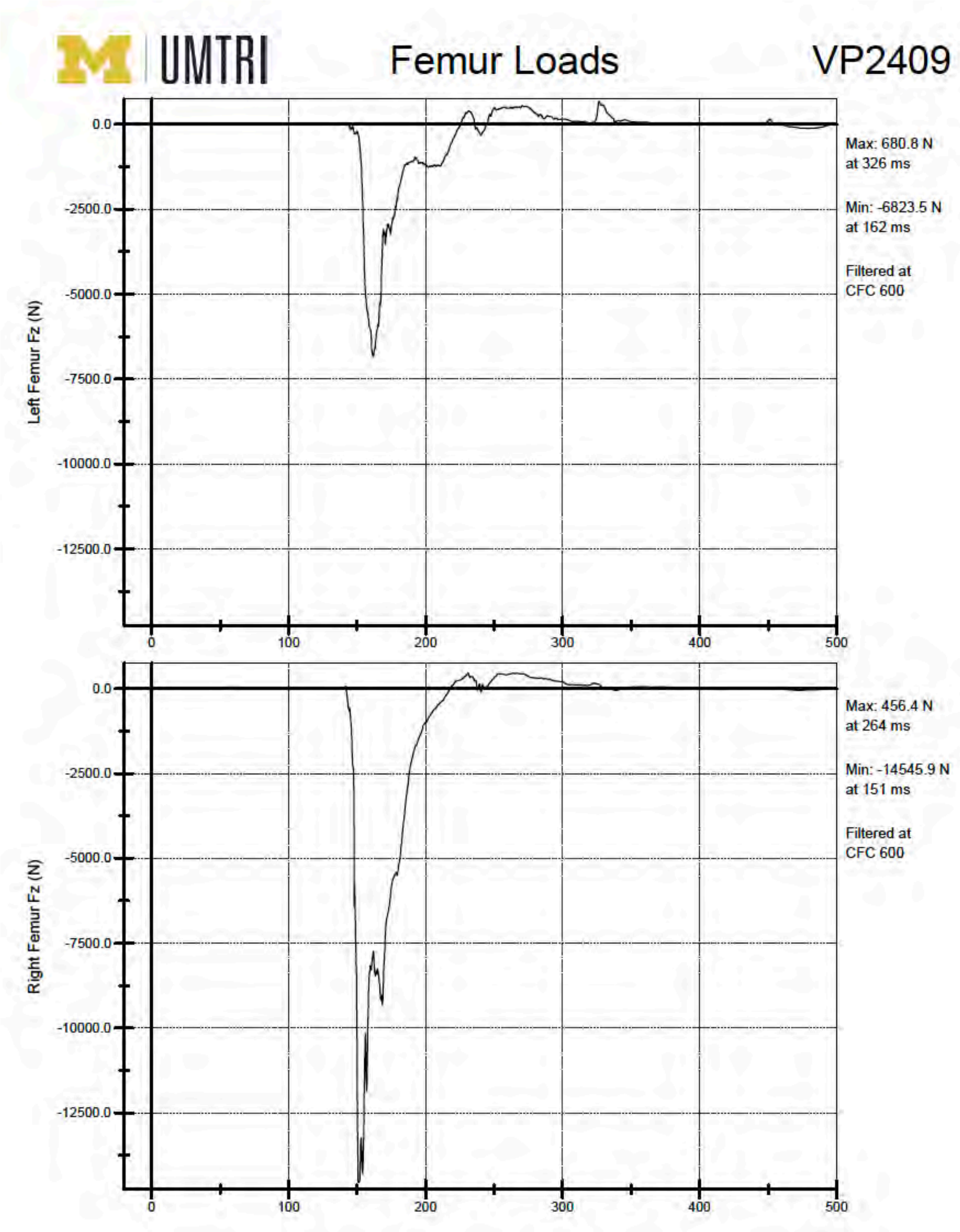

Figure B23. VP2409 Femur Loads

Abbreviations and Acronyms

ACRONYM	DEFINITION
ADA	Americans with Disabilities Act
ANSI	American National Standards Institute
APTA	American Public Transportation Association
ATD	Anthropomorphic Test Device
AV	Automated Vehicle
g	gravity
FMVSS	Federal Motor Vehicle Safety Standard
FRA	Federal Railroad Administration
HIC	Head Injury Criteria
IARV	Injury Assessment Reference Value
ISO	International Standards Organization
NTE, NTF, NCE, NCF	Neck, Tension/Compression, Extension/Flexion
NHTSA	National Highway Traffic Safety Administration
RESNA	Rehabilitation Engineering Society of North America
RD&T	Research, Development, and Technology
RVAAC	Rail Vehicle Access Advisory Committee,
SAE	Society of Automotive Engineers
SWC	Surrogate wheelchair
UDIG	Universal Docking Interface Geometry
UMTRI	University of Michigan Transportation Research Institute
VRTC	Vehicle Research and Testing Center
WC	Wheelchair
WTORS	Wheelchair Tiedown and Occupant Restraint System