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Development of Side Impact Test Procedures for Improved Wheelchair Transportation Safety

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16. Abstract

This report presents the development of side impact test procedures for evaluating wheelchairs, wheelchair tiedowns and occupant restraint systems (WTORS), and vehicle-based occupant protection systems for wheelchair seating stations. Background includes review of existing relevant voluntary standards and past research. The method for developing elements of the testing procedure includes analysis to develop a relevant crash pulse, placement of the wheelchair station relative to simulated vehicle interior, seatbelt conditions, and appropriately simulated vehicle intrusion. Sled tests were performed to validate surrogate fixtures and commercial hardware being used to develop finite element (FE) models that can demonstrate the procedure. Additional tests were performed to determine how to adapt the Surrogate Wheelchair Base (SWCB) for use as a Surrogate Wheelchair for Side Impact (SWCSI), as well as to evaluate proposed performance criteria for wheelchairs and WTORS in side impact. Validated FE models were developed for the SWCB, SWCSI, a manual wheelchair (Ki Mobility Catalyst 5), and a power wheelchair (Quantum Rehab Edge 2.0). Additional FE models of a heavy-duty anchor meeting the Universal Docking Interface Geometry (UDIG), surrogate four-point strap tiedowns (SWTORS), a traditional docking station, and the surrogate wall fixture were also developed. Comparisons of sled tests and FE models show acceptable validation results. The proposed wheelchair side impact test procedure includes separate sections for testing wheelchairs, WTORS, and vehicle-based occupant protection systems. Detailed procedures and exemplary testing results are documented in this report.

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Introduction

Objectives

The goal of this project was to develop test procedures to improve safety in side impact crashes for people who travel while seated in their wheelchairs. Elements needed to achieve this are:

- Wheelchairs that retain structural integrity during lateral impact and keep the occupant positioned appropriately relative to vehicle side structures, seatbelt systems and/or airbags.
- Tiedowns that secure wheelchairs under lateral loading and limit lateral excursion.
- Occupant protection systems for nearside and farside impact

The test procedures, tools, and models developed in this project address the different needs of wheelchair manufacturers, wheelchair tiedowns and occupant restraint systems (WTORS) manufacturers, and vehicle manufacturers while also considering how to maximize both independence and safety of wheelchair users. The project has also developed finite element (FE) models of tools, fixtures, and commercial products as part of the process to develop test procedures.

Voluntary Testing Standards

There are currently no federal standards requiring wheelchairs to be crashworthy for use as vehicle seating. Instead, the Rehabilitation Engineering and Assistive Technology Society of North America (RESNA) has a suite of standards contained in four volumes that establish ways to measure, define, and test wheelchairs, WTORS, and wheelchair components, including Volume 4 Wheelchairs and Transportation. Volume 4 currently has four sections: Section 10 *Wheelchair Containment and Occupant Retention Systems for use in LATV, Systems for Rear-Facing Passengers (WC10),* Section 18 *Wheelchair Tiedowns and Occupant Restraint Systems (WC18)*, Section 19 *Wheelchair used as Seats in Motor Vehicles (WC19)*, and Section 20 *Wheelchair Seating (WC20).* A set of similarly-intentioned voluntary standards exist for global use within the International Organization for Standardization (ISO) that are developed and maintained by international experts in a working group under Technical Committee 173, Subcommittee 1, Working Group 6. These ISO standards overlap significantly with the RESNA standards, with standards 10865-1, 10542-1, 7176-19, and 16840-4, being international versions of WC10, WC18, WC19, and WC20, respectively. The set of ISO standards also includes 10865-2, which specifically address wheelchair spaces in LATVs (large accessible transit vehicles) for forward-facing passengers and places a high emphasis on independent use.

Many of these standards and test procedures were developed at UMTRI (Karg et al. 2009; Manary et al. 2003; Manary, Ritchie, and Schneider 2005; Ritchie et al. 2006; Schneider et al. 2008). The RESNA procedures incorporate a surrogate wheelchair (shown in Figure 1, left) to dynamically test commercial WTORS, a surrogate wheelchair base (shown in Figure 1, right) to test wheelchair seating systems, and a surrogate WTORS system (shown in Figure 2) to dynamically test commercial wheelchairs. The surrogate wheelchair base can be adjusted to different widths to allow testing of smaller and larger wheelchair seating systems.

Figure 1. Surrogate wheelchair and surrogate wheelchair base.

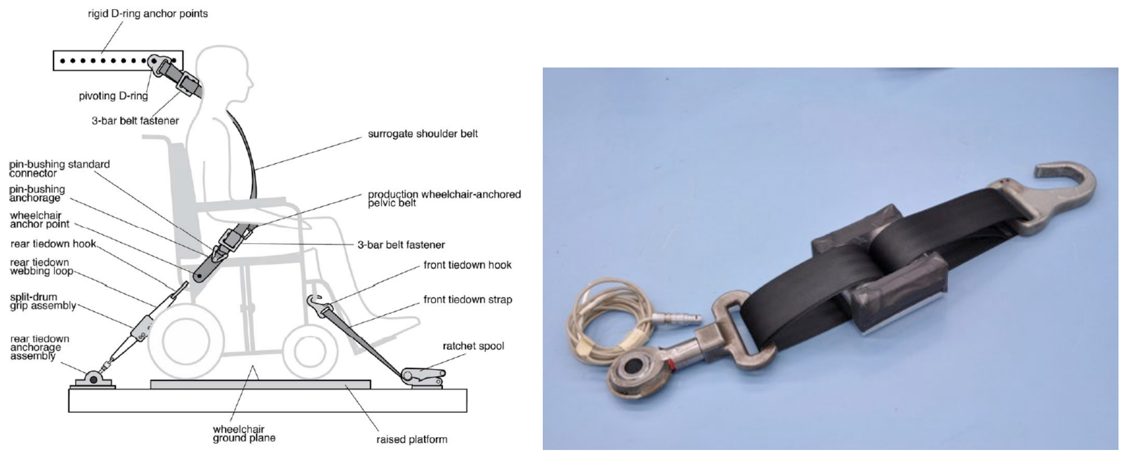


Figure 2. Surrogate WTORS

These standards currently include test protocols for frontal and rear impacts. The primary intent of these procedures is to ensure that wheelchairs and tiedowns have sufficient strength to remain intact in a crash, that wheelchairs work as stable, supporting seating surfaces, and that wheelchairs do not prevent acceptable seatbelt routing and fit. The wheelchair must not completely fail or fracture, and components over a 150 g cannot break free. While ATDs are used in these test procedures, standard injury assessment reference values such as HIC or chest accelerations are only monitored and are not part of the standard's pass/fail criteria. Instead, the primary focuses of sled testing are product structural integrity, ability to limit forward excursion of both the ATD and wheelchair, and a provision that the ATD must remain in an upright supported seated position after the impact.

NHTSA AWTORS Project

This recently-completed NHTSA-funded project conducted at UMTRI developed an automated WTORS (AWTORS) that could be safely and independently used to secure a wheelchair in a vehicle equipped with automated driving systems (ADSV) by someone unable to transfer to conventional vehicle seating (Klinich et al. 2021). The project used past research, computational modeling, prototype construction, volunteer evaluation, and dynamic testing to demonstrate feasibility.

Computational modeling was used to optimize placement of the wheelchair station, locate the wheelchair anchorages relative to the occupant, optimize belt anchor locations, and determine airbag characteristics for front and side impacts. Frontal simulations showed improved injury measures with a SCaRAB airbag, particularly with suboptimal belt geometry. Side impact simulations showed adequate protection in nearside crashes with standard curtain airbags and outboard shoulder belt location. However, changes to belt geometry were insufficient to keep the occupant within the wheelchair during farside impacts, leading to design of a Center Airbag To Contain Humans (CATCH). Computer models of power and manual wheelchairs were developed and used to choose restraint and geometry parameters for sled testing.

The concept for securing the wheelchair to the vehicle used hardware meeting specifications of a Universal Docking Interface Geometry (UDIG) that have been included in RESNA and ISO standards. Any wheelchair with UDIG-compatible features on the rear of the wheelchair should be able to independently dock in a vehicle with UDIG-compatible vehicle anchorages. Vehicle anchorages meeting the specifications were constructed, as were attachment designs for a commercial manual and power wheelchair. The occupant restraint portion of the AWTORS includes an automatic seatbelt donning mechanism based on a past UMTRI prototype, but with geometric improvements.

Volunteer testing was performed with eight wheelchair users. Using the two study wheelchairs equipped with UDIG anchors, the study evaluated the usability of four in-vehicle wheelchair seating stations with different geometries, each with two different belt conditions. Data included videos of ingress and egress, scans of volunteer posture, and questionnaires to document the time spent docking the wheelchair and donning the seatbelt, belt fit, comfort, and potential usability issues. Average time for entry, docking, and donning was less than 2 minutes in all conditions. For three-quarters of trials, participants would recommend use of the docking and donning systems. The preparation of test fixtures for volunteer testing identified challenges in implementing optimal geometry defined through simulations.

Ten frontal sled tests were performed to demonstrate differences in occupant protection levels with belt geometry and airbag presence, as well as to check the durability of UDIG anchors and attachments. Eight farside impacts were run to evaluate different versions of the CATCH airbag, as well as to check durability of UDIG attachments in side impact.

In the NHTSA AWTORS study, validated MADYMO models were used to identify the optimal location of the vehicle UDIG securement hardware relative to other interior vehicle components for both frontal and side impact conditions. Exemplar UMTRI MADYMO wheelchair model validations are shown in Figure 3. Simulations analyzed how to balance the occupant position relative to belt anchorage locations and airbags, considering that the wheelchair size and position will be more variable than that experienced with a vehicle seat. Simulations also considered placement of components relative to recommendations for space to accommodate wheelchairs and the amount of room needed to navigate into the wheelchair seating station. Restraint design optimization in frontal crashes was conducted using an integrated MADYMO model by combining the surrogate wheelchair base (SWCB) model, the Hybrid III midsize male ATD model, the model representing the UDIG design, a three-point seat belt system model, and airbag models. Optimizations were conducted for both right-front and second-row-left locations. The results provide improved understanding on how seatbelts may interact with wheelchair-seated occupants in a wide range of UDIG and belt anchorage locations considering the size of the wheelchair, with and without airbags.

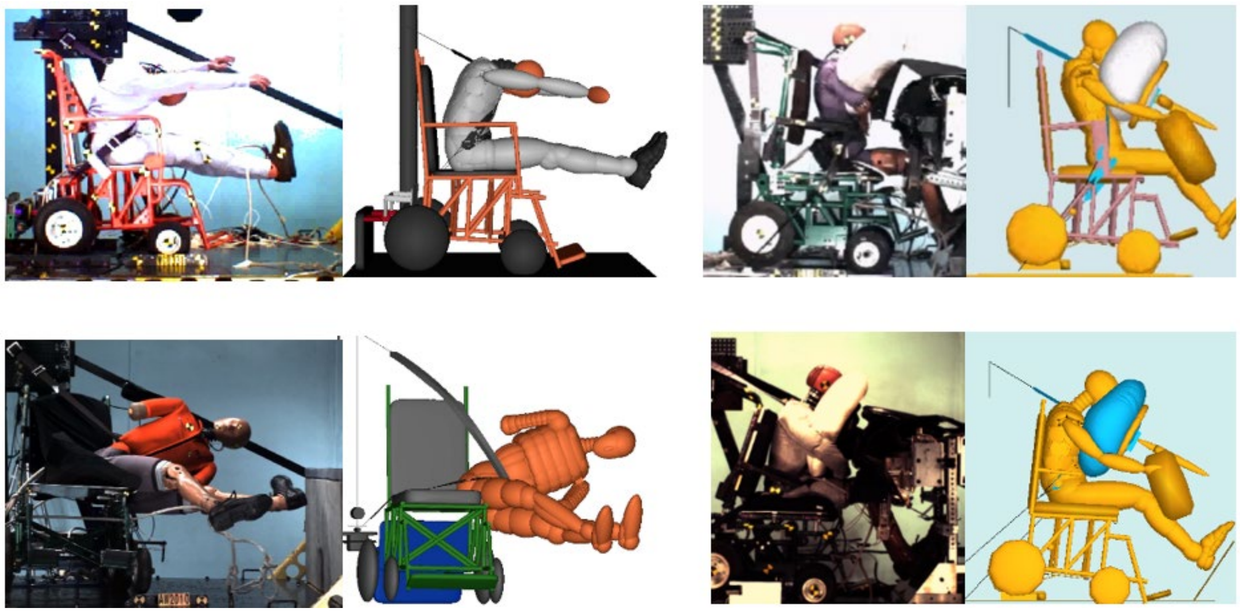


Figure 3. Exemplar UMTRI MADYMO wheelchair model validations against sled tests

In the design optimization for side impacts, a set of MADYMO models similar to those used in frontal crashes was used for side impact simulations, except that the ES-2re ATD replaced the HIII ATD, and a representation of a side door based on a Dodge Caravan geometry (modified for wheelchair use) was included. Simulations examined wheelchair station location and belt geometry with and without airbags in near and farside impacts. Alternative belt configurations with an inboard rather than an outboard D-ring were examined. Optimization results were harmonized with frontal optimizations. Because adequate restraint in farside crashes was not feasible with only belt restraint, modeling was used to design the innovative CATCH. The next modeling task developed MADYMO models representing the manual and power wheelchairs being used in volunteer and dynamic testing. Simulations evaluated the differences in frontal response using the SWCB and the two wheelchair models, using geometry for the wheelchair seating station and seatbelts that was feasible to achieve in the test vehicles. These simulations were used to identify test conditions for dynamic testing.

Procedure Development

General Considerations

The goal of this project was to develop test procedures for improving safety in side impact for wheelchair users, address the varying needs of different stakeholders, and harmonize with current wheelchair transportation safety testing and practices. Several factors that influenced the proposed procedure are described below.

Voluntary wheelchair standards covering the use of wheelchairs as motor vehicle seats have been available since 1999, and hundreds of wheelchair models can be ordered with "the transit option," indicating that they meet the RESNA WC19 standard. However, among the approximately 45 volunteers who use wheelchairs that UMTRI has recruited for several studies in the last two years, none were using a WC19 wheelchair.

Several factors contribute to the limited use of WC19 wheelchairs. Wheelchair manufacturers do not usually promote this option in their marketing materials, most insurance companies do not cover the extra cost for these features, and most users and prescribers are unaware that it is an available and recommended option if a wheelchair would be used as seating during travel. Since a wheelchair's primary function is a medical mobility device to assist in the activities of daily living, we would not expect that a wheelchair would provide any occupant protection in side impact, other than remaining structurally intact and staying secured to the floor, just as most vehicle seats keep the occupant seated and in position to benefit from the vehicle-integrated occupant protection systems during side impact events.

Wheelchairs are medical devices regulated by the US FDA. While the FDA recognizes the voluntary RESNA wheelchair transportation standards, only wheelchairs that claim to be suitable for use as a motor vehicle seat must show proof of compliance. A side impact test procedure that was incorporated into the voluntary standards, in an approach similar to what is used for frontal testing, would likely result in compliance from wheelchair manufacturers; adapting hardware and methods already used in existing standards for side impact testing would reduce barriers to compliance. If a side impact procedure is novel, expensive, and complicated, wheelchair manufacturers may choose to ignore it.

WTORS are solely used for transportation safety and manufacturers crash test most of their products using the WC18 protocols for frontal impacts, even though compliance with recommendations from RESNA, NMEDA, ISO, and SAE is voluntary. Because the ADA regulations were developed with public transit vehicles in mind, they do not require crash testing of WTORS. Given their past demonstrated interest in testing to voluntary standards, WTORS manufacturers would likely adapt to new side impact testing requirements if they were reasonable and cost effective. When developing the test procedures, the best conditions for ensuring crashworthy tiedowns may differ from the best conditions for evaluating crashworthy wheelchairs.

When developing this procedure, we also need to prioritize the needs of the wheelchair users, and make sure new testing procedures do not result in unintended negative consequences. In our past studies involving volunteers who are wheelchair users, many of them prioritize independence over safety. During the AWTORS project, we received feedback from manual wheelchair users that they place a high priority on minimizing the weight of their wheelchairs, to facilitate their ability to independently propel, stow, and handle their wheelchairs. This led us to redesign the original 9-lb UDIG attachments for the manual wheelchair to create a version that only added 2 pounds to the wheelchair mass. If a worst-case nearside impact test condition would require substantial addition of mass to a manual wheelchair for it to be robust enough to pass the proposed nearside impact test, it could lead to people avoiding choosing the transit option altogether to have a lighter-weight wheelchair, which would end up reducing safety rather than improving it.

Until recently, vehicle manufacturers have not tried to design integrated wheelchair stations for smaller passenger vehicles (< 25 feet) that provide occupants using wheelchairs with the same level of protection as occupants riding in conventional vehicle seating. Instead, most accessible vehicles of this size have been modified after sale for wheelchair use, and their manufacturers have received exemptions allowing them to modify the original safety equipment in the vehicle. This is often required because the process of lowering the floor and removing vehicle seats disrupts the sensors and wiring used to deploy airbags and advanced belt systems in a crash.

Because vehicle manufacturers are now working to develop ADSV that can be used in a shared-services scenario, they are legally required to provide accessible options and cannot be exempt from safety standards (unless additional exemptions are granted). As a result, vehicle manufacturers have expressed interest in both physical and virtual tools that they can use to design occupant protection systems for integrated wheelchair seating stations. They have specifically requested information on the surrogate tools used in RESNA standards. They have also expressed interest in data showing the range of sizes of available wheelchairs, and computational models of wheelchairs that could be used to design occupant restraint systems. The current process for developing side impact occupant protection systems begins with computational modeling, followed by sled testing with a body-in-white and prototype airbag designs. An example test setup is shown in Figure 4. Because loading under side impact conditions depends largely on the characteristics of the vehicle side structure, it is unlikely that vehicle manufacturers would use a generic side impact test fixture to develop side airbag systems. However, they would likely welcome guidance on how to locate wheelchair seating stations in their vehicles (for both physical and virtual testing) in a manner that is consistent with how the wheelchairs and WTORS are evaluated.

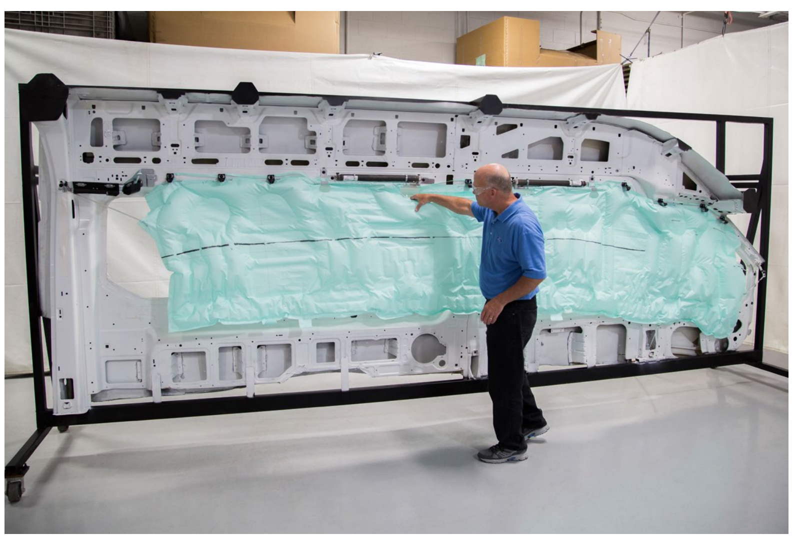


Figure 4. Testing of prototype curtain airbag using a body-in-white fixture.

While the procedure now included in FMVSS No. 213 for side impact testing of child restraints includes a representation of an intruding door that might be adapted for a wheelchair side impact test procedure, there are several reasons why we did not pursue this approach. These procedures (as well as international standards) took many years to develop because loading characteristics depend strongly on vehicle characteristics, which can vary widely and change over time. The pulse and loading wall characteristics for the FMVSS No. 213 test procedures are based on six small vehicles, while only large vehicles such as minivans and SUVs can be adapted for wheelchair use. Because harnessed child restraints generally place a child occupant below the zone where a curtain airbag deploys, the FMVSS No. 213 test procedure does not include a representation of an airbag or the upper part of the vehicle door. For an occupant seated in a wheelchair, using an intruding door feature without a curtain airbag does not represent a realistic condition, as all current vehicles include a curtain airbag to meet side impact and occupant retention requirements. If a vehicle manufacturer was developing a curtain airbag specifically to protect a nearside occupant seated in a wheelchair, we expect that they would use a computational model of their particular vehicle, rather than any generic representation we could achieve through this project. We are unaware of a “generic” curtain airbag that might be available for use in a standardized test procedure.

We also need to consider how a side impact testing procedure would harmonize with existing voluntary wheelchair testing standards and best practices. Wheelchair and WTORS manufacturers would be more likely to comply with voluntary standards if the procedures incorporate elements from the current frontal impact procedures, and similar types of performance requirements that focus on product integrity rather than traditional ATD IARVs. In addition, we need to consider how the procedure could lead to manual wheelchairs that offer improved performance in side impact without adding excess weight that makes them less usable for activities of daily living.

Side Impact Test Pulse

To aim for a similar level of protection for people seated in wheelchairs as those seated in vehicle seats, the test procedure should represent the conditions used in FMVSS No. 214 “Side impact protection” crash tests. To represent a severe intersection collision between two vehicles, FMVSS No. 214 specifies full-scale crash test procedures to evaluate injury risk when a 1,360 kg moving deformable barrier (MDB) strikes the left side of a vehicle. The specifications simulate a vehicle traveling at 48.3 km/h striking another vehicle traveling at 24 km/h. Signals collected from ATDs seated on the struck side of the vehicle in the front and rear seat are used to evaluate head, thorax, and pelvis injury risk. During this type of crash, the MDB impacts the left side of the vehicle, causing lateral intrusion into the occupant compartment. When the striking vehicle contacts the sill, it pushes the struck vehicle away. As the door intrudes towards the nearside occupant, the vehicle seat moves away. Interaction with the intruding door accelerates the occupant away from the door until they match the vehicle velocity.

Currently, there are no standardized methods for simulating FMVSS No. 214 type loading for adults in sled tests. However, NHTSA now has a sled test procedure to evaluate harnessed child restraints in a condition simulating the FMVSS No. 214 MDB test (NHTSA 2014). The procedure uses a test bench mounted on rails, oriented 80 degrees from the frontal direction. The main sled platform sled uses a 20-*g* deceleration pulse with a velocity of 26 to 29 km/h. As the child restraint moves along the rails, deformable honeycomb is used to control its response.

Properties of an interior door are simulated with a foam structure assembly. The goal of the test procedure is to demonstrate the ability of the CRS to restrain the child within the CRS, and prevent injurious head contact with either the CRS or simulated vehicle structure while avoiding excessive chest loading. Structural integrity of the CRS would also be evaluated.

The initial side impact testing of wheelchairs conducted in our prior AWTORS project (Klinich et al. 2021) used the pulse proposed for the FMVSS No. 213 side impact test, as well as an 80-degree orientation to simulate the frontal component present in most side impact crashes. However, review of the methods for developing the FMVSS No. 213 pulse indicated that they were based on the average pulse of six small vehicles under FMVSS No. 214 loading conditions. Vehicles that can be adapted for wheelchair use are necessarily larger to allow space to maneuver and secure the wheelchair, and generally consist of minivans, vans, and some SUVs.

To investigate an appropriate sled pulse for evaluating wheelchairs in side impact, we reviewed available side impact test data from the NHTSA website collected on vehicles that are frequently adapted for wheelchair use. Because FMVSS No. 214 data were not available, we instead used data from 18 US Side NCAP tests to develop a corridor, and then scale it down from the 38.5 mi/hr SNCAP impact velocity to the 33.5 mi/h FMVSS No. 214 impact velocity. Vehicles included the Dodge Caravan, Toyota Sienna, Chevy Traverse, Chrysler Pacifica, Honda Odyssey, Ford Transit, and Chrysler Town and Country, with model years ranging from 2008 to 2021. Figure 5 shows the range of resultant vehicle CG XY velocities for the vehicles of interest. Data were zeroed using the time of pelvic contact with the intruding door using the methods described by (Miller et al. 2013).

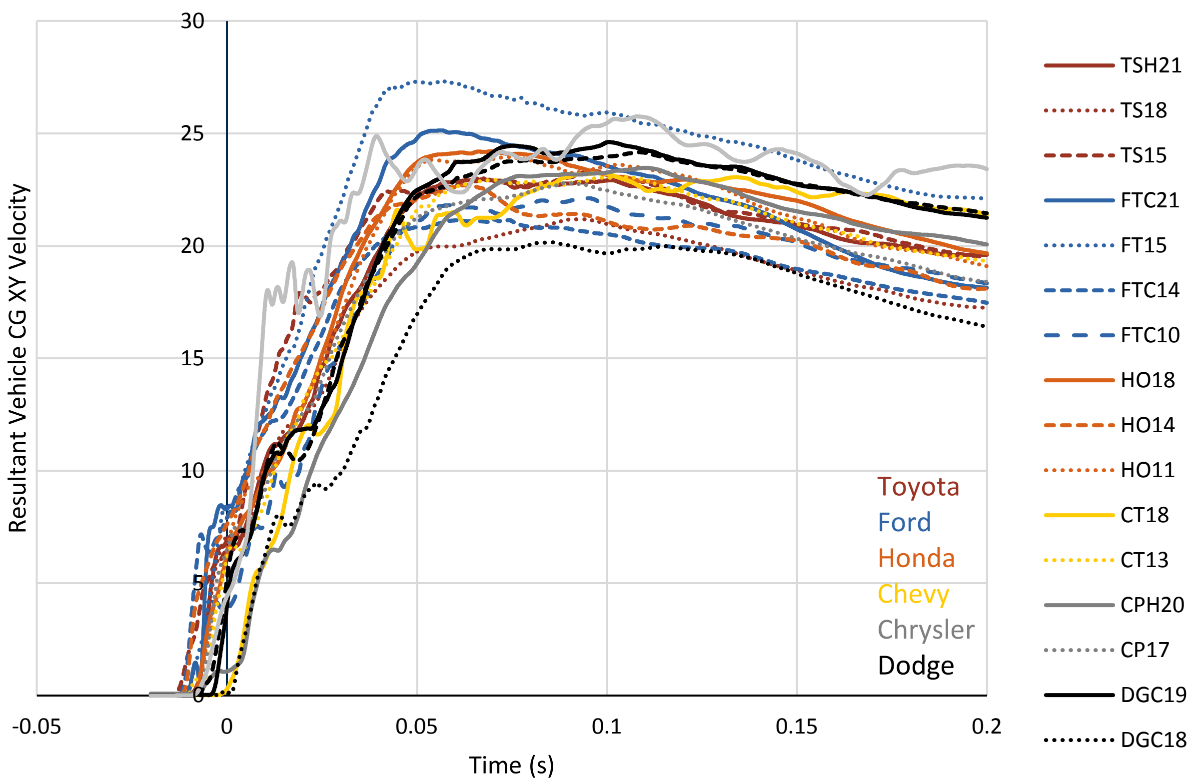


Figure 5. Comparison of US Side NCAP vehicle CG velocities for relevant vehicles.

These acceleration profiles were averaged together and integrated to develop a velocity corridor plus or minus two standard deviations about the mean. As shown in Figure 6, when comparing the US Side NCAP based corridor (thin navy lines) to the 213-based velocity used in the AWTORS study (maroon centerline), the velocity based on the smaller vehicles was much higher than those commonly used as adapted vehicles. A corridor (thicker blue lines) estimating the range of vehicle CG velocities seen in FMVSS No. 214 tests was created by multiplying the US Side NCAP-based corridor by 0.87, the ratio of impact velocity between FMVSS No. 214 and US Side NCAP tests. A proposed corridor represented by orange line segments bounds the estimated FMVSS No. 214 corridor. The yellow dashed curve is a sample integrated velocity meeting the proposed corridors that was used for the tests in this study. Figure 7 shows that this pulse, together with an 80-degree orientation of the wheelchair on the sled, provides a good representation of the vehicle X and Y CG velocities estimated for FMVSS No. 214 tests.

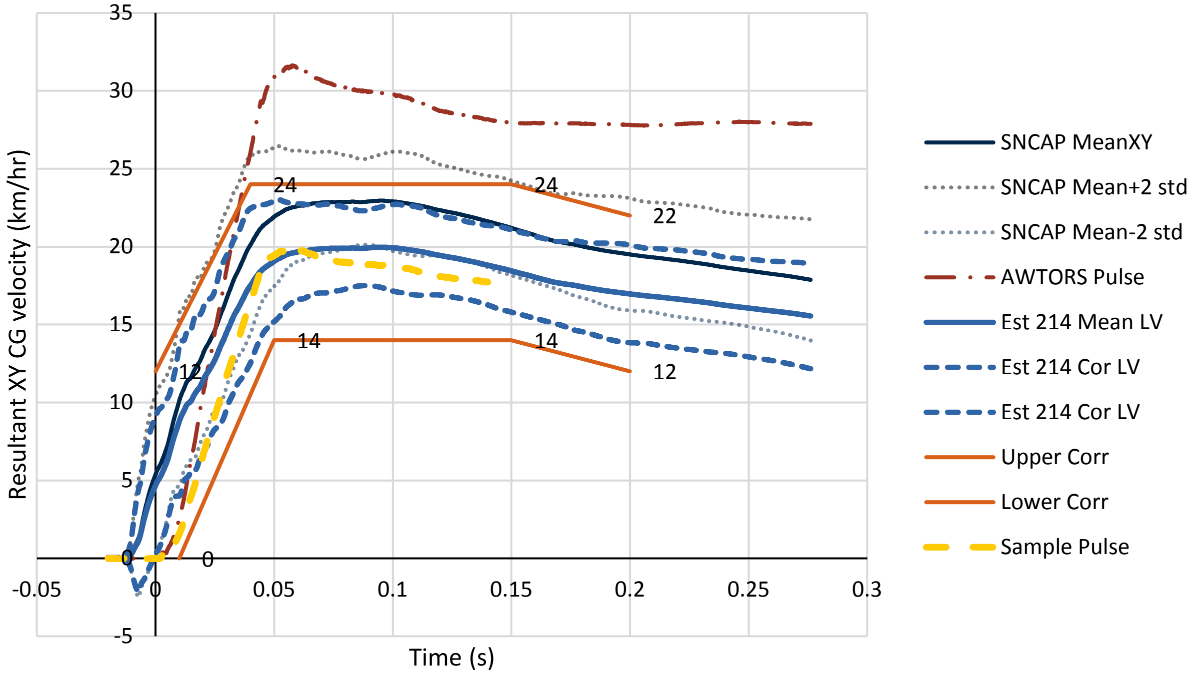


Figure 6. Sample AWTORS and WCSI resultant velocities compared to corridors based on SNCAP, estimated for 214, and proposed for WCSI.

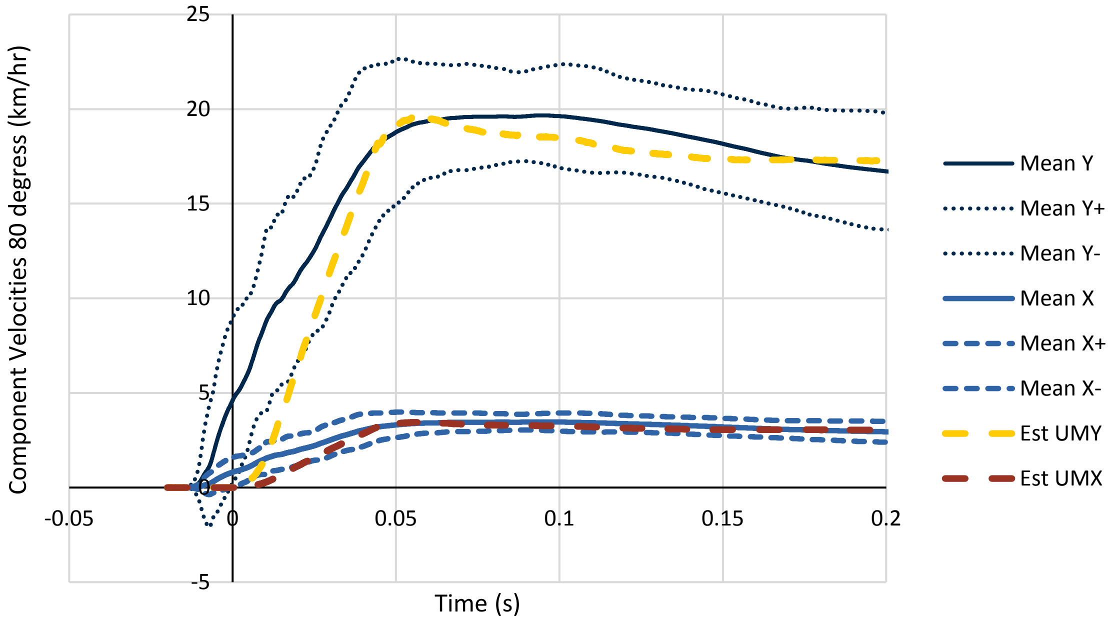


Figure 7. Sample WCSI pulses split into x and y components with 80-degree orientation compared to estimated FMVSS No. 214 corridors for x and y velocities.

Interior Vehicle Geometry

The initial review of US NCAP side impact pulses from a range of vehicles often modified to be accessible for use by a person seated in a wheelchair shows general similarity. We also compared scans of the vehicle interior geometries from multiple modified vehicles to determine their similarity and how well a range of geometries could be represented using a single generic wall. We used a Sense handheld optical scanner to collect the interior contours of four vehicles modified for wheelchair use: Chevy Traverse, Honda Odyssey, Chrysler Pacifica, and Ford Explorer. Figure 8 shows an overlay of the four vehicle interior scans compared to the Dodge Caravan, aligned at the rear track location, while Table 1 compares key relevant dimensions extracted from each scan. The vertical vehicle dimensions have the least variation, while the D-ring vertical locations vary more.

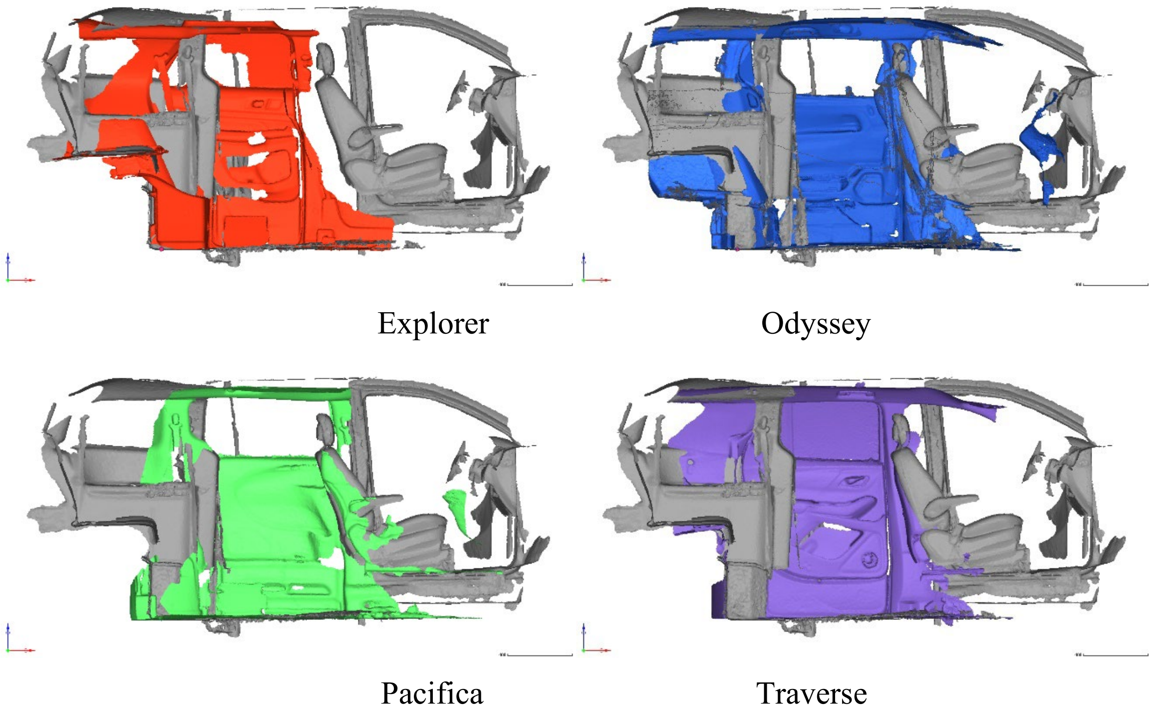


Figure 8. Overlay of vehicle interior scans compared to Caravan.

Table 1. Comparison of key dimensions of accessible vehicles

Type	Measurement (cm)	Direction	Explorer	Odyssey	Pacifica	Traverse	Average	Stdev
Belt	Distance from 2nd row D-ring to vehicle centerline	Y	71	55	57	77	65	9.4
Belt	Distance from 2nd row outboard belt anchor to vehicle centerline	Y	73	75	65	60	68	6.0
Belt	Floor to Dring anchor	Z	164	NA	118	129	137	19.7
Belt	Floor to outboard belt anchor	Z	30	NA	22	20	24	4.5
Side interior	Distance between B-pillar and C-pillar at bottom of window	X	92	80	79	99	87	8.4
Side interior	Door width at center, 2nd row	X	81	81	78	96	84	7.1
Side interior	Floor to top of window, 2nd row center	Z	139	135	139	140	138	2.2
Spacing	Distance between driver seat and 3rd row, at vehicle centerline	X	96	130	127	141	124	17.0
Spacing	Floor to roof at vehicle centerline	Z	143	143	149	151	147	3.6

Given the similarities between the pulses and interior dimensions of these modified vehicles, it seems reasonable to use the intruded door profile from the FE simulation of the Caravan FMVSS No. 214 test to represent the intrusion across these vehicles.

Wheelchair Selection

Two wheelchairs from the prior AWTORS study (Ki Mobility Catalyst 5 and Quantum Rehab Q6 Edge 2.0 with Synergy Seating shown in Figure 9) were selected to demonstrate and develop the test procedure, to take advantage of existing data and the availability of previously tested wheelchairs for measurement and component testing. During the AWTORS study, we selected these two products from a review of available wheelchair models that met the main requirement of the current WC19 standard for frontal impact.

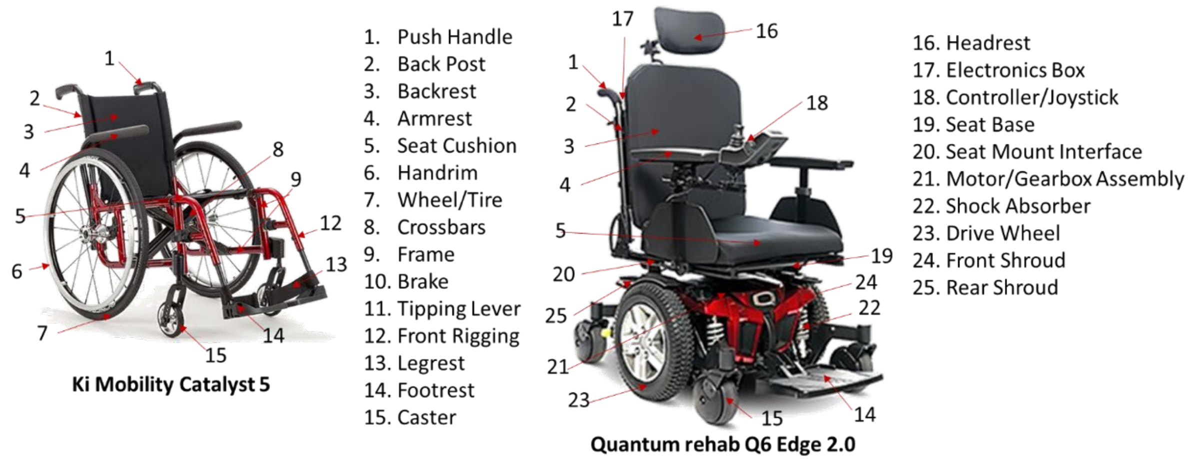


Figure 9. Components of a manual and a power wheelchair selected in this study

Placement of Wheelchair Station

The simulations conducted in the AWTORS study provided insight on locating the wheelchair with respect to a simplified interior vehicle geometry, both fore-aft and laterally. We chose to represent a second-row seating position for the proposed test procedure, as this is the most likely location to place an automated docking station in an ADSV because of space and accessibility requirements. While this may not be the worst-case loading condition for an occupant in a wheelchair, it would achieve parity with other occupants; all occupants travel in vehicles designed to meet the FMVSS No. 214 test conditions, regardless of their seating position and the range of side impact types/impact points in the field.

The nearside simulations in the AWTORS study showed that placing the wheelchair further away from the struck-side wall improved safety. It is common practice in paratransit vans to locate the wheelchair station along the vehicle centerline, to improve the ease of maneuvering the wheelchair to the station while allowing sufficient space for the driver to secure the occupant with the 4-point strap tiedown system. However, this tends to lead to poor shoulder belt fit if the D-ring is located on the C-pillar. To determine a baseline location for a wheelchair station, we considered realistic locations that would meet accessibility guidelines. Through another UMTRI project to develop Design Guidelines for Accessible Automotive Vehicles, we have learned from our colleagues at BraunAbility that if the 30”x 48” wheelchair station is positioned within a 60” diameter circle of clear space, most people can maneuver easily into the station using a range of wheelchair sizes (Klinich, Orton, and Manary 2022).

Based on this recommendation, initial simulations using the preliminary MADYMO model of a Dodge Caravan placed the wheelchair station in the position shown in Figure 10. This involved placing the driver's seat in midtrack position, and then placing the 60" circle as far forward as possible and adjacent to the interior door. We then placed the 30"x 48" station as far to the left side of the circle as possible. The D-ring was placed on the C-pillar, representing a common current practice.

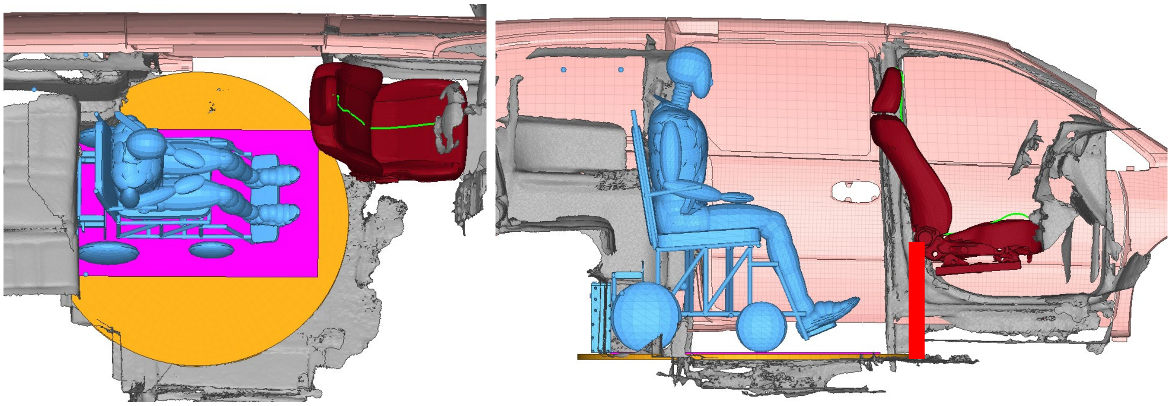


Figure 10. Baseline condition of wheelchair seating station relative to interior components.

Seatbelt conditions

In current WC19 test procedures, each wheelchair is tested with an integrated crashworthy lap belt (connected to a shoulder belt with a vehicle mounted D-ring). Testing with a completely vehicle-anchored seat belt is a "due care" option for testing to WC19. Given that the test with the crashworthy lap belt is a more severe test of the wheelchair structure, we propose that the WCSI procedure be performed only with a wheelchair-mounted lap belt, attached to the vehicle mounted shoulder belt. This will ensure that the crashworthy lap belt designed for frontal impact also works in side impact. In addition, it will prevent potential unrealistic interference problems that could result from locating hardware to mount lap belt anchors.

In the frontal WC19 procedure, the intent is to evaluate the wheelchair performance while holding other parameters, such as the WTORS characteristics, constant. Rather than having a fixed vehicle belt anchorage geometry that may be suboptimal for a particular wheelchair geometry, the WC19 test procedure allows adjustment of the D-ring anchor so it is located in a good position to protect a particular size occupant in a particular wheelchair. For frontal tests, once the ATD is placed in the wheelchair, the D-ring anchor point is adjusted to be 300 mm ± 15 mm (11.8 in. ± 0.6 in.) behind and 173 mm ± 15 mm (6.9 in. ± 0.6 in.) above the top of the ATD's shoulder. The lateral location is adjusted to optimize shoulder belt fit so that it passes over the center of the ATD's shoulder.

FE Modeling Vehicle to Simulate Intrusion

We used a publicly available FE model of a 2007 Dodge Caravan to perform simulations of an FMVSS No. 214 side impact test as well as an US NCAP side impact test to obtain an approximation of the intruded left side profile, shown in Figure 11. This simulation also provided an estimate of the vehicle CG deceleration, door acceleration, and prescribed door intrusion. The peak intrusion measured at the B-pillar at the windowsill was about 300 mm for the FMVSS No. 214 simulation, and about 400 mm for the US NCAP side impact simulation.

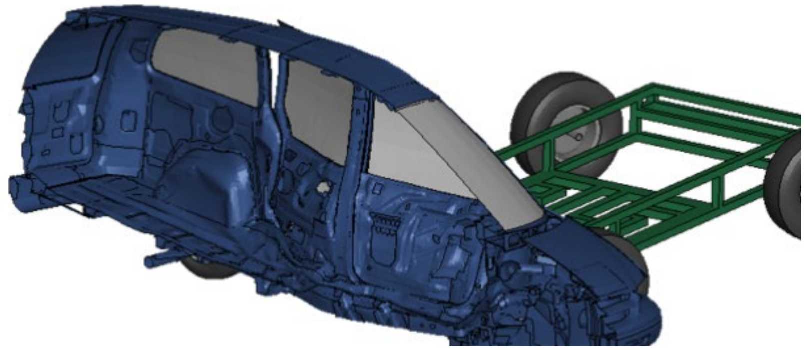


Figure 11. Deformed Caravan vehicle interior after being loaded by FMVSS 214 deformable moving barrier.

To demonstrate that our proposed test procedure produces realistic loading, our original plan was to compare the kinematics and ATD measures from a test run using an FE simulation of the test fixture to a simulation of the FMVSS No. 214 test with an occupant seated in a wheelchair. However, the baseline Caravan is not tall enough to fit a wheelchair seated occupant. As shown in Figure 12, we began to create a modified version of the baseline Caravan FE model by shifting the body location upwards relative to the wheels and dropping the floor, matching measurements on the modified Caravan we have available in our lab.

After reviewing the geometry of the modified Caravan, we decided to pause this effort for several reasons. Dropping the floor shifts the lateral crossbeams under the floor so they are no longer in an optimal location relative to the FMVSS No. 214 barrier for maintaining passenger compartment integrity and minimizing intrusion. We hypothesize that this would lead to greater intrusions compared to the baseline Caravan. However, there are no publicly available vehicle crash tests documenting the performance of modified vehicles under side impact loading conditions to validate this model and test our hypothesis. Since vehicles modified for wheelchair use are exempt from many federal safety regulations, it is quite possible that the modified version of the Caravan would not meet FMVSS No. 214 requirements. In the future, we anticipate that vehicles with integrated wheelchair stations would be able to meet FMVSS No. 214 requirements and maintain compartment integrity under side impact loading. For the purposes of this project, it would not be useful to compare our proposed sled test procedure to the conditions seen in a vehicle that may not meet FMVSS No. 214 requirements.

Figure 12. FE model of modified Caravan compared to modified Caravan.

As an alternative, we decided to evaluate loading under three conditions that provide the modified vehicle with sufficient height to allow an occupant seated in a wheelchair. We compared the response of the proposed test procedure with a fixed staggered wall to three different vehicle conditions relative to the FMVSS No. 214 MDB as shown in Figure 13. For the first condition, the floor of the baseline Caravan model is shifted 140 mm down and the roof is raised 135 mm higher, which matches the configuration of the modified vehicle we have used for testing at UMTRI. The second condition lowers the floor by 275 mm, while the third condition raises the roof by 275 mm. We hypothesize that the actual performance of a vehicle modified for wheelchair use would fit within the range of these conditions, although no crash test data are available to confirm.

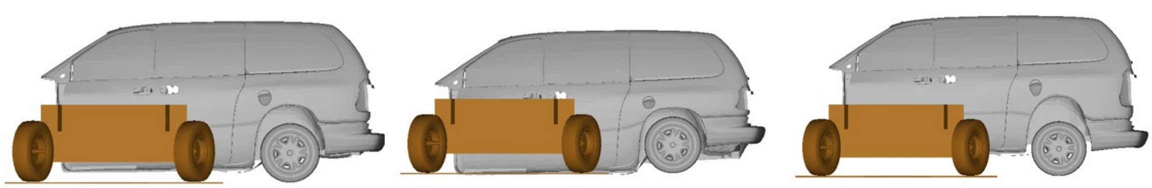


Figure 13. FE model vehicle modifications relative to FMVSS 214 MDB.

MADYMO Modeling of Potential Test Conditions

The initial effort to develop a side impact test procedure for wheelchairs began with MADYMO simulations of nearside impact using the models developed in the AWTORS study. Figure 14 illustrates the parameters that were initially proposed to be examined through preliminary modeling. However, many of the factors that would affect the test conditions have already been selected for the reasons described previously. These include the location of the wheelchair station relative to the undeformed interior, location of the D-ring, magnitude of the sled pulse, and orientation of the station at 80 degrees. Thus, the main goals of the preliminary simulations were to identify how to create an interior door representation that produces loading and kinematics similar to an intruding door, and to estimate how results may vary with the type of wheelchair securement system.

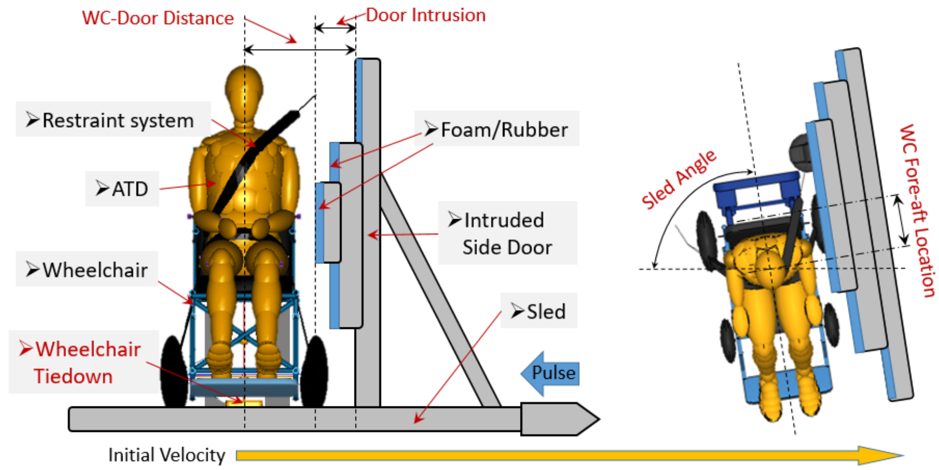


Figure 14. Side impact test concept illustration (testing parameters to be determined are highlighted in red)

The baseline MADYMO simulations developed in AWTORS were used as the starting point. The MADYMO model of the SWCB was placed as described previously in the "Placement of the Wheelchair Station" and illustrated in the left side of Figure 15. The optimal vehicle belt geometry determined in the AWTORS project was used for preliminary simulations, and the wheelchair station was rotated 80 degrees from the forward direction. Generic contact characteristics (~100 N/mm) were used between the door interior and occupant/wheelchair in all simulations.

The first simulation (center of Figure 15) moved a representation of the residual door deformation into the wheelchair using the acceleration profile from the FE simulation. The dummy's torso and head contacted the interior structure, while the lower extremities swung away from the intruding wall. The second simulation (right of Figure 15) just simulated the vehicle motion without an intruding wall. The kinematics of the lower extremities were different than the case with the simulated deformed wall. The results from the first simulation were reviewed to identify the timings of when the wheelchair, hip, and shoulder contacted the simulated door interior.

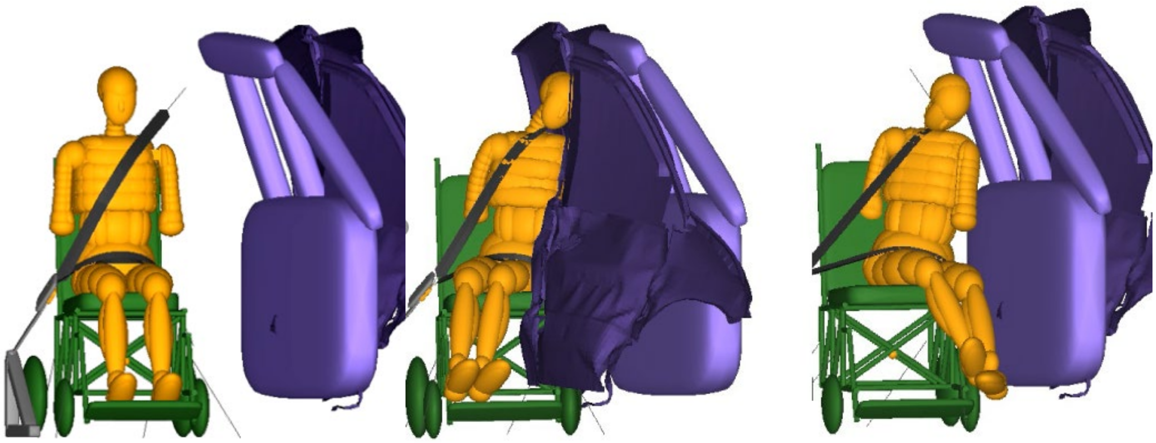
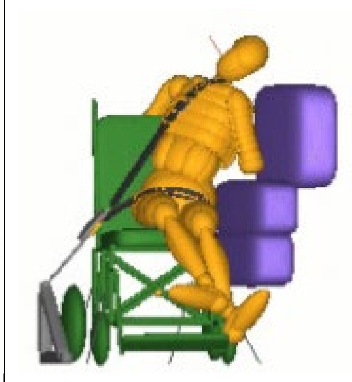
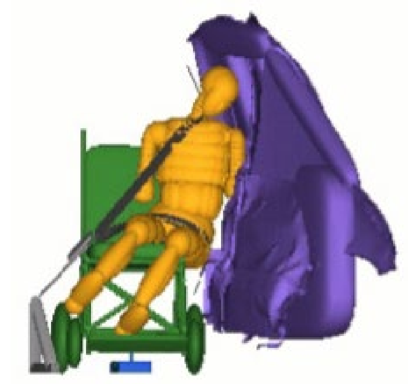
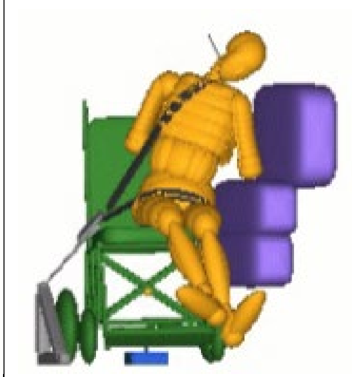
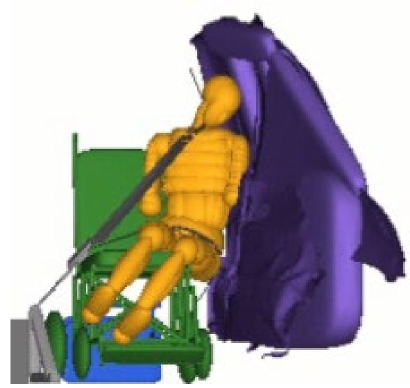
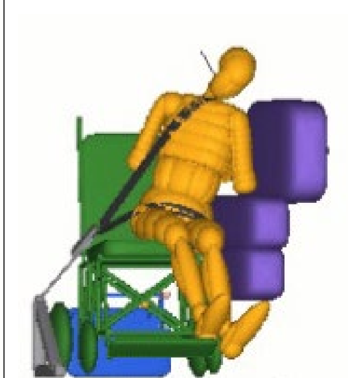
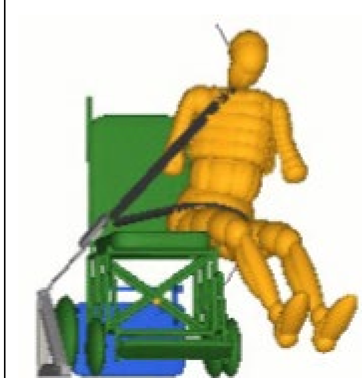


Figure 15. Initial position of wheelchair relative to vehicle interior (left), kinematics with intruded door shape (middle), and kinematics with undeformed door (right).

The next round of simulations used a staggered wall design that produced loading timings and resulting kinematics that were similar to the results with the simulated intruding wall, and evaluated variation with the type of securement as summarized in Table 2. Kinematics are shown intruding wall, staggered wall, and no wall using four-point strap tiedown, traditional docking, and UDIG securement. As shown in Figure 16, the occupant excursions, contact timings, and contact forces between the simulated intruding wall and the static staggered wall are similar to each other. Because the preliminary simulation results with the intruding wall and static staggered wall are similar, results demonstrate that a static staggered wall can reasonably mimic an intruding wall in the side impact condition. Additionally, these simulations suggest that securement of the wheelchair with the four-point strap tiedown results in the highest force on the wheelchair from the side wall as the straps allow for the most lateral excursion of the wheelchair relative to the vehicle.

Table 2. Variations in kinematics with different wheelchair securements and side impact walls.

	Intruding wall	Static wall	No wall
4-pt strap tiedown			
Traditional docking			
UDIG			

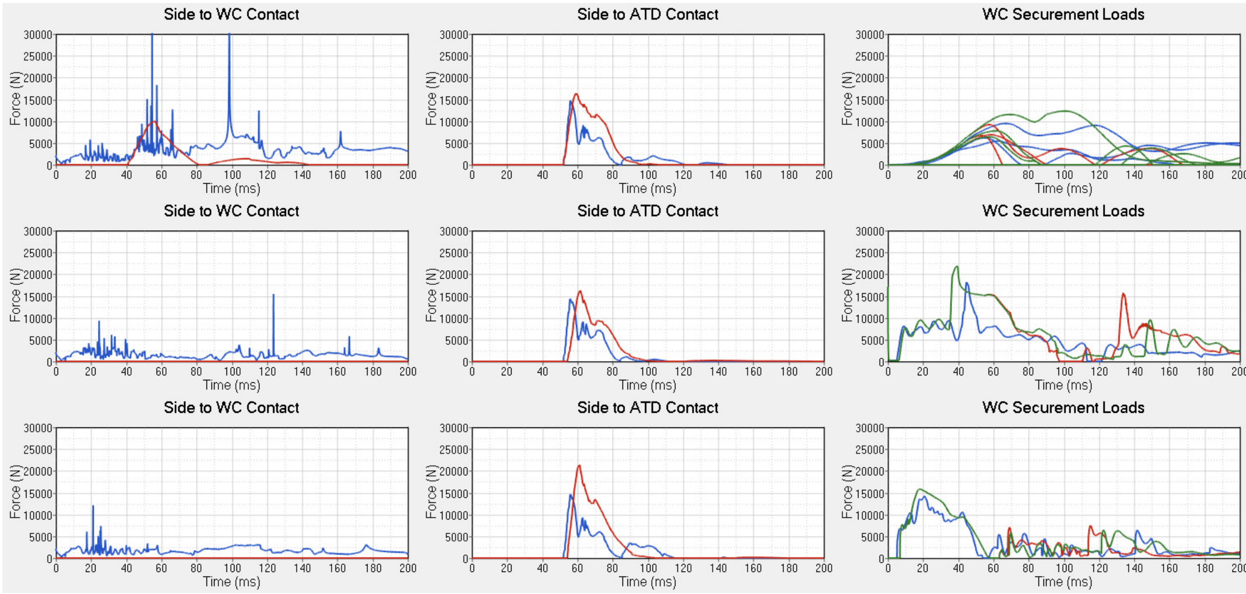


Figure 16. Comparison of wheelchair contact forces, ATD contact forces, and WC securement loads for intruding wall (blue), staggered wall (red), and no wall (green) for 4-point strap tiedown (top row), traditional docking (middle row) and UDIG (bottom row).

FE Modeling of Potential Test Conditions

After demonstrating the feasibility of simulating intrusion with a staggered wall with MADYMO models, we performed additional simulations using an FE model of the staggered wall as shown in Figure 17. The model includes foam representing the vehicle interior, as well as a plywood base and steel supports. Results using this model were compared to three different simulations used to approximate FMVSS response for modified vehicles: floor lowered and roof lifted (left), floor lowered only (center), and roof lifted only (right).

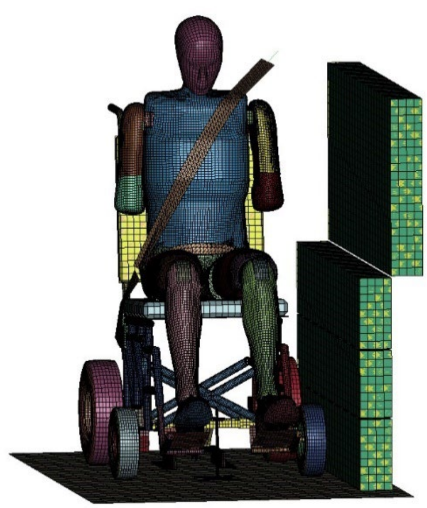


Figure 17. FE model of validation setup, with SWCB secured by traditional docking.

Comparisons of simulations of these three conditions to the proposed test procedure are shown in Figure 18 through Figure 20 at time 0, 90 ms, and 120 ms. At 90 ms, all of the SWCB models have rotated toward the door with the inboard wheels above the floor, the ATD torso contacts the interior, and the lower door has contacted the lower extremities; ATD kinematics appear fairly similar. At 120 ms, the lower extremities in the proposed procedure have not been pushed out of the way by intrusion like the other simulations, and the head has rotated much further than in the vehicle simulations. In the three vehicle simulations, the floor has deformed upward towards the center of the vehicle.

Figure 21 compares the forces between the wall and ATD and wall and wheelchair for the four conditions. The ATD loading from the proposed procedure is similar in magnitude to two of the conditions; the roof only has the lowest loading to the ATD. The three vehicle conditions have ATD loading earlier than the proposed procedure; this is likely caused by different loading to the lower extremities from the lower part of the wall. However, the loading to the wheelchair is substantially lower in the proposed test procedure than the three vehicle simulations. We hypothesize that the floor deformation is contributing to more severe wheelchair loading.

Because the proposed test procedure will use SWTORS rather than traditional docking, additional simulations were performed to compare this securement strategy. Contact force results in Figure 22 show better agreement between the proposed test and simulated vehicle deformation when SWTORS are used to secure the wheelchair rather than docking.

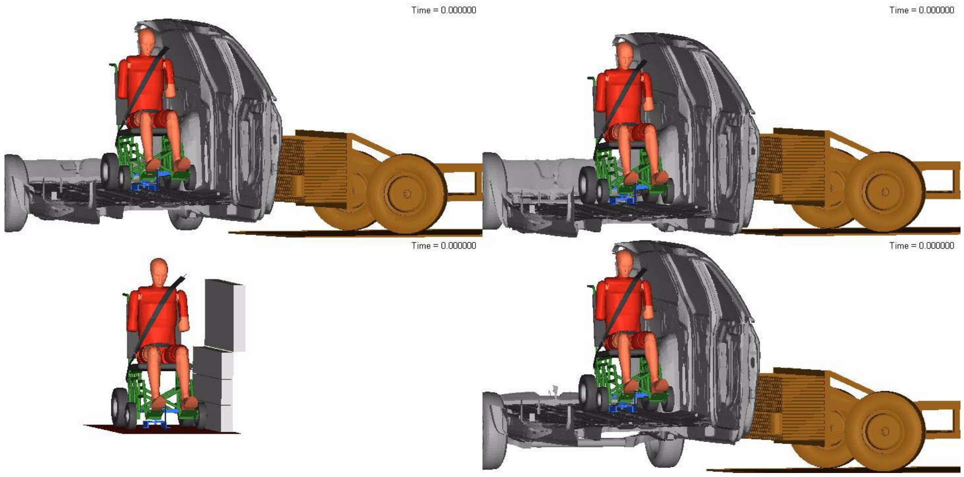


Figure 18. Simulation comparison time 0: floor+roof (upper left), floor only (upper right), proposed procedure (lower left), and roof only (lower right).

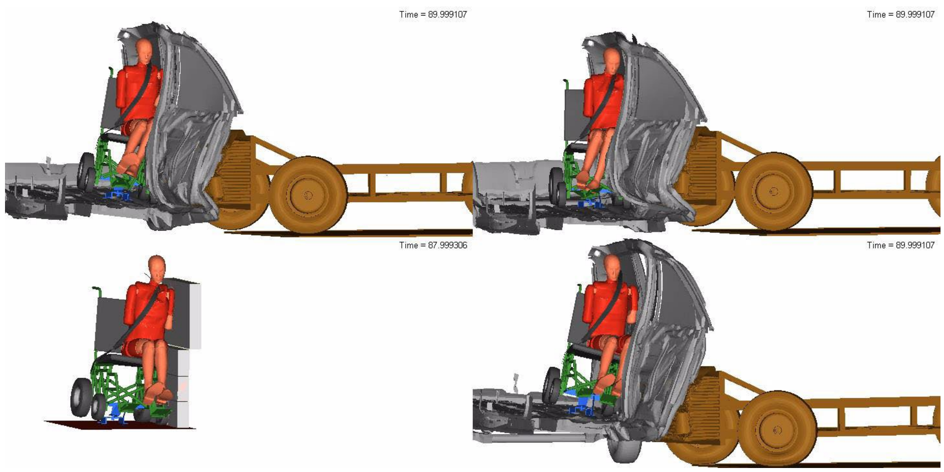


Figure 19. Simulation comparison time 90 ms: floor+roof (upper left), floor only (upper right), proposed procedure (lower left), and roof only (lower right).

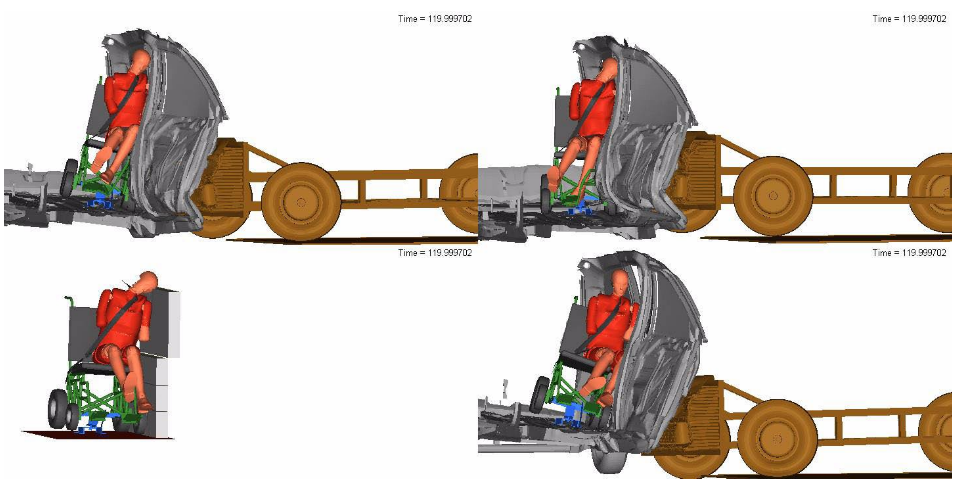


Figure 20. Simulation comparison time 120 ms: floor+roof (upper left), floor only (upper right), proposed procedure (lower left), and roof only (lower right).

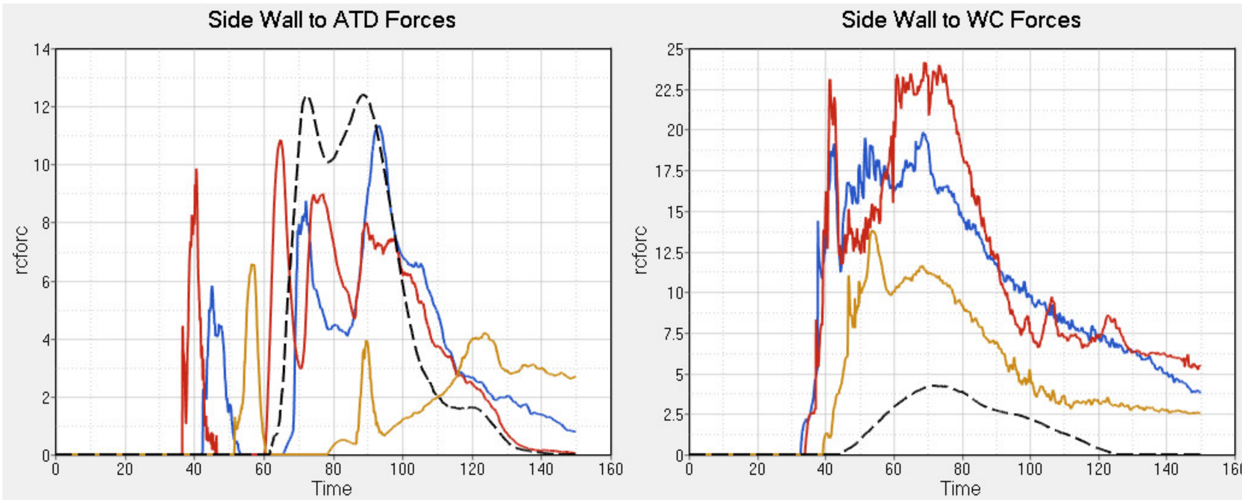


Figure 21. Comparison of sidewall forces on ATD and wheelchair for four conditions: floor+roof (blue), floor only (red), roof only (yellow), and proposed test (dashed black)

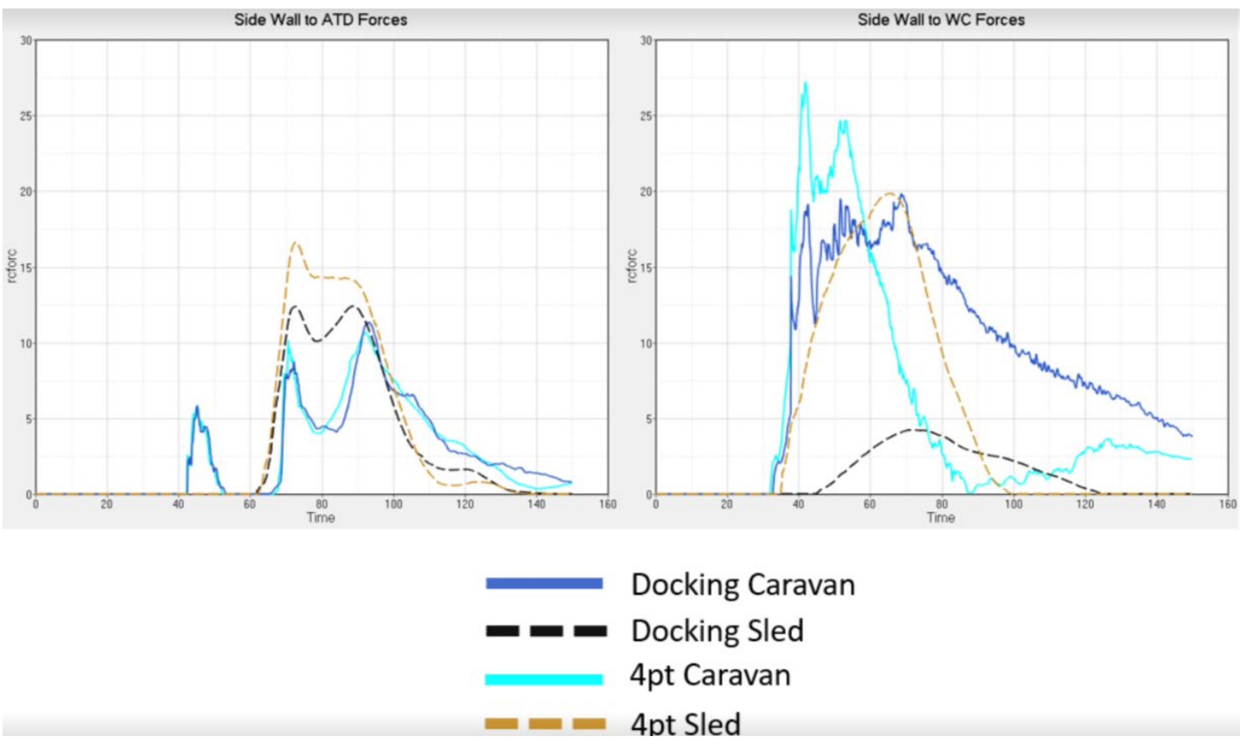


Figure 22. Comparison of sidewall forces on ATD and wheelchair when secured by docking vs. SWTORS for proposed test (dashed) and floor+roof condition.

Preliminary Validation Tests

To allow creation of FE models to demonstrate the proposed procedure, we performed sled tests to supplement those available in the UMTRI database that could be used for model validation. Table 3 summarizes the test conditions. While the main focus of this project was side impact, the FE wheelchair models were also validated in rear and frontal impact conditions. Appendix A contains results from two nearside impact tests run with commercial wheelchairs and a preliminary version of the loading wall. Results from the other preliminary tests are included in Appendix B (Validation of Surrogate FE Models), Appendix C (Validation of Manual Wheelchair FE Model), and Appendix D (Validation of Power Wheelchair FE Model).

Table 3. Initial validation test conditions.

Test ID	Direction	Wheelchair	Tiedown	Restraint	Results in Appendix
WX2201	Rear	*Ki Mobility Catalyst 5*	Q'Straint docking	WC-mounted lap belt only	C Manual
WX2202	Rear	*Quantum Rehab Edge 2.0*	AMF Bruns 4-point tiedowns	WC-mounted lap belt only	D Power
WX2203	Rear	**SWCB**	UDIG	WC-mounted lap belt only	B Surrogate
WX2204	Nearside	**SWCB**	Q'Straint docking	WC-mounted lap belt and shoulder belt using WC19 relative position	A Preliminary Nearside
WX2205	Nearside	*Ki Mobility Catalyst 5*	UDIG	WC-mounted lap belt and shoulder belt using WC19 relative position	C Manual
WX2206	Nearside	*Quantum Rehab Edge 2.0*	AMF Bruns 4-point tiedowns	WC-mounted lap belt and shoulder belt using WC19 relative position	A Preliminary Nearside

Rear Impact

The rear impact validation tests were conducted using the test procedures found in ISO 7176-19 Annex G using a 14-*g* 25 km/h crash pulse. The crash severity was adapted from the rear-impact tests of CRS found in ECE Regulation 44 and is intended to test the structural integrity of the wheelchair. This is in contrast to lower severity rear impact tests intended to address whiplash-related injury that can occur in low-speed conditions. Previous research that examined the rear impact response of wheelchairs showed that the shoulder belt had minimal or no effect on kinematics. As a result, the rear impact tests were performed only with a wheelchair-mounted lap belt.

The SWCB has cane inserts that are replaced after each test and connect the back support structure to the base. The standard canes are made out of ASTM E527-83 aluminum 6061T6, which provides realistic representation of commercial wheelchair response in frontal impacts. Previous research on wheelchairs in rear impacts evaluated multiple materials for use in rear impact. For the validation test, we chose to use 1018 steel for the cane inserts as shown in Figure 23.

The rear impact validation tests used the Hybrid III Midsized Male ATD. Instrumentation included head and chest accelerations, seatbelt load, and UDIG anchor loads for test WX2203.

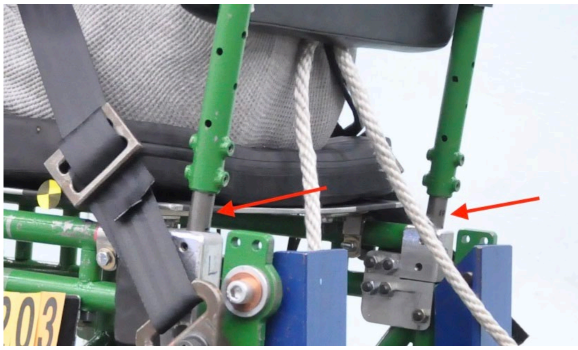


Figure 23. Steel cane inserts used in rear impact validation test with SWCB.

Figure 24 shows the peak rearward movement of the test run with the SWCB secured by the UDIG anchor. As expected, there was some bending of the wheelchair back support. However, this test also resulted in damage to the heavy-duty UDIG anchors, in that the four fasteners securing the anchor track to the load cells sheared off, leading to bending of the track components as well.

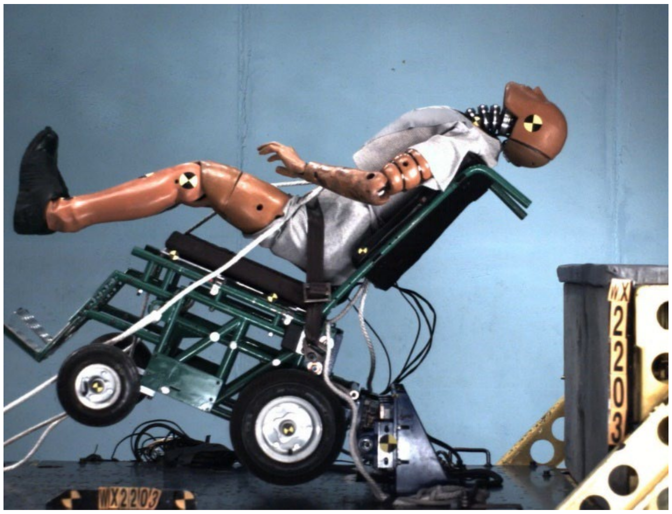


Figure 24. Peak rearward movement of ATD in SWCB secured by heavy-duty surrogate UDIG anchor.

The peak rearward movement of the ATD in the manual wheelchair secured by traditional docking is shown in Figure 25. Photos of the traditional docking hardware are shown in Figure 26, where a drop down bolt on the SWCB securement adaptor hardware engages with the docking device on the sled floor, and an additional bracket mounted to the front of the adaptor hardware engages with stabilizing hook on the sled floor. During the test, the SWCB disengaged from the front stabilization hook as shown in Figure 27, causing deformation of the main bracket and allowing the wheelchair and ATD to rotate rearward substantially. The main bolt remained engaged with the dock but both the dock and the securement adapter bracket were severely deformed. The back support attachment hardware also failed, which allowed the ATD to fall out of the wheelchair as shown in Figure 28.

Figure 25. Peak rearward movement of ATD in manual wheelchair secured by traditional docking station.

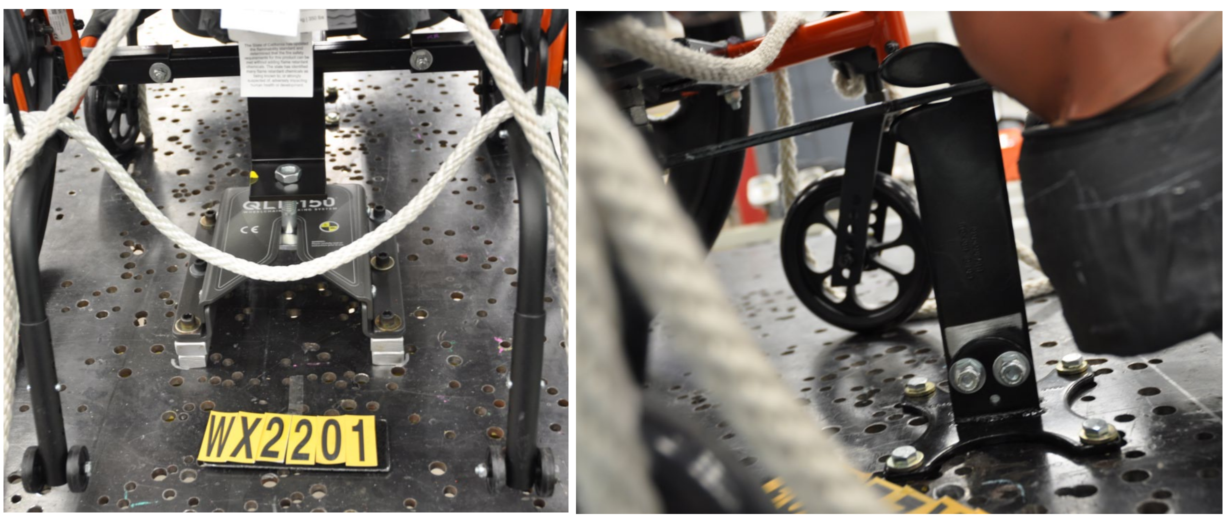


Figure 26. Elements of traditional docking system.

Figure 27. Wheelchair disengaged from front stabilization hook, leading to deformation of main mounting bracket.

Figure 28. Back support attachment hardware also failed, allowing ATD to fall out of chair.

Peak rearward excursion of the ATD in the power wheelchair secured by 4-point strap tiedowns is shown in Figure 29. The back support did not fail in this test. Although designed to provide postural support and not head restraint, the head rest did help limit rearward extension of the head and neck.

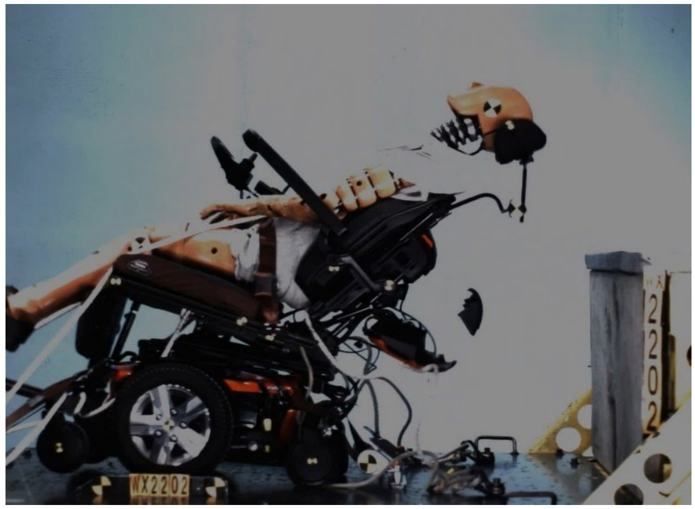


Figure 29. Peak rearward movement of ATD in power wheelchair secured by commercial 4-point strap tiedowns.

Exploratory Nearside Impact

Preliminary validation tests under nearside impact test conditions were run using an early draft of the test procedures. Figure 30 shows how the existing wheelchair test buck was modified to achieve the side impact testing conditions. First, we installed the fixture that allows the D-ring to be mounted in optimal locations for a particular size of occupant and wheelchair. We then used a fabric template sized to represent the minimum required size of a wheelchair station of 30”x48”. We placed the template at an 80-degree angle relative to the forward motion of the sled and positioned it as far to the right as possible while still allowing the anchoring track to be secured to the buck. The UDIG anchor was placed adjacent to the rear boundary of the station. When testing 4-point strap tiedown systems, the UDIG anchor was removed and replaced with the rear anchoring track.

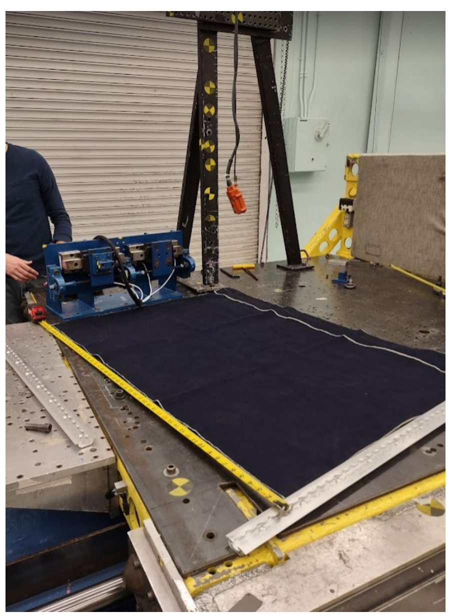


Figure 30. Setting up the layout for side impact validation tests.

Although these validation tests were not intended to represent the final proposed side impact test conditions, our preliminary simulations indicated that nearside loading conditions would be represented by some type of fixed staggered loading wall, so we constructed an initial version for the validation tests. Figure 31 shows how the wall was constructed with a steel frame and plywood base, plus an MC2900 foam panel. This material was selected because it has been used previously to simulate realistic side impact loading characteristics in the UMTRI Dual sled (Miller et al. 2013). It was covered with the same type of Sunbrella fabric specified for the latest FMVSS No. 213 buck; a metal strap secured the fabric to the base at the transition between the two blocks of foam. We added a piece of cardboard on the wall surface to protect the fabric, which also turned out to be useful for documenting contact locations of the wheelchair. For the validation tests, the wall was mounted parallel to the wheelchair station centerline such that the surface of the wall closest to the wheelchair was at the lateral edge of the 30-in wide wheelchair station.

Figure 31. Construction of preliminary side impact load wall.

These tests, as well as all of the subsequent side impact tests, used the ES-2re ATD. Instrumentation included head, thorax, and pelvis accelerometers, abdomen, pelvis, and neck load cells, and IR-TRACC sensors to measure rib deflections. In addition, loads were measured for the tiedowns when using UDIG or 4-point strap tiedown systems and for the lap and shoulder belts. A FARO digitizer tool was used to ensure the ATD was seated symmetrically on the wheelchair seat and to compare belt positions on the ATD across conditions.

As shown by comparing the peak excursion frames in Figure 32, kinematics of the power wheelchair, SWCB, and manual wheelchair were fairly similar. The UDIG and SWTORS securement systems did not sustain any damage, while the traditional docking experienced some deformation but maintained securement of the SWCB. The loading wall did not appear to move as the wheelchair and ATD contacted it, and the foam was not visibly damaged during testing.

Figure 32. Comparison of peak lateral kinematics for power chair secured by 4-point strap tiedown (left), SWCB secured by traditional docking (center) and manual wheelchair secured by UDIG (right).

Test Procedures

Overview

Results from the preliminary MADYMO simulations and experience with the side impact validation tests were used to formulate the test procedures. To harmonize with current voluntary frontal wheelchair standards, we used the text of WC19 and WC18 as a starting point. The procedures are organized to address three types of side impact testing: wheelchairs, WTORS, and vehicle occupant protection systems. All the procedures initially focus on using a midsized male ATD for testing, although they could likely be used to assess performance of wheelchairs designed for other sizes of occupants as well. Appendix E contains the test procedures developed through this project. This section describes the factors considered in designing the test fixtures and developing the positioning procedures and performance criteria.

Wheelchair Procedure

The wheelchair test procedures use the SWTORS to anchor the wheelchair, and the test is performed to simulate side impact into a fixed intruded wall. Performance criteria focus on assessing the structural integrity of the wheelchair and position of the ATD post-test. Although excursion limits are included as criteria in frontal testing of wheelchairs, we do not believe they are valuable for the nearside impact condition given that excursion is mainly limited by the presence of the wall.

The procedures used in the preliminary validation nearside tests placed the wall parallel to the lateral edge of the 30-in wide wheelchair station and centered the wheelchair within the station. Within the wheelchair station, narrower wheelchairs would have a greater gap to the wall compared to wider wheelchairs, which is consistent with what would be seen in the field. This wider gap between wheelchair and wall would be considered a benefit in the field because it would provide more space to avoid intrusion. However, because there were also concerns that the draft procedure would benefit wider wheelchairs by having less space before striking the wall, we conducted simulations to evaluate how variations in the distance between the wheelchair and wall affects response. Figure 33 shows a comparison of simulation kinematics using initial spacings set to a 5-, 45-, or 85-mm gap. The resultant force between the side wall and wheelchair shown in Figure 34 indicates that the force is lowest with a small gap, but is at a higher similar level for the 45- and 85-mm gaps. The ATD loading shown in Figure 35 shows decreasing levels with increasing gap widths. However, it would be reasonable to set a fixed gap between the wall and wheelchair for all products because the focus of wheelchair side impact testing criteria is wheelchair integrity and post-test ATD position. Because the kinematics were similar for the different gaps, we have proposed setting a consistent 50-mm gap between the wheelchair and wall in the procedure.

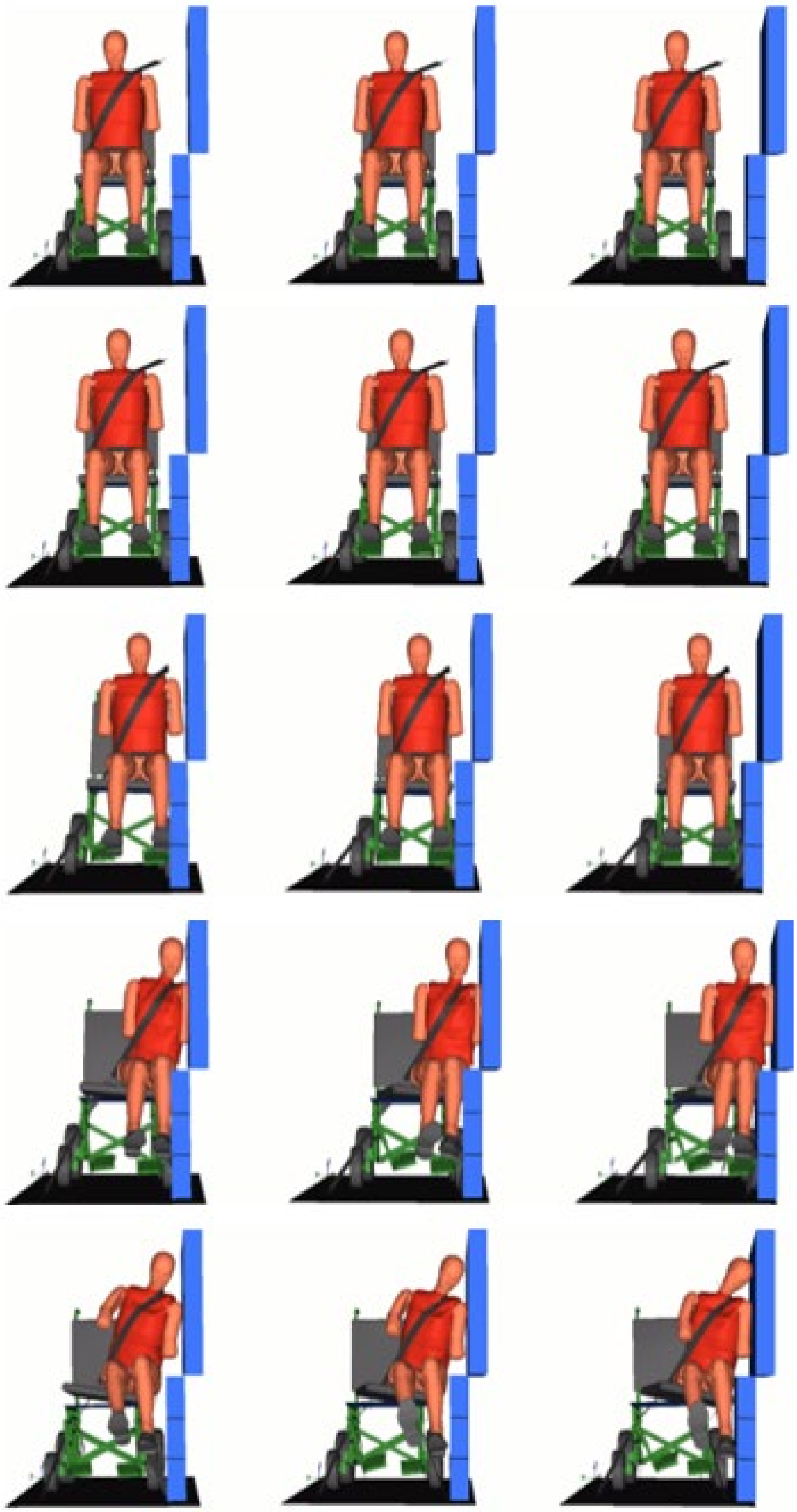


Figure 33. Simulations using wheelchair-to-wall gaps of 5 (left), 45 (middle), and 85 (right) mm, at approximately 0, 30, 60, 90, and 120 ms.

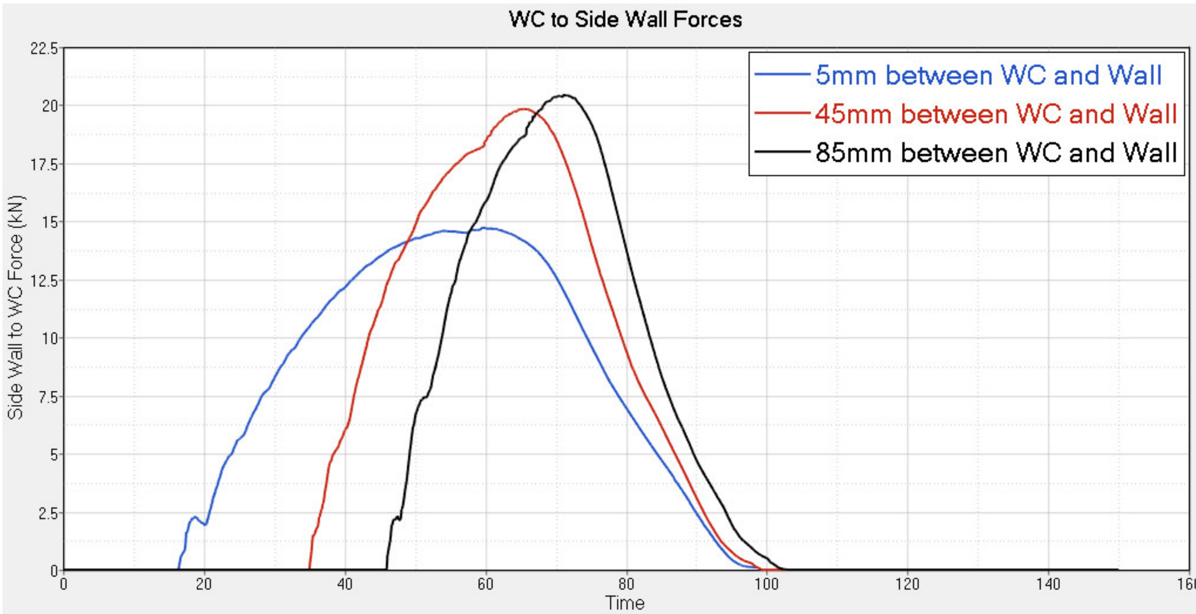


Figure 34. Side wall forces from simulations used to explore effect of gap width between wheelchair and side impact wall.

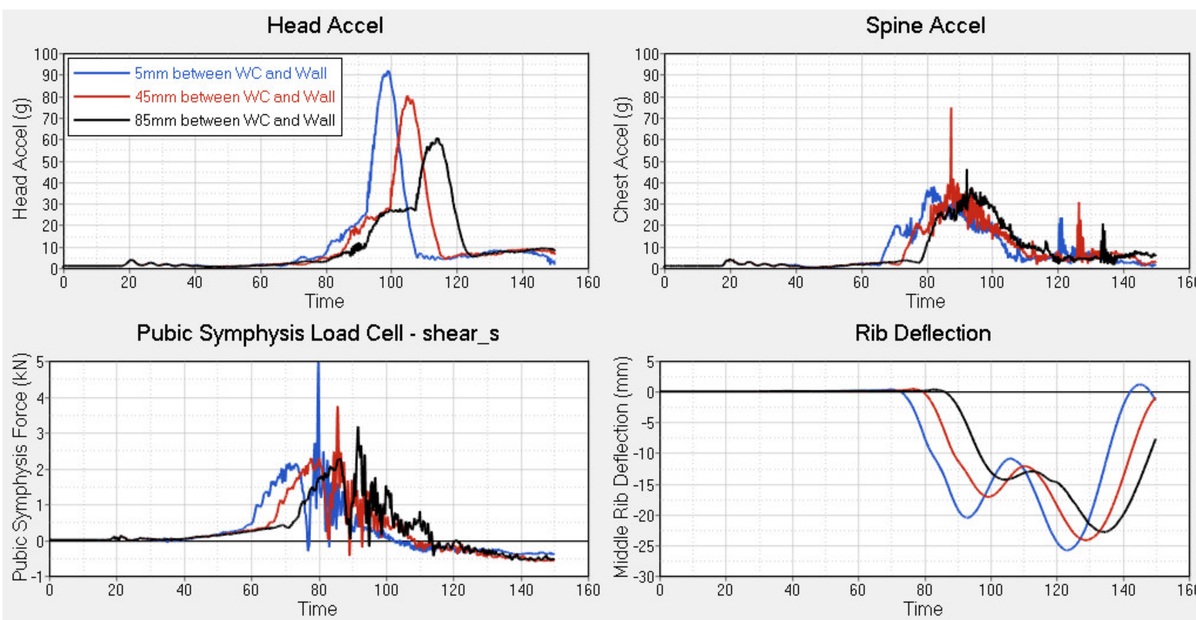


Figure 35. ATD measures from simulations used to explore effect of gap width between wheelchair and side impact wall.

The updated wall fixture proposed for testing wheelchairs is shown in Figure 36. The wall is MC2900 foam covered with Sunbrella Marine fabric, the same type specified for the FMVSS No. 213 bench. The upper wall thickness is 50 mm (2 in), while the lower wall thickness is 100 mm (4 in).To avoid damaging the wall, we also added a 32 mm (0.125 in) thick piece of ABS plastic, which is similar to the plastics used in vehicle interiors. (Simulations were performed to show that the addition of the plastic facing would not affect dynamic response.) Figure 36 also shows a 50 mm thick positioning tool used to set a consistent gap between the wheelchair being tested and the impact wall.

Figure 36. Updated wall and 50-mm thick positioning tool proposed for testing wheelchairs in nearside impact.

Figure 37 shows a diagram of how the buck layout was designed. We first shifted the wall to the forward edge of the plate and oriented it at 80 degrees. A review of wheelchair geometry indicates that the widest wheelchairs are approximately 34” wide. To accommodate testing this width of wheelchair, we located a baseline centerline 19” away from the wall, to allow a 2” gap and 17” distance to the wheelchair centerline. We then added holes to the fixture plate (Figure 38) so the wall could be shifted in increments to accommodate testing the narrowest wheelchairs which are approximately 20” wide.

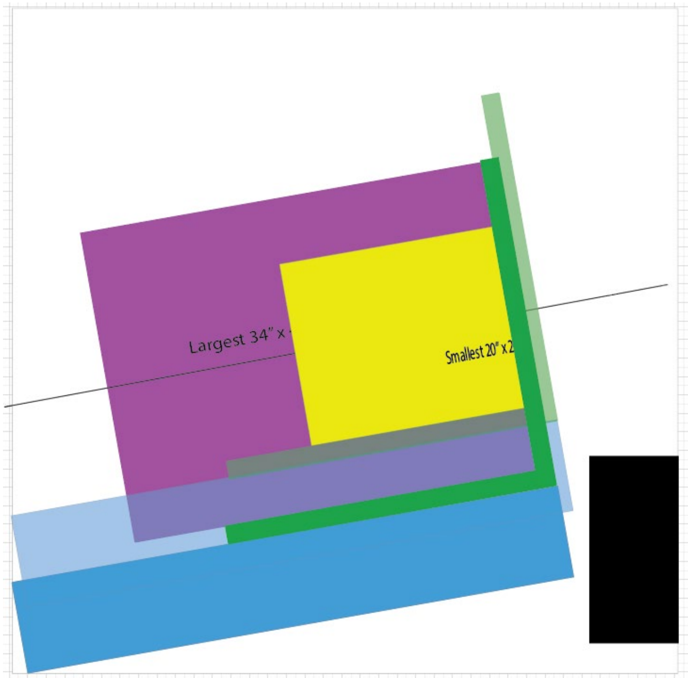


Figure 37. Factors considered in layout of buck design.

Figure 38. Adjustment holes that allow shifting of wall in 1 cm increments.

Compared to the preliminary nearside tests run previously, the wall was constructed to be higher to prevent unrealistic bending and contact between the ATD head/neck and the top of the wall. We also wanted to prevent the head and feet of the ATD from extending beyond the forward and rear edges of the wall. To estimate the size of a wall that would be needed, we reviewed the geometry of pretest photos from 75 different wheelchairs, shown in Figure 39. As a result, we increased the length of the lower part of the wall from 123 cm (48 in) to 152 cm (60 in), and raised the wall height by 23 cm (9 in) compared to the preliminary side impact tests. Simulations shown in Figure 40 confirmed that the higher wall produced reasonable kinematics.

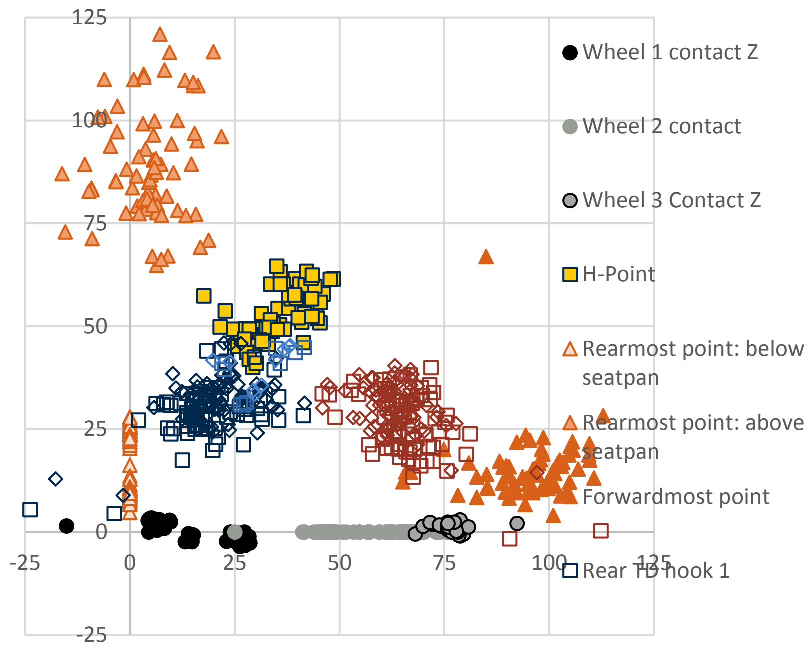


Figure 39. Key geometric landmarks from 75 pretest photos of wheelchair tests.

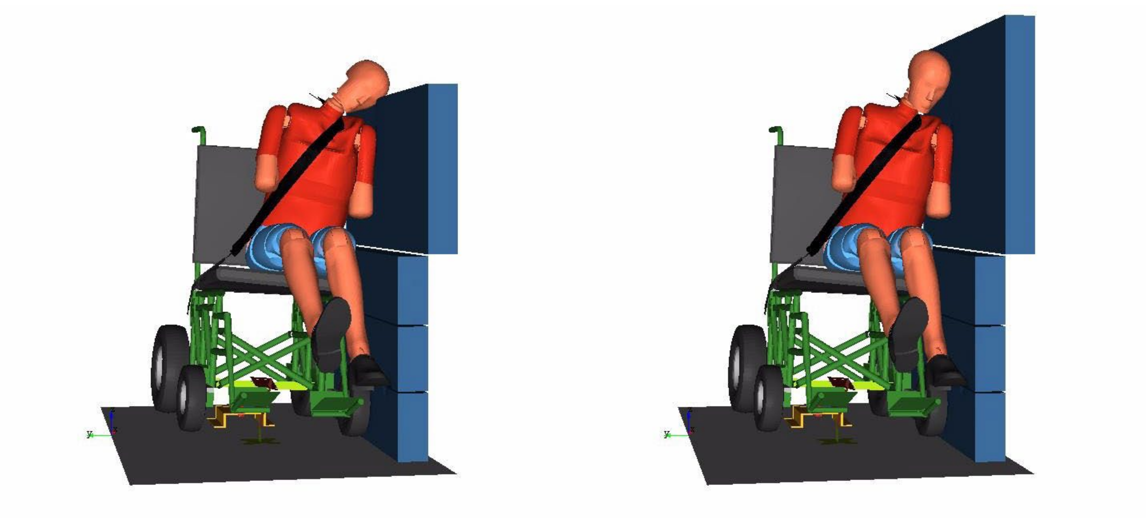


Figure 40. Comparison of kinematics under impact with validation wall (left) and taller proposed wall (right).

When performing testing to evaluate the procedure, tests WC2207 (SWCB), WC2208 (Quickie 2), WX2211 (Ki Mobility Catalyst 5), WX2302 (Leggero Enzo) and WX2302 (SWCSI) used the same SWTORS used in WC19 test procedures without any issues. Appendix F contains overlay plots for these tests, as well as illustrations of kinematics.

Appendix E also contains examples of data collection forms that would be used to evaluate performance of commercial wheelchairs. The requirements are similar to those used in frontal WC19 testing, focusing on wheelchair integrity. While WC19 includes excursion requirements, we did not consider those for the nearside testing condition where excursion is limited by the wall rather than characteristics of the wheelchair. The power wheelchair and two of the manual wheelchairs met the proposed test requirements, but the Leggero Enzo did not because the lateral frame members with attached front casters failed and detached from the main frame on both sides of the wheelchair as shown in Figure 41.

Figure 41. Component failure in nearside impact test of Leggero Enzo.

WC19 moves the D-ring to provide optimal geometry for each wheelchair to focus testing on the wheelchair performance. Our initial approach used this strategy to locate the D-ring in side impact test conditions. However, this led to unrealistic head contact with the D-ring hardware under some conditions. Instead, we modified the procedure to first locate the D-ring hardware so it is 50 mm above the ATD head. Because the lateral position of the shoulder belt affects the amount of lateral movement of the ATD head and torso, for consistency, we locate the D-ring , 30 cm (12 in) left of the ATD centerline and 30 cm (12 in) back from the clavicle, placing it at the center of the ATD's outboard shoulder.

One change made to the SWCB that would make its profile more realistic in side impact but not change its performance in frontal impact was to switch the front wheel style and bolts used to secure the wheels. Figure 42 shows a photo of the protruding bolt heads used previously on the SWCB, while the right photo shows the new bolts and front wheel used with more recessed profiles; the rear wheel sizes were not available with the recessed design so only the bolt head style was changed.

Figure 42. Original (left) and revised (right) wheels and bolts used on SWCB.

WTORS Procedure

Because loading to the WTORS is more severe without a vehicle sidewall to stop lateral motion of the wheelchair, the procedure for evaluating them does not use a wall. Our preliminary tests used the SWCB, which was designed to load WTORS in frontal impacts in a realistic manner compared to commercial wheelchairs. It was also designed to be a base fixture when testing different wheelchair seating systems; we chose to use it in this project (rather than the SWC fixture) because it allows us to examine different styles of armrest and how they function in side impact.

Ideally, WTORS should limit excessive lateral movement of the wheelchair. While the amount of space available in a vehicle depends both on the original placement of the wheelchair station and the amount of intrusion in a crash, developing a lateral excursion criterion would promote this outcome. While we used the loading wall to simulate nearside testing conditions for wheelchairs, when evaluating WTORS, we propose using a condition without a wall to generate higher loading on the tiedown systems, as well as to develop a lateral excursion criterion independent of interior vehicle geometry location. The suitability of using either the existing or modified SWCB under this condition also needed to be determined. If needed, the updated fixture would be called the Surrogate Wheelchair for Side Impact (SWCSI). While the primary use of the SWCSI would be for evaluating WTORS, a secondary use would be that vehicle manufacturers could use it as a surrogate for commercial wheelchairs during vehicle side impact testing for evaluation of side impact protection systems.

The tests listed in Table 4 and reported in Appendix F using commercial wheelchairs were conducted to examine whether the SWCB, designed for frontal impact, also performs realistically in side impact. The SWCB was fitted with a basic planar seatpan and back support and equipped with basic flat foam seat and back cushions. Tests were run with and without a wall, to represent conditions where it might be used by vehicle manufacturers as well as conditions for evaluating WTORS. The goals of these tests were to determine:

- Performance of three commercial wheelchairs under side impact loading with a wall to inform design of SWCSI for in-vehicle testing and to confirm that the surrogate has representative kinematics and ATD measures compared to manual wheelchairs under this loading condition.

- Performance of three commercial wheelchairs under side impact loading without a wall to inform design of SWCSI for WTORS testing and to confirm that the surrogate has representative kinematics and ATD measures compared to manual wheelchairs under this loading condition.
- Measure baseline performance of SWCSI secured by SWTORS with and without a wall.
- Any relationships between ATD measures and ATD/wheelchair excursions.
- The range of excursions seen in a sample of current WTORS products.
- Determine setup procedures consistent with wheelchair testing.
- Validate models of SWCSI and tiedowns under the proposed loading conditions.

Table 4. Side Impact Tests

Test #	Wheelchair	Tiedown	Wall?	Purpose	Results Appendix
WX2207	SWCB	SWTORS	Y	Baseline with wall	B, F
WX2310	SWCB	SWTORS	N	Baseline without wall	B, F
WX2208	Quickie 2	SWTORS	Y	Inform SWCSI design	F
WX2214	Quickie 2	SWTORS	N	Inform SWCSI design	F
WX2212	Ki Mobility Catalyst 5	SWTORS	Y	Inform SWCSI design	F
WX2213	Ki Mobility Catalyst 5	SWTORS	N	Inform SWCSI design	F
WX2301	Leggero ENZO	SWTORS	N	Inform SWCSI design	F
WX2302	Leggero ENZO	SWTORS	Y	Inform SWCSI design	F
WX2303	SWCSI	SWTORS	Y	Baseline with wall	B, F
WC2304/6	SWCSI	SWTORS	N	Baseline without wall	B, F
WX2305	SWCSI	AMF Bruns	N	Develop WTORS performance criteria	G
WX2308	SWCSI	QLK-150	N	Develop WTORS performance criteria	G
WX2307	SWCSI	QRT-360 w/ Q8-5325-A belt system	N	Develop WTORS performance criteria	G
WX2309	SWCSI	EZLock	N	Develop WTORS performance criteria	G

Figure 43 shows images from time of peak loading and comparison of signals that led to modifications to the SWCB to turn it into the updated fixture, the SWCSI. When we compared the peak lateral shift of the ATD pelvis in the SWCB to that in the commercial wheelchairs, the right side of the ATD pelvis reached the centerline in the SWCB, while it only shifted to a point about 25-33% of the seat cushion width for the commercial wheelchairs. When comparing the ATD signals (Appendix F), the timing of the head/neck signals aligned more closely than the pelvis/abdomen signals, which were lower and peaked later compared to the commercial wheelchairs. Several factors seem to be contributing to the differences:

- Presence of armrests in commercial wheelchairs
- ATD pelvis being better contained/hammocked more by seatpan/cushion characteristics of commercial wheelchairs.
- Propel wheels on two manual wheelchairs prevented lateral motion.
- Height of SWCB relative to the intruded part of the simulated wall.
- Location of lap belt anchors relative to the ATD H-point (closer on most manual wheelchairs compared to the SWCB).

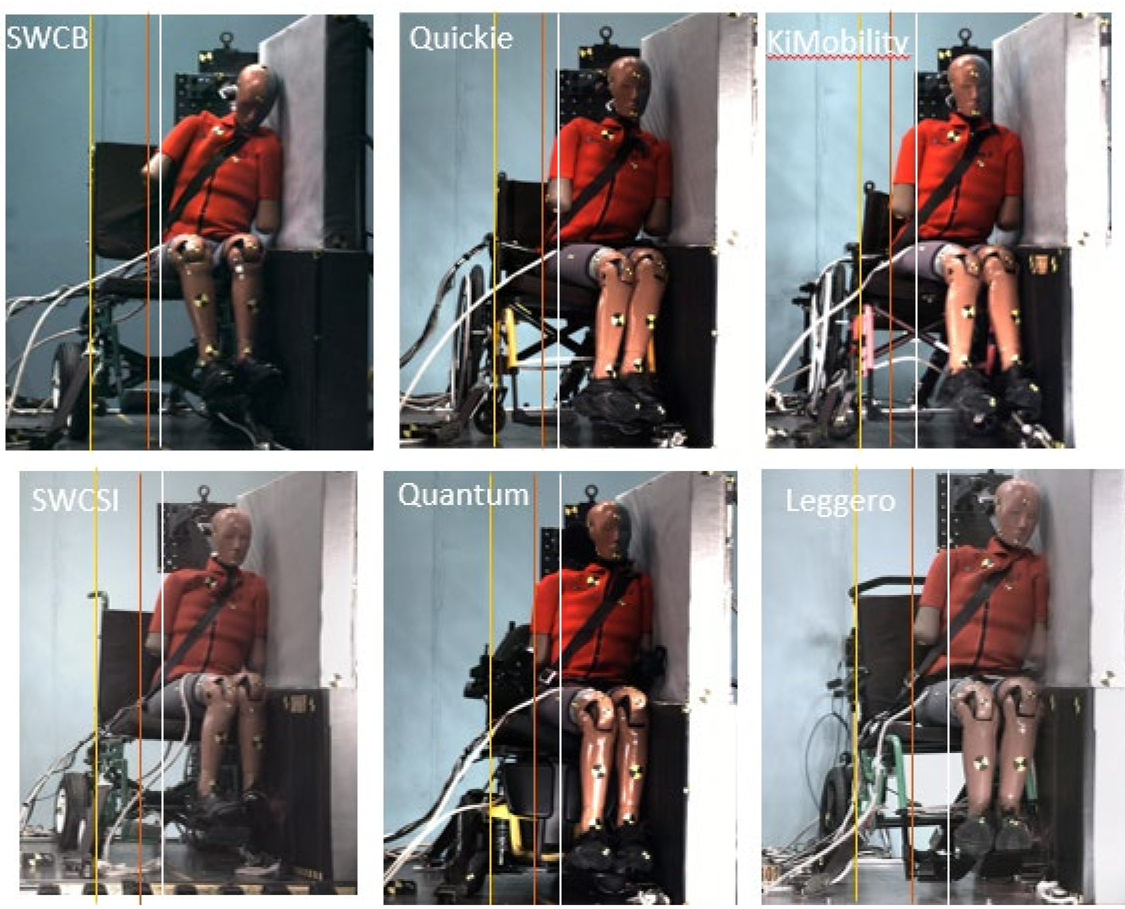


Figure 43. Comparison of ATD travel in SWCB, commercial wheelchairs, and SWCSI. Yellow=right seatback, white=WC centerline, orange=ATD right hip.

Figure 44 shows the modifications made to create the SWCSI. First, we moved the lap belt anchors forward approximately 50 mm. We added a rigid armrest to the loaded side. When positioning the armrest, we designed it so the rear positioning post was rearward of the pelvis load cell, and the front positioning post was forward of the thigh-pelvis gap. The horizontal component of the armrest was located so the top would load the upper part of the pelvis bone. We also added wedges to the top of the flat seat cushion to better simulate the performance of commercial wheelchairs. As seen in Figure 45 and signals from the tests run with the SWCSI (Appendix B and F), these modifications made the performance closer to what was seen with the commercial wheelchairs. A benefit of these modifications is that it directs loading from the ATD to the wheelchair (rather than falling off) making it a more severe test of the WTORS.

Figure 44. Modifications to turn SWCB into SWCSI: adding armrest, moving lap belt anchors forward, adding contour to flat seat.

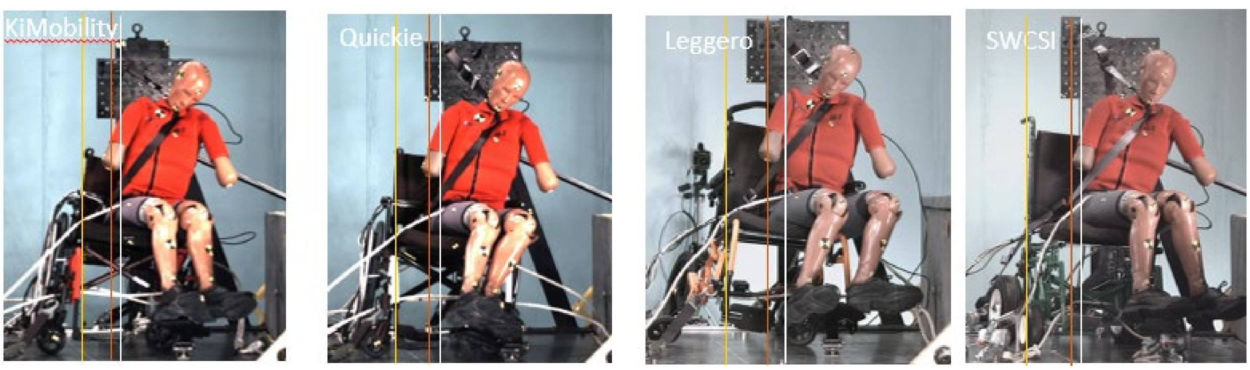


Figure 45. Comparison of kinematics between three commercial manual chairs and SWCSI.

Once the performance of the SWCSI was deemed representative of commercial wheelchairs, we performed the tests of the commercial tiedown systems. These tests allowed us to develop proposed performance criteria for WTORS. For side-impact WTORS should limit excessive lateral movement of the wheelchair. While the amount of space available in a vehicle depends both on the original placement of the wheelchair station and the amount of intrusion in a crash, developing a lateral excursion criterion would promote this outcome. As shown in Figure 46, test conditions evaluated four different commercial tiedown systems (as well as the SWCSI secured by SWTORS).

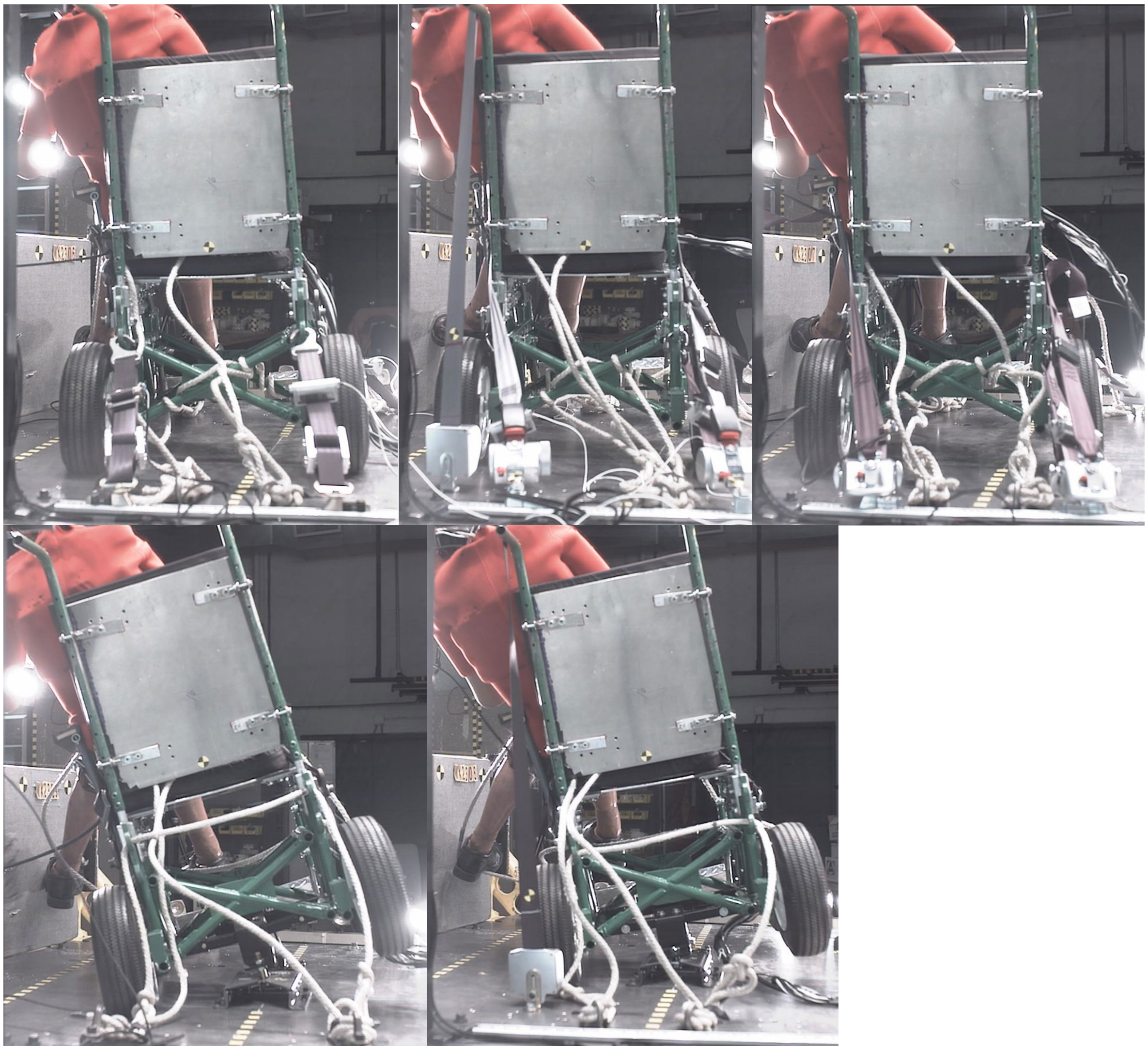


Figure 46. Peak excursions of WTORS tests with SWCSI: SWTORS, 4-point #1, commercial 4-point #2, traditional docking #1, traditional docking #2.

While we measured the ATD signals during these tests, we did not include evaluation of them in the performance criteria because the best way to protect occupants in side impact is through vehicle-based features such as curtain airbags where WTORS design has little impact. The WTORS function is to keep the wheelchair secured to the vehicle and to help keep the occupant within the wheelchair. As shown in Appendix G, all of the ATD measures collected during the tests were well below FMVSS No. 214 IARVs for the ATD, despite using the SWCSI with a rigid armrest designed for repeated testing.

These tests also allowed us to add language to the test procedure on how to use manufacturer-provided occupant restraint systems when testing a complete WTORS system. (Some manufacturers only provide the WT component, so the procedure also includes directions on using a generic seatbelt.)

To determine quantitative performance criteria for the ability of the WTORS to control the motion of the wheelchair during lateral loading, we assessed the data from the tests of commercial and surrogate WTORS loaded with the SWCSI without a wall, as per the WTORS side impact test procedures in Appendix E. Ideally, the wheelchair would perform similarly to conventional vehicle seating during side impact, staying anchored to the vehicle floor and remaining stable, with seating surface level in the YX plane, and at a constant height to allow the wheelchair seated occupant to maintain good belt fit and stay aligned with airbag zones and padded areas of the vehicle side wall.

Table 5 shows the excursions and lateral tipping data for the WTORS tests. While the WTORS procedure will use the SWCSI to represent a commercial wheelchair, the test matrix also included tests of commercial wheelchairs secured with the SWTORS in this configuration. During test WX2301, the commercial wheelchair frame experienced a weld failure, which makes that test an outlier. The data suggests two criteria for WTORS performance measures: the lateral movement and lateral tipping of the SWCSI. The lateral excursion of the SWCSI is defined as the difference in position of the far side lateral side rail of the wheelchair near point-P (see Figure 47 below) from pre-impact to maximum forward position; these measures range from 136 to 270 mm. The lateral tipping of the SWCSI is defined as the maximum angle of the wheelchair centerline during the impact event relative to vertical and the values from the test series range from 4 to 17 degrees in these tests. These initial data suggest that a lateral SWCSI excursion limit of 250 mm and a maximum angle of 12 degrees are performance limits that are achievable with current commercial product designs but would encourage improvements in WTORS performance.

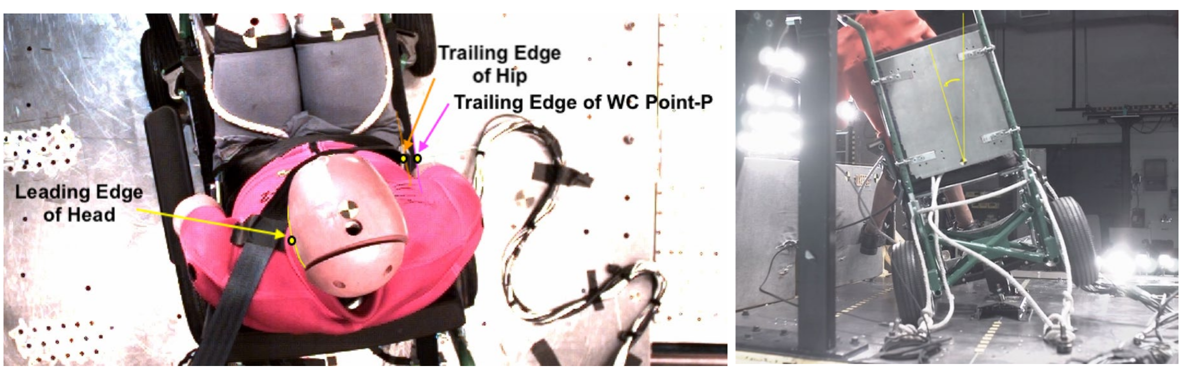


Figure 47. Reference points for excursion and angle measurements for WTORS testing.

Table 5. Excursions (mm) for WTORS test conditions

`Test ID	WC	Securement	Peak WC	Peak Pelvis	Peak Head	Max BP Angle (deg)
WX2213	Manual #1	SWTORS	253	375	943	12
WX2214	Manual #2	SWTORS	192	356	915	8
WX2301	Manual #3	SWTORS	245	495	898	16
WX2304	SWCSI	SWTORS	220	353	909	5
WX2305	SWCSI	4 PT#1	270	398	906	5
WX2306	SWCSI	SWTORS	197	342	901	5
WX2307	SWCSI	4 PT #2	239	381	906	4
WX2308	SWCSI	Dock #1	136	325	1031	14
WX2309	SWCSI	Dock #2	161	345	1018	17
WX2310	SWCB	SWTORS	209	384	965	2
		Proposed limit	275		1000	12

Vehicle Evaluation of Occupant Protection Systems for Wheelchair Users

Based on our understanding of how vehicle occupant protection systems are designed, we do not believe vehicle manufacturers would use a generic sled test configuration to evaluate occupant protection systems designed for wheelchair users. Airbags and seatbelts are designed first through computational modeling. Initial prototypes of airbags are tested on a sled using a body-in-white of the particular vehicle under consideration. Thus, the procedures and requirements for designing occupant protection systems for integrated wheelchair stations focus on how to set up wheelchairs, tiedowns, and seatbelts for virtual or physical testing within a vehicle. To aim for safety equity with other passengers, we recommend that the injury reference values used for assessment of conventional seating positions also be used to assess the performance of ATDs seated in wheelchairs. This recommendation is based on our preliminary simulations of nearside impact without intrusion performed in the NHTSA AWTORS project, which showed that when considering feasible wheelchair seating station locations relative to side structures, current curtain airbag designs and seatbelts provided adequate protection for occupants seated in wheelchairs, when evaluated relative to IARVs used in existing side impact test procedures.

The SWCSI designed for evaluating WTORS could be used by vehicle manufacturers in either physical testing or simulations when designing vehicle-based occupant protection systems.

However, we recommend testing without the armrest (since many wheelchairs do not have them) as a worst-case condition for evaluating the vehicle-based occupant protection systems.

Computational Models

This project developed FE models of test fixtures and commercial products to facilitate test procedure development. The models are also being made available to the public to allow vehicle manufacturers and others to use these tools to improve occupant protection for people traveling while seated in their wheelchairs. To facilitate use of these models, we have documented the development and validation of the surrogates (SWCB/SWCSI), manual wheelchair, and power wheelchair in Appendices B, C, and D, so each appendix can be included as a standalone reference document with each model.

Surrogate Fixtures

Test Fixture Intruded Wall

Figure 48 shows an illustration of the final version of the intruded wall test fixture included in the test procedure. The main part of the wall is modelled as solid-elements with foam material properties matching the physical wall. Around the foam is a set of shell elements to represent the liner and are used for contact definitions. Behind (outboard on the vehicle) and attached to the foam are rigid shell elements that move with the sled. In front of the lower part of the wall is an additional set of shell elements with thermoplastic material properties matching the physical wall.

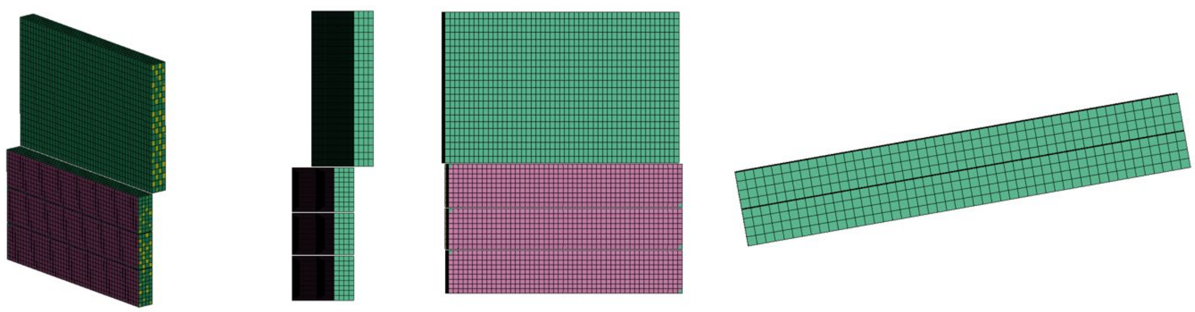


Figure 48. FE Model of final test wall.

UDIG Anchor

Geometry

When evaluating crashworthiness of UDIG anchors, a previous project (Hobson and van Roosmalen 2007) developed a heavy-duty version of a UDIG anchor (shown in Figure 49) for repeated testing and measurement of restraint loads. Because UDIG docking has the greatest potential for allowing safe and independent docking by wheelchair users in an ADSV, we created a model of the fixture for use in FE simulations, as well as a drawing so it can be used as a surrogate fixture in dynamic testing (Figure 49). We originally constructed the model to be rigid, since the fixture did not seem to move in the previous AWTORS frontal and side impact tests. However, the model elements were changed to be deformable based on the damage seen in the rear impact validation test, therefore deformable material properties were assigned in the FE model.

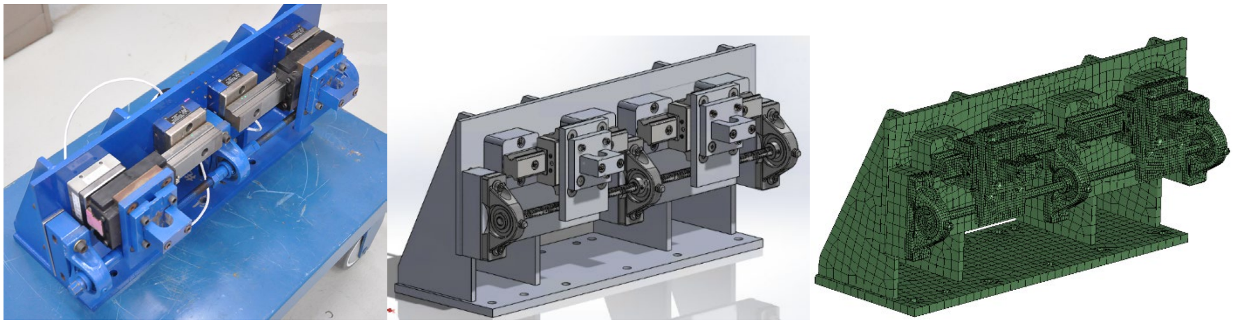


Figure 49. Heavy-duty surrogate UDIG anchor.
(left: physical UDIG, middle: CAD drawing, right: FE model)

The FE model of the UDIG fixture was validated under frontal, side, and rear impact conditions. Kinematics comparisons showing a time near peak excursion are shown in Figure 50 through Figure 52. Additional kinematics results, as well as a comparison of signals, are found in tests with the SWC/SWCB (Appendix B, frontal tests WC0331 and AW2102 and rear test WX2203), manual wheelchair (Appendix D, nearside test WX2210) and power wheelchair (Appendix C, frontal test AW2115).

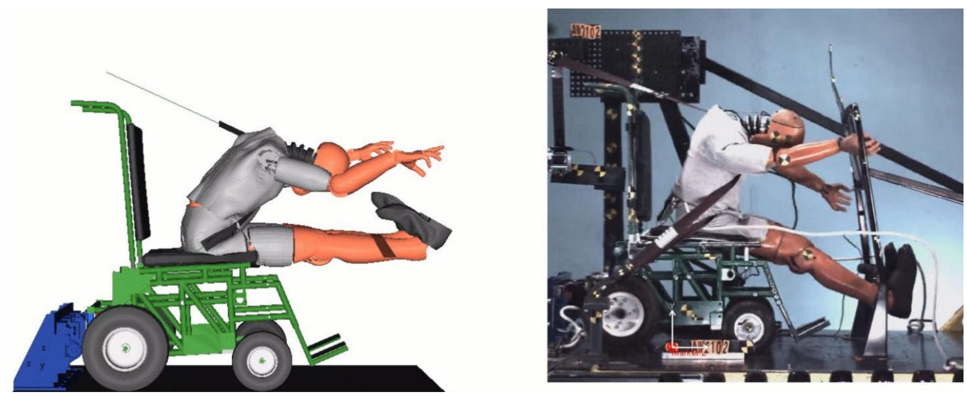


Figure 50. Peak excursion comparison of FE model of SWCB secured by UDIG to test (AW2102).

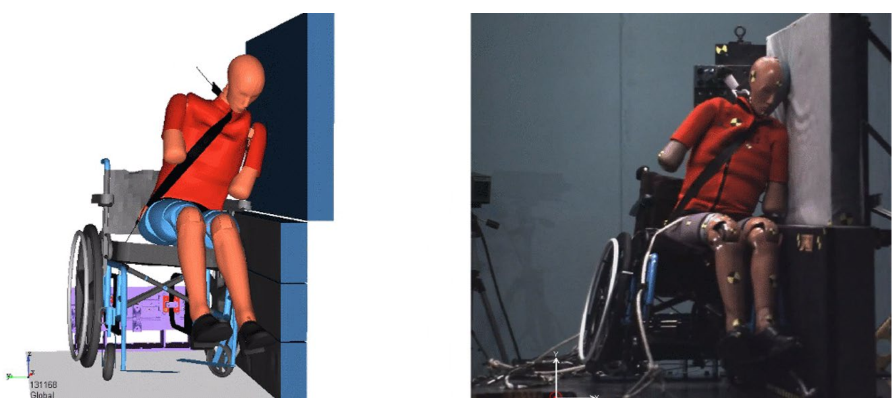


Figure 51. Peak excursion comparison of FE model of SWCB secured by UDIG to test (WX2210).

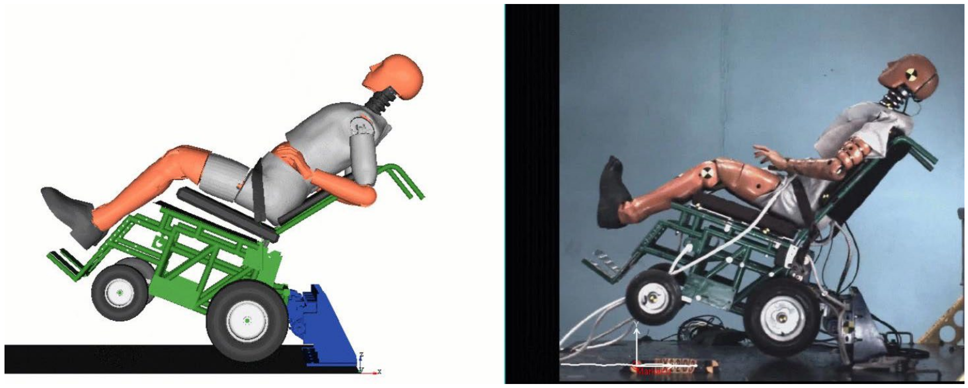


Figure 52. Peak excursion comparison of FE model of SWCB secured by UDIG to rear impact test (WX2203).

Surrogate 4-point Strap Tiedowns

A set of four surrogate tiedowns (shown in Figure 53) is currently used during WC19 testing of wheelchairs in frontal impact conditions as a substitute for testing each wheelchair with every type of commercial tiedown system. FE models of the front and rear tiedowns are shown in Figure 54. Because the surrogate tiedown fixture was designed at UMTRI as part of a previous research project to support standards development, we had a complete set of fixture drawings available to develop the geometry for the SWTORS. For the front tiedowns, the ratchet and hook are modelled as rigid shell-element parts and there is a joint modelled to the sled at the location of the bolt hole. For the rear tiedowns, the split drum, hook, and rod fixture are all modelled as shell element rigid parts, while a joint is defined to connect the rod-end and rod. Contact is defined between the tiedown hooks and the SWCB securement brackets. This model will provide vehicle manufacturers with another useful tool for designing occupant protection systems for wheelchair stations.

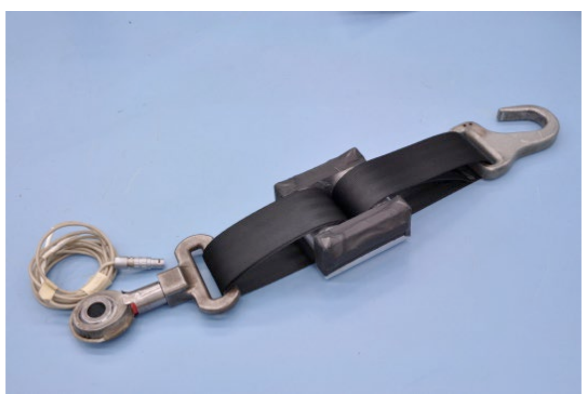


Figure 53. Surrogate WTORS (rear).

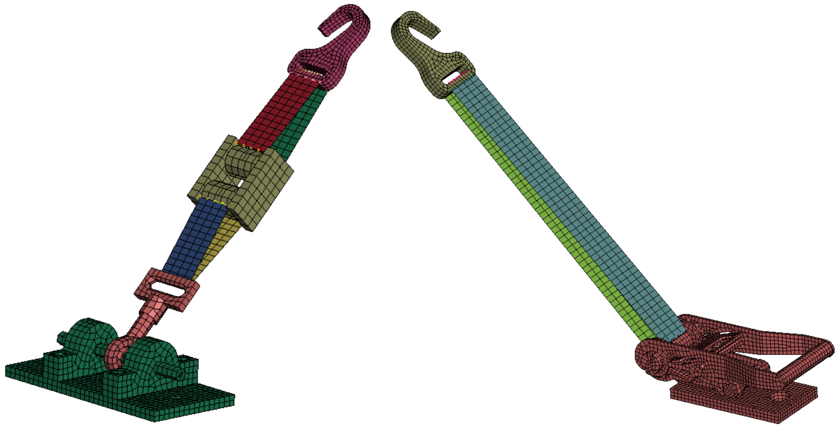


Figure 54. Surrogate wheelchair tiedown FE models (left=rear, right=front).

A simplified version of the SWTORS was also created as shown in Figure 55 This model uses a single band of webbing using 1d and 2d seatbelt elements which makes it much easier to set up and adjust. To replicate the looped seatbelt used in the SWTORS the stiffness of the simplified SWTORS was doubled.

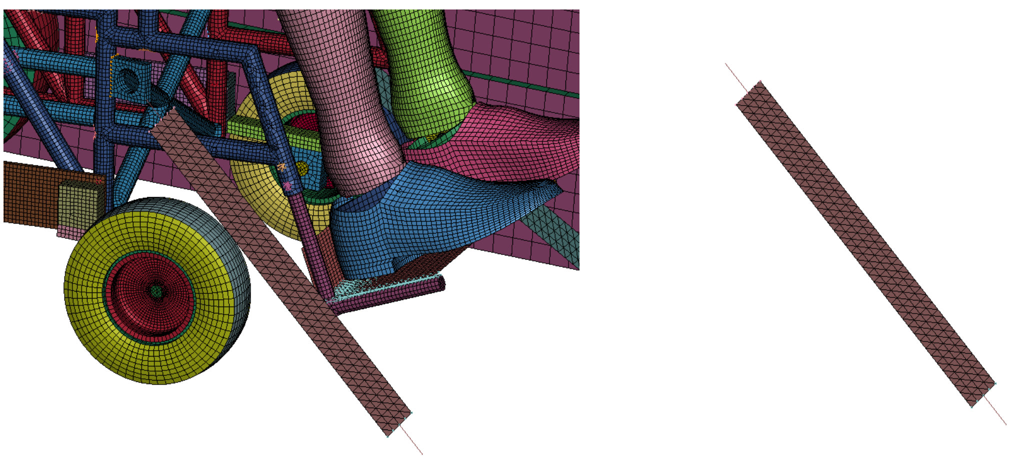


Figure 55. Simplified version of SWTORS.

The SWTORS were validated under frontal, side, and rear impact conditions. Figure 56 through Figure 62 show examples of peak kinematics under each loading condition. Additional comparisons of kinematics and signals can be found in:

- Appendix B, frontal with SWCB, test WC1602
- Appendix B, nearside with SWCB, test WX2207
- Appendix B, nearside (center), SWCB, WX2306
- Appendix D, frontal with manual wheelchair, Test KM0901
- Appendix C, frontal with power wheelchair, Test PM1602
- Appendix C, nearside with power wheelchair, test WX2209

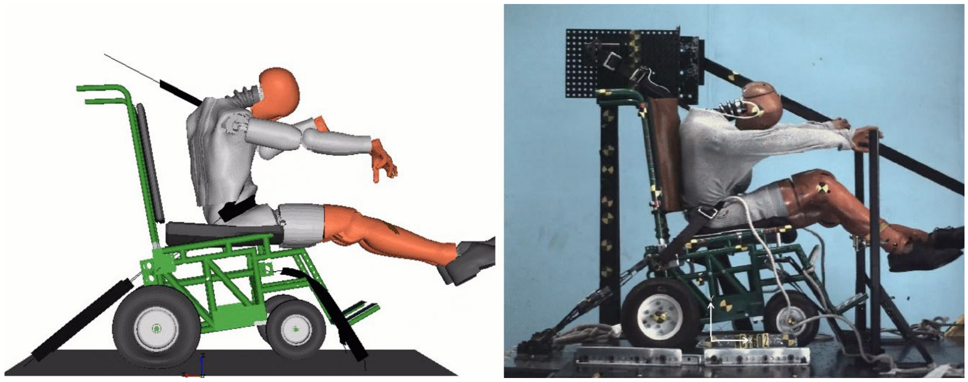


Figure 56. Peak excursion comparison of FE model of SWCB secured by simplified SWTORS model to test WC1602 under frontal impact.

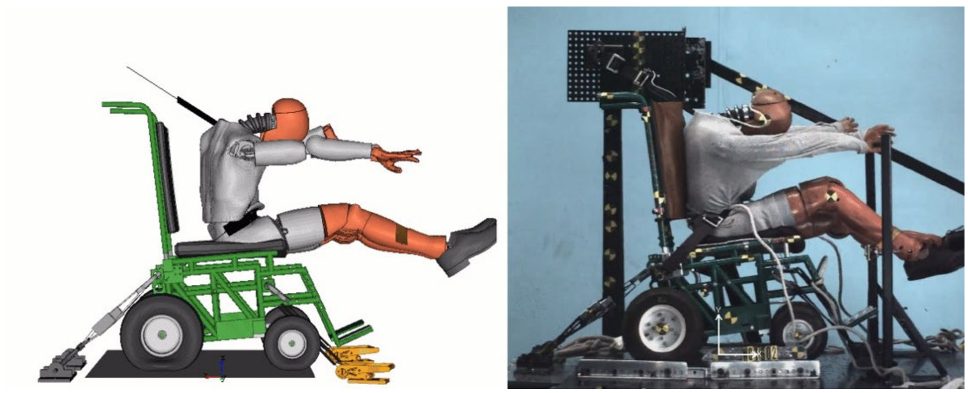


Figure 57. Peak excursion comparison of FE model of SWCB secured by detailed SWTORS model to test WC1602 under frontal impact.

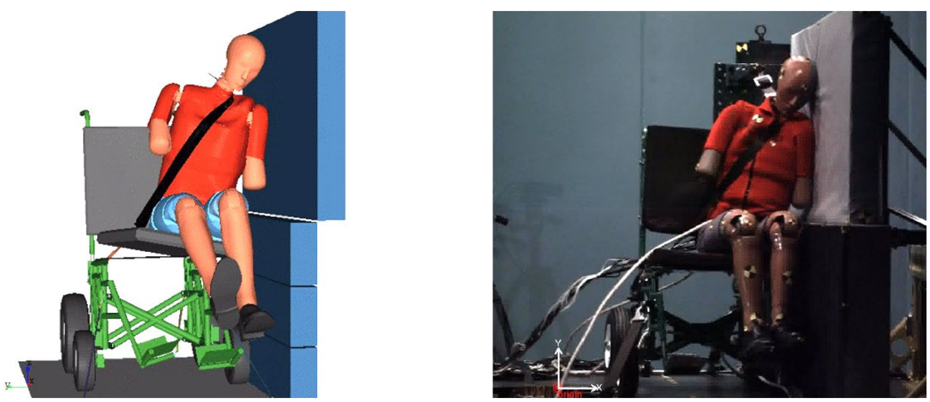


Figure 58. Peak excursion comparison of FE model of SWCB secured by SWTORS to test WX2207 under nearside impact.

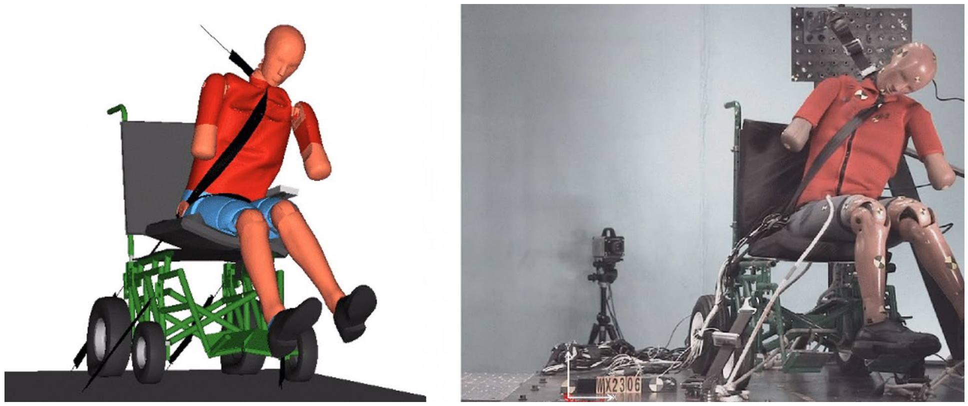


Figure 59. Peak excursion comparison of FE model of SWCSI secured by SWTORS to test WX2306 under nearside (center) impact.

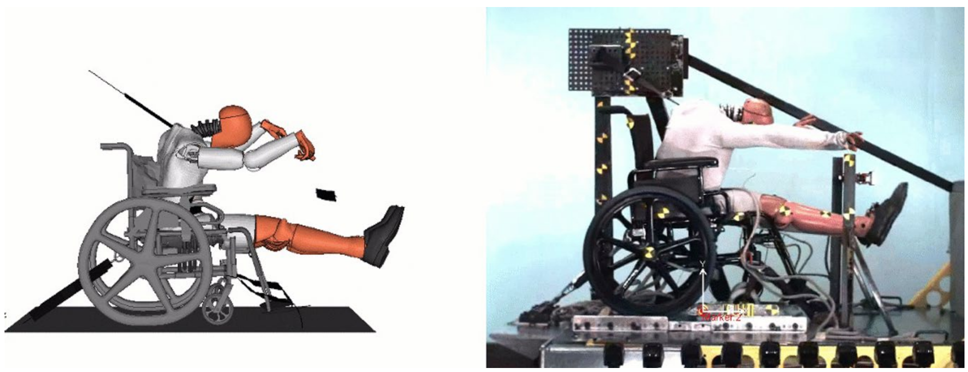


Figure 60. Peak excursion comparison of FE model of manual wheelchair secured by SWTORS to test KM0901 under frontal impact.

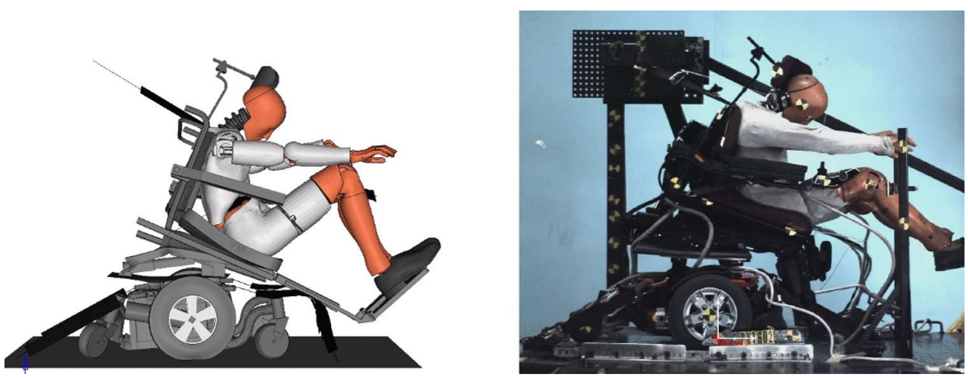


Figure 61. Peak excursion comparison of FE model of power wheelchair secured by SWTORS to test PM1602 under frontal impact.

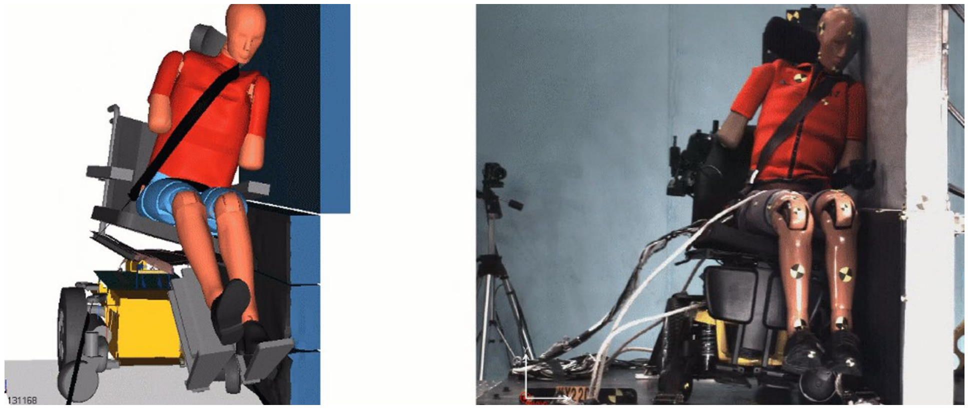


Figure 62. Peak excursion comparison of FE model of power wheelchair secured by SWTORS to test WX2209 under nearside impact.

Commercial Products

Traditional Docking Anchor

A common style for commercially available docking system sued in private vehicles employs the addition of a hanging bolt attached to the wheelchair securement adaptor that is located below the wheelchair and interfaces with a docking device mounted to the vehicle floor. Some versions also have an additional front stabilizer bracket. Figure 63 shows photos of the Q'Straint QLK-150 used in test WX2205 with the SWCB, while Figure 64 shows the FE models. The dock and bolt are both modelled using solid hexahedral elements with steel material properties, and there is a defined contact between the two. The rest of the fixture is modelled using shell elements with steel material properties. Nodal rigid body connections are used to attach the fixture to the SWCB and sled.

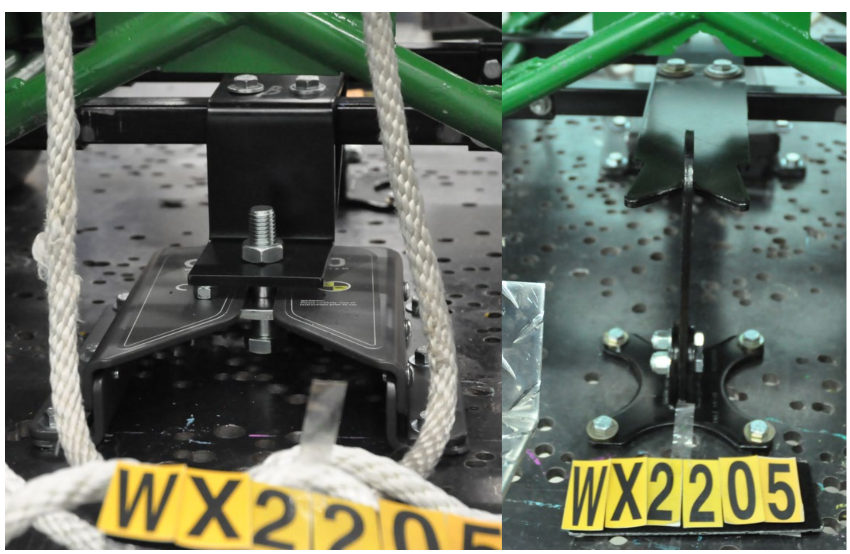


Figure 63. Main docking device (left, view from rear) and front stabilizer bracket (right, view from front).

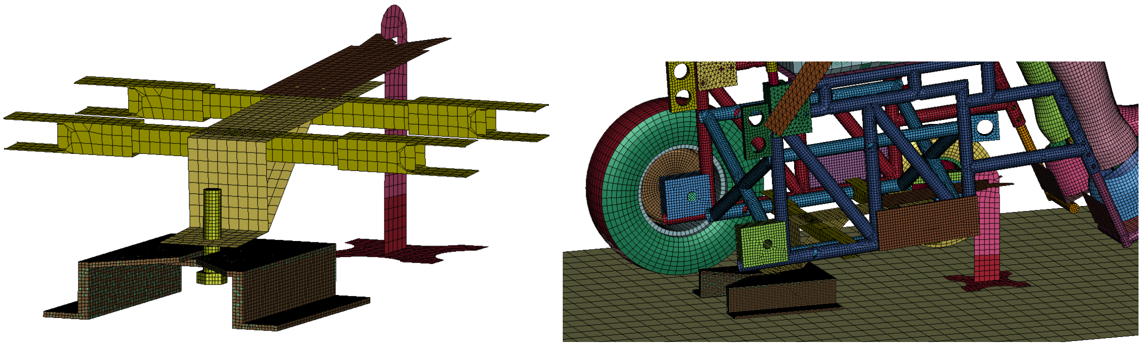


Figure 64. Illustration of traditional docking FE model, as well as secured to SWCB.

Figure 65 through Figure 71 show comparisons of model and tests with the traditional docking system, as well as a deformation comparison. Additional validations results for this docking system can be found in:

- Appendix B, frontal with SWC, test QS1301
- Appendix B, nearside with SWCB, test WX2205
- Appendix D, rear impact with manual wheelchair, test WX2201
- Appendix C, nearside with power wheelchair, test WX2111

To validate the traditional docking station in frontal impact, we did not have a test using the SWCB available, but we did have one using the SWC as shown in Figure 65. Because the SWCB is not as rigid as the SWC, the orientation of the wheelchair at the peak timing differs. However, Figure 69 shows a comparison of the residual deformation of the docking station in the test and FE model, showing similarities.

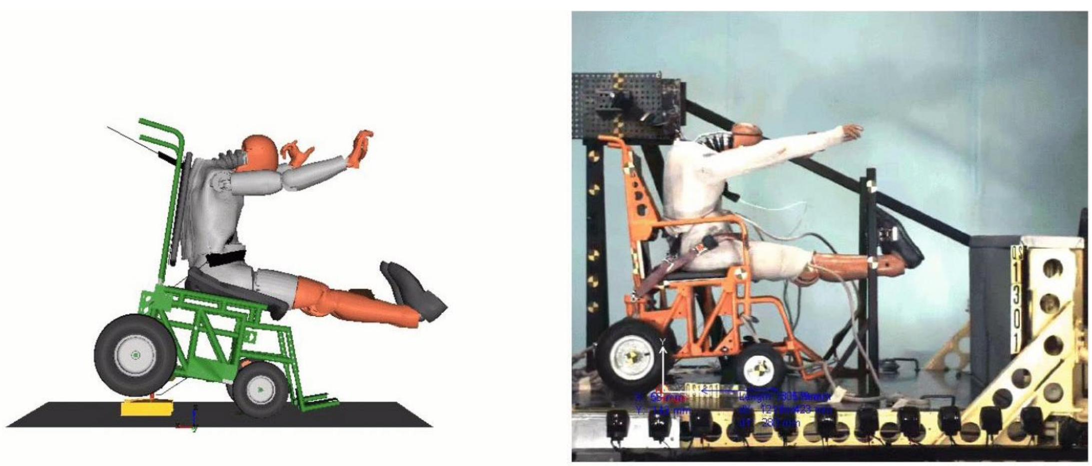


Figure 65. Peak excursion comparison of FE model of SWCB secured by traditional docking to test with SWC (QS1301) under frontal impact.

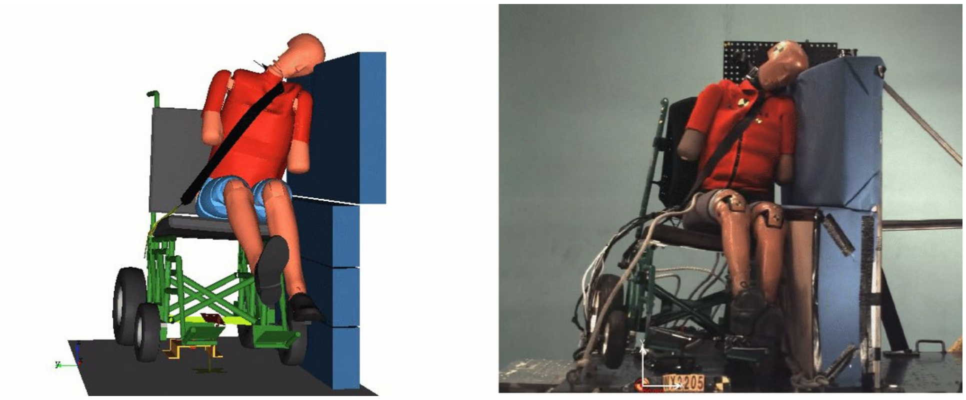


Figure 66. Peak excursion comparison of FE model of SWCB secured by traditional docking to test (WX2205) under nearside impact.

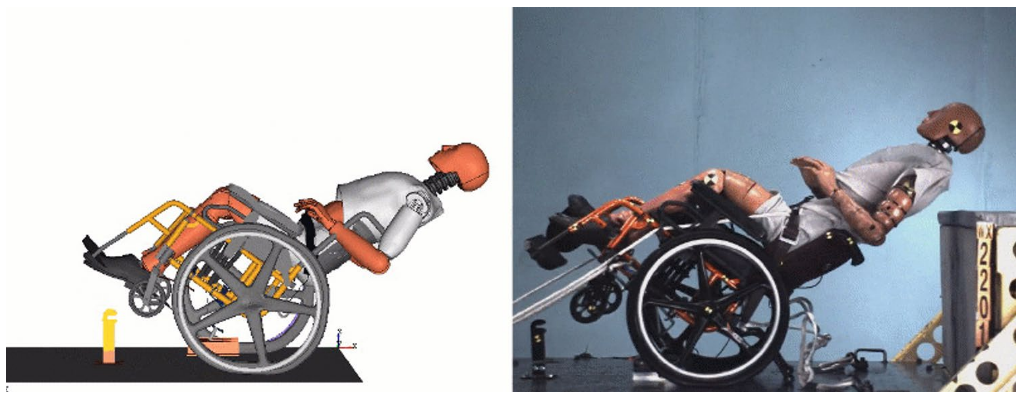


Figure 67. Peak excursion comparison of FE model of manual wheelchair secured by traditional docking to test (WX2201) under rear impact.

Figure 68. Peak excursion comparison of FE model of power wheelchair secured by traditional docking to test (WX2211) under nearside impact.

The locations of damage are similar, although the magnitude is slightly higher in the model. We believe this is reasonable because of the differences in wheelchair motion between the SWC and SWCB.

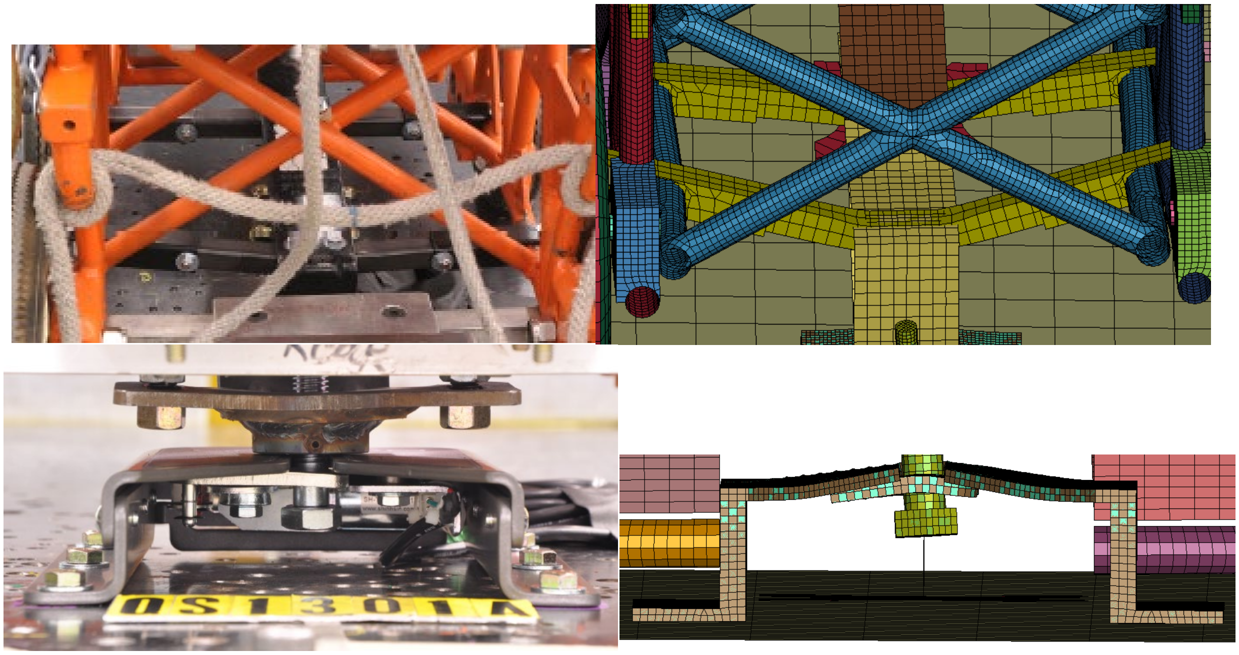


Figure 69. Post-test photos of a docking station showing residual deformation, plus similar views from the FE model.

A comparison between the test and FE model of the SWCB secured by a traditional docking station is shown in Figure 70. ATD kinematics were similar in the test and model, although the SWCB appeared to rotate and deform slightly more during the test. Additional data are included in Appendix B. The largest discrepancy is in the head Z acceleration which is larger in the test compared to the model. Rib deflections are larger in the model than in the test, while pubic loads are larger in the test compared to model.

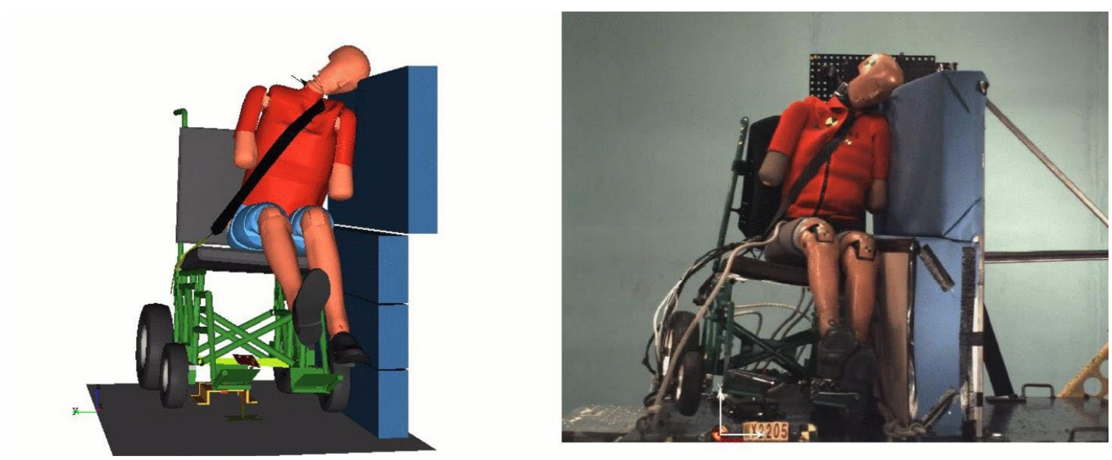


Figure 70. Peak excursion comparison of FE model of SWCB secured by traditional docking to nearside impact test (WX2205).

4-point Strap Tiedowns

As mentioned previously, a simplified version of the SWTORS was created shell elements for most of the belt, plus 1d belt elements at the ends. This simplified model was also successfully used to simulate commercial 4-point strap tiedowns. Validations of commercial tiedowns using this model can be found in Appendix C, and an example of peak kinematics in rear impact is shown in Figure 71, while a nearside comparison is shown in Figure 72.

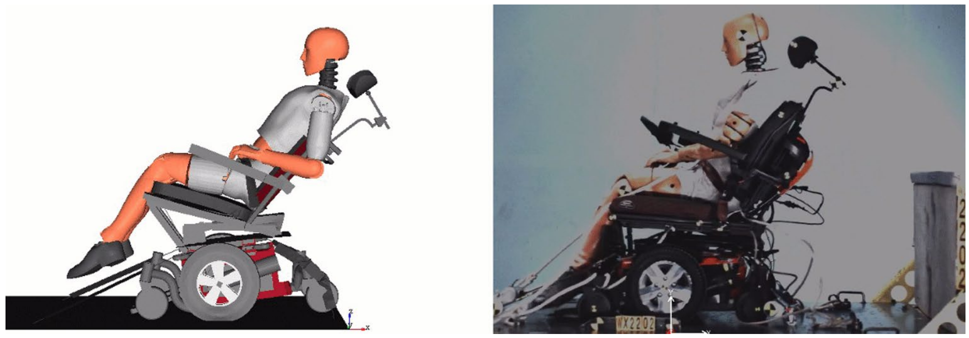


Figure 71. Peak excursion comparison of FE model of power wheelchair secured by commercial 4-point strap tiedowns in rear impact test (WX2204).

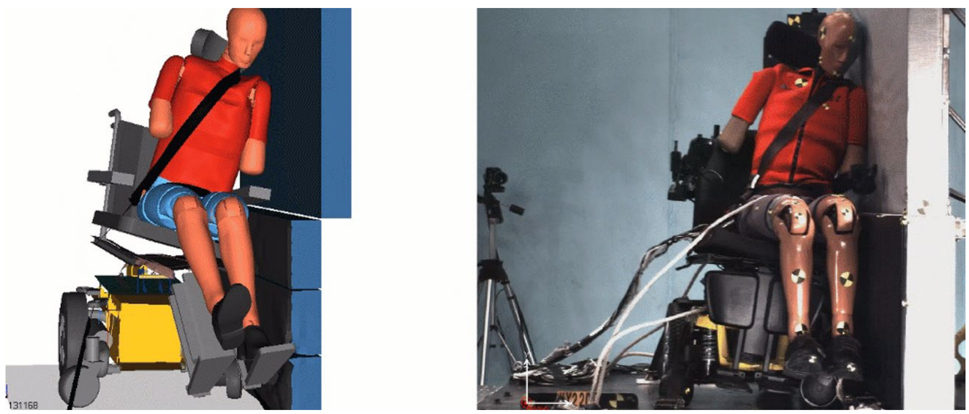


Figure 72. Peak excursion comparison of FE model of power wheelchair secured by commercial 4-point strap tiedowns in nearside impact test (WX2202).

Power Wheelchair

Details on the development and validation of the power wheelchair are included in Appendix C, so it can be included with the model download files as a standalone document.

Manual Wheelchair

Details on the development and validation of the manual wheelchair are included in Appendix D, so it can be included with the model download files as a standalone document.

Discussion

This project developed test procedures for evaluating wheelchairs, WTORS, and vehicle wheelchair stations under side impact test conditions. Following the practice used in current voluntary wheelchair tiedown and WTORS standards, we prioritized evaluation of product integrity, wheelchair and occupant movement and acceptable post-test position of the ATD rather than traditional IARVs. We did measure IARV's, and they were well below recommended thresholds in all tests with commercial products. Previous research efforts indicate that it should be reasonable to use standard IARVs when performing testing and simulations of occupant protection systems designed for integrated wheelchair stations in vehicles.

Throughout this project, we balanced the need to simulate a realistic side impact loading condition, with the need to preserve the essential wheelchair features and functions essential to activities of daily living and the need to minimize the mass of manual wheelchairs, highly prioritized by wheelchair users. As a result, the loading pulse used is based on side impact test data collected on larger vehicles that can be modified for wheelchair use, rather than the side impact testing pulse included in FMVSS No. 213, based on several smaller vehicles as a worst case condition. In addition, we tried to harmonize with existing voluntary standards as much as possible to provide cost effective testing options for wheelchair and WTORS manufacturers. Because the standards are voluntary, we had concerns that a complicated procedure would not be accepted by manufacturers. This led us to use a static deformed wall rather than an intruding wall configuration. However, we believe our approach using modeling to demonstrate a similar level of loading and timing showed that the simpler strategy is suitable.

Our test procedures include different strategies for positioning seatbelts and the wheelchair, depending on the product type tested. For developing integrated wheelchair stations, we provide guidance on how to locate the wheelchair within a station, how to position four-point strap tiedowns according to best practice, and recommendations for where belt anchors should be placed relative to the station. For wheelchair and WTORS testing, we wanted to avoid unrealistic head contacts with the D-ring fixture. As a result, we begin by raising the D-ring mount to be 50 mm above the ATD head when seated in the wheelchair. To provide consistent interaction with the ATD across conditions, we then shift the D-ring anchor so the shoulder belt is located at a consistent location relative to the ATD centerline and clavicle. When testing wheelchairs under side impact, we designed the test fixture with an adjustable wall to allow a consistent 50 mm gap between the wheelchair and wall during setup. This allows consistent loading of each wheelchair during the test.

Our testing and modeling efforts in this project used the ES-2re. However, some preliminary models showed that the H3 midsized male ATD had similar kinematics. Since the proposed test procedures do not assess IARVs in the requirements, it may be helpful to investigate whether the H3 50th ATD produces similar requirements; wheelchair or WTORS manufacturers may already have this ATD and may hesitate to purchase an additional ATD for use in side impact evaluations. It would also be useful to evaluate whether there would be any issues testing pediatric wheelchairs with the procedure using child ATDs, as a previous project (Hu et al. 2023) identified some challenges in using the H310YO and 6YO under side impact conditions.

While the focus of this project was side impact testing, we also ran tests under several rear impact conditions to collect data for validating the FE models under this type of loading. An unexpected outcome was the failure of the heavy duty UDIG anchor fixture in test WX2203. The original research and development efforts that led to inclusion of the UDIG specification in voluntary standards did not involve rear impact testing. Given the renewed interest in using UDIG wheelchair securement systems in ADSV to allow passengers to dock independently when no driver is available, future research could investigate how UDIG anchors and attachments perform in rear impact. These tests also demonstrated the limited capabilities of wheelchairs to appropriately contain the occupant in rear impact due to the low strength of the back and head supports. Research to investigate vehicle-based solutions for providing occupant protection in rear impacts for people using integrated wheelchair stations would also be valuable.

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Appendix A: Preliminary Nearside Impact Test Results

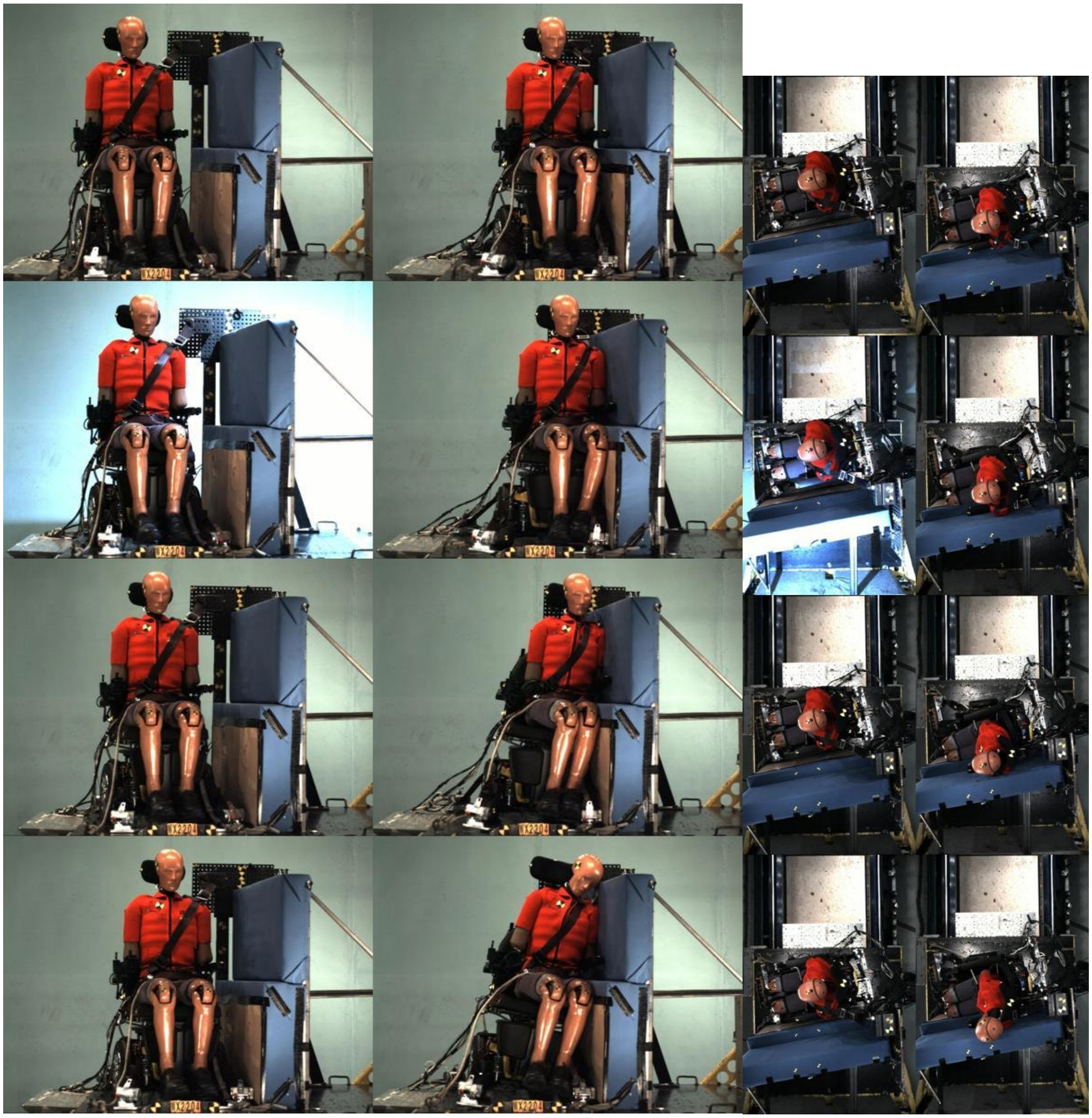


Figure 73. WX2204 side impact test of power wheelchair secured by 4-point strap tiedown.

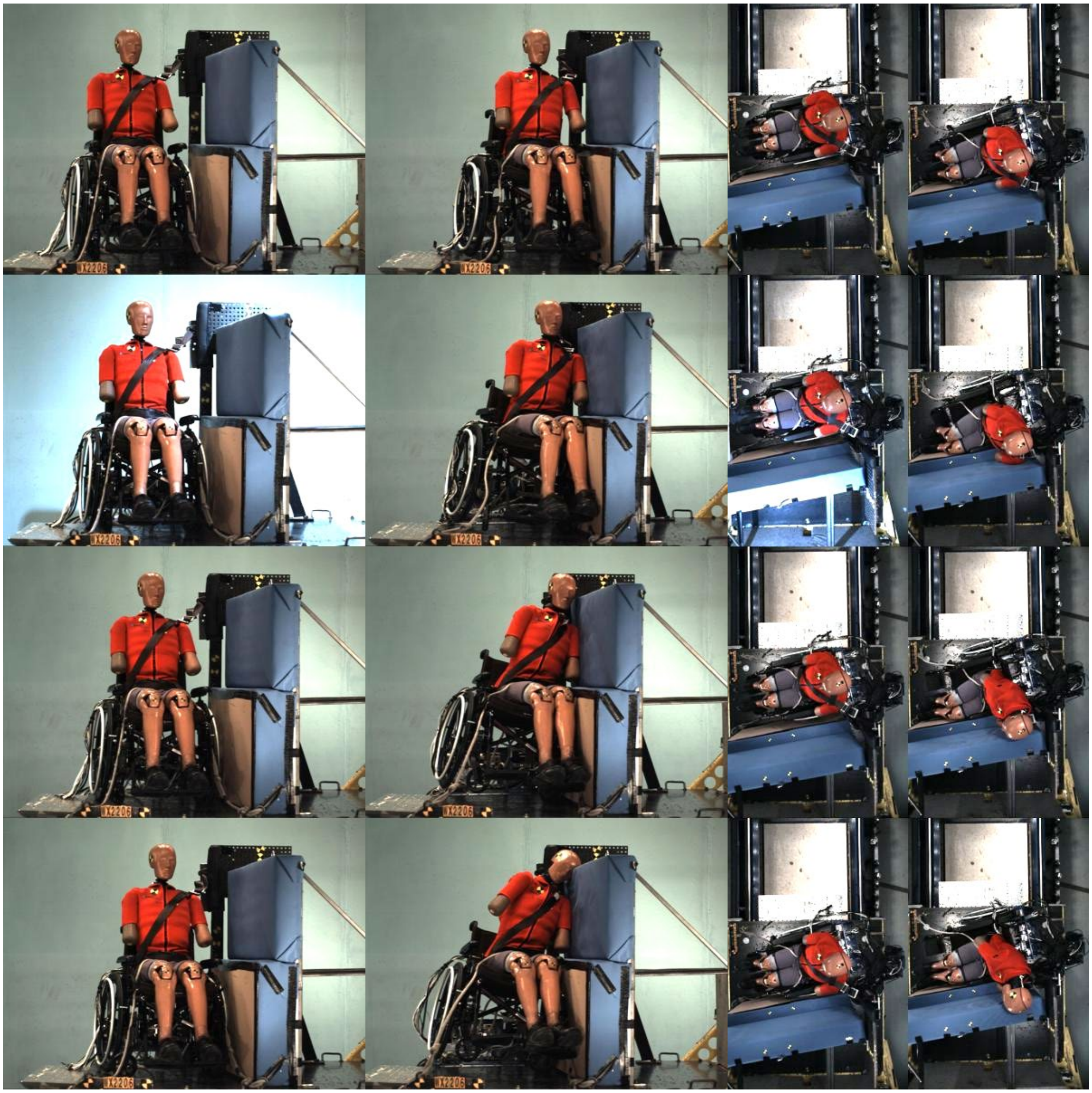


Figure 74. WX2206 side impact test of manual wheelchair secured by UDIG.

Appendix B: Surrogate Wheelchair Base (SWCB) /Surrogate Wheelchair for Side Impact (SWCSI) Models, including UDIG attachments

A finite element (FE) model of a the Surrogate Wheelchair Base (SWCB) included in RESNA Standard WC-20, shown in Figure 104, was created as part of project funded by the National Highway Traffic Safety Administration to develop side impact test procedures for evaluating wheelchairs, wheelchair tiedowns and occupant restraint systems (WTORS), and vehicle occupant protection systems for wheelchair seating stations. The project also developed a modified version of the SWCB, the Surrogate Wheelchair for Side Impact (SWCSI), shown in Figure 76. The project deliverables include publicly available FE models of these fixtures that could be used to improve safety for people who travel while seated in their wheelchairs.

Figure 75. Generic seats used with SWCB, with and without cushion.

Figure 76. Photo of the SWCSI, modified from the SWCB to includes different wheels and attachment bolts, a shifted lap belt anchor location, a left armrest, and a contoured seat cushion.

The SWCB is designed to evaluate performance of different types of seating systems (including different widths). For the purposes of the project to create a generic surrogate for a wheelchair, we built the FE model using a generic planar aluminum seat pan and back support, each with a basic foam cushion pad 50 mm thick. Figure 77 shows the SWCB geometry, while Figure 78 shows the FE mesh. The SWCB model uses deformable shell elements for the steel frame of the chair. It includes deformable hexahedral elements at the seatback canes and front casters that are replaced after each test to improve the fidelity to real wheelchair response. The seat pan and back support are each modelled with a plate and a solid cushion with foam material properties that are similar to a typical vehicle seat cushion. The tires are modelled using deformable rubber-like shell elements with a simple pressure-volume airbag definition to represent the tire pressure. Our past research projects developed a UDIG-compatible attachment for use with the SWCB, with the geometry and mesh depicted in Figure 79.

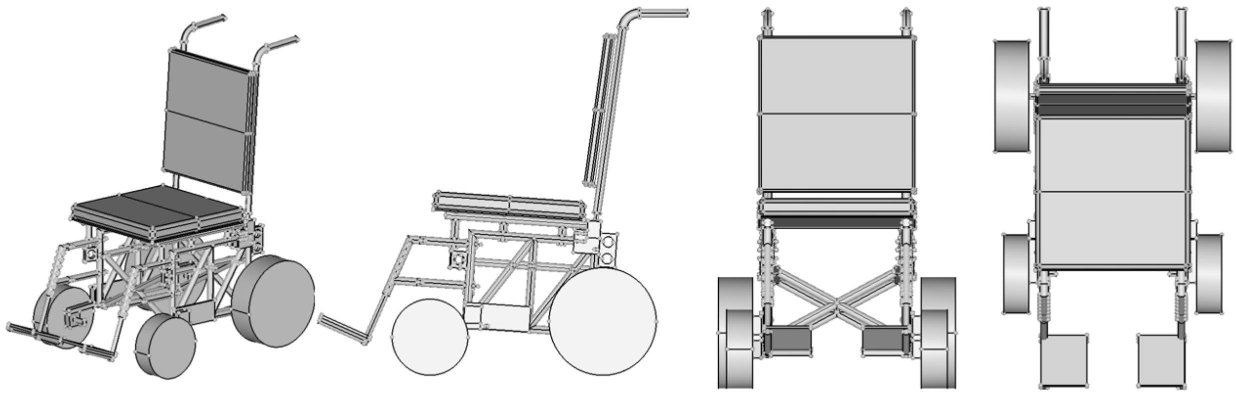


Figure 77. SWCB geometry, geometry/mesh overlay, and model mesh.

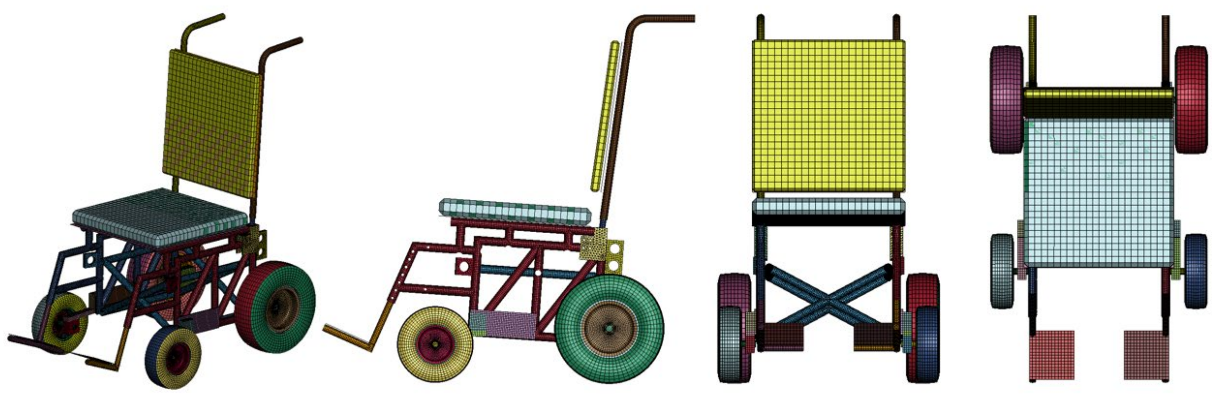


Figure 78. SWCB geometry, geometry/mesh overlay, and model mesh.

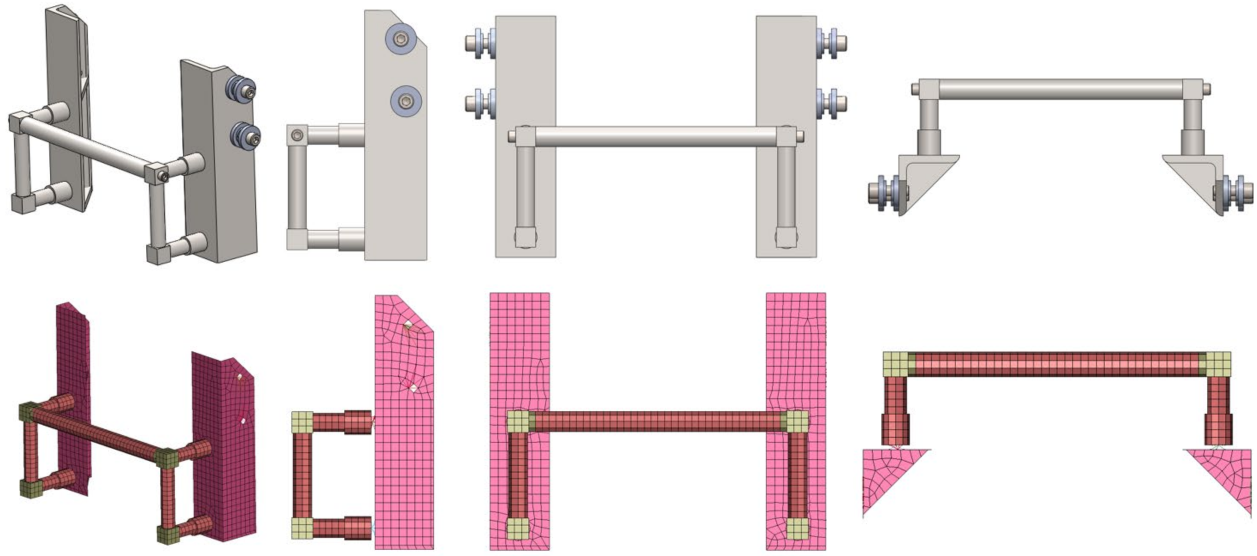


Figure 79. Geometry and FE model of surrogate UDIG attachment for SWCB

The SWCSI model includes modifying the seat, and adding an armrest. Details of the geometry and FE model for the seat cushion are shown in **Error! Reference source not found.**, while the armrest geometry and model are shown in Figure 80.

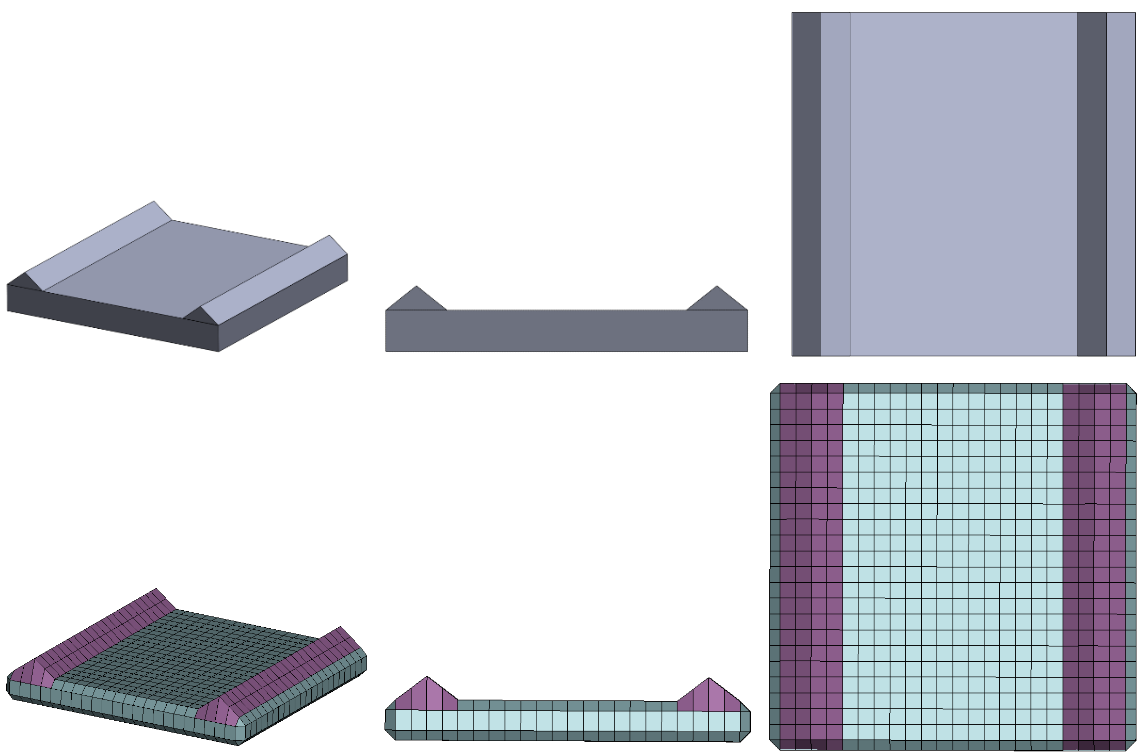


Figure 80. Geometry and FE model of alternative cushion for SWCSI.

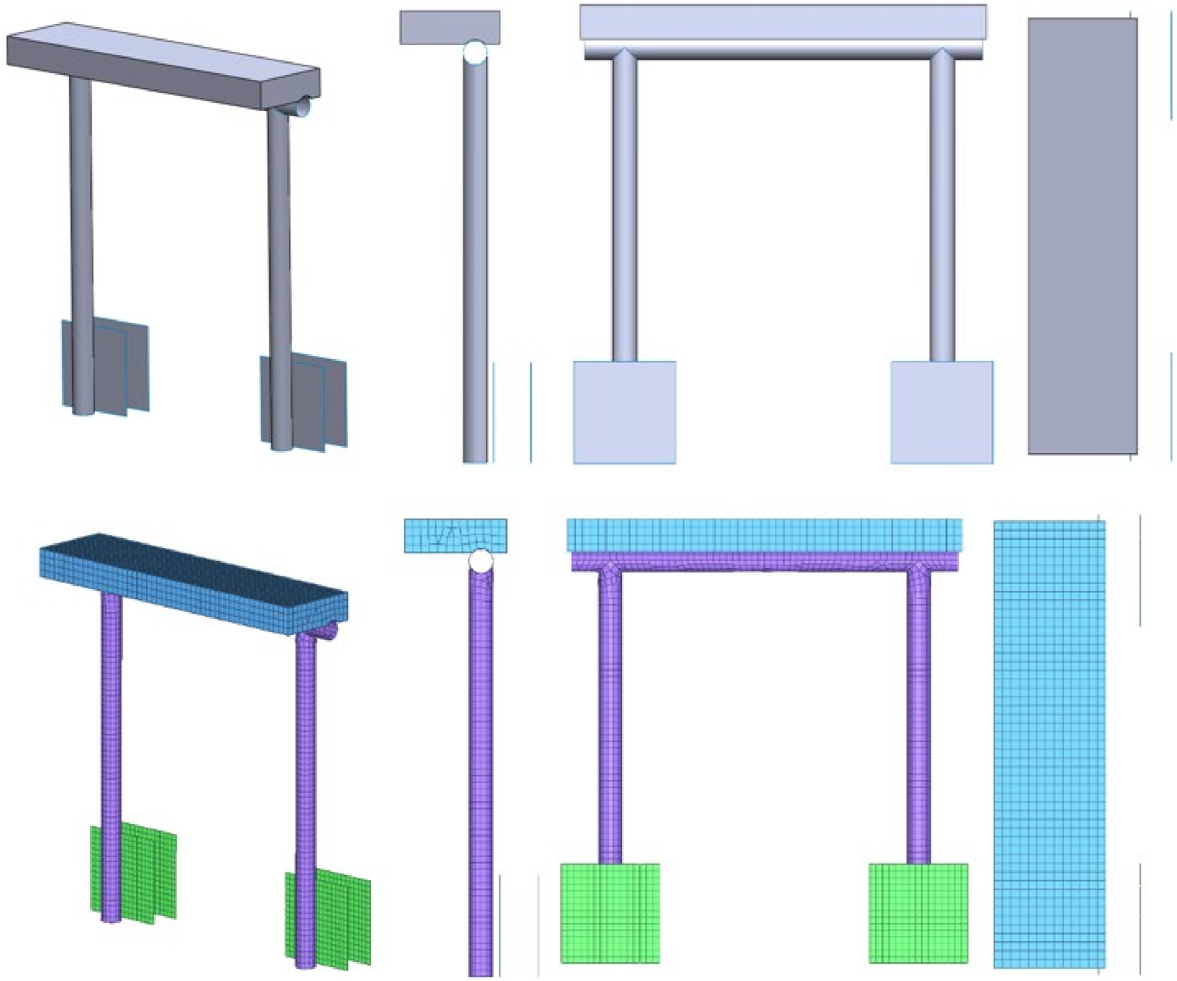


Figure 81. FE model of armrest attachment for SWCSI.

Figure 82 compares the physical and model masses for the SWCB and SWCSI model components, showing good agreement. The tests listed in Figure 83 show the conditions used to validate the models. Test WC1602 was used to validate both simple and detailed models of the SWTORS. CORA scores for resultant head and chest acceleration are provided in Figure 84. (They are not provided for test QS1301, as the test used the SWC and the model used the SWCB.)

Figure 85 through Figure 103 show comparisons of kinematics and signals for each pairing of model and validation test. Detailed illustrations comparing deformation of commercial docking hardware are also included in Figure 87.

Figure 82. Comparison of physical and model masses for SWCB/SWCSI model components

Component	Physical mass (kg)	Model mass (kg)
Main structure	37.38	36.76
Wheels	12.08	11.90
Seating System: SWCB	6.94	5.90
Seating System: SWCSI	7.02	5.98
Armrest	2.62	2.77
Total: SWCB	56.80	54.6
Total: SWCSI	59.51	57.4

Figure 83. Tests used to Validate SWCB/SWCSI

Test ID	**Direction**	**WC**	**Tiedown**	**Occupant Restraint**	Mean accel (g)	Delta V (km/h)
QS1301	Front	SWC	Qstraint docking	Commercial Vehicle-mounted	-21.8	49.7
AW2102	Front	SWCB	UDIG	Vehicle mounted optimal 3PB	-22.4	51.4
WC1602*	Front	SWCB	SWTORS	WC-mounted lap belt and shoulder belt	-20.2	48.1
WX2205	Nearside	SWCB	Qstraint docking	WC-mounted lap belt and shoulder belt	-10.6	21.0
WX2207	Nearside	SWCB	SWTORS	WC-mounted lap belt and shoulder belt	-10.1	22.1
WX2306	Nearside (center)	SWCSI	SWTORS	WC-mounted lap belt and shoulder belt		

WX2203	Rear	SWCB	UDIG	WC-mounted lap belt only	-13.9	31.3

* Used to validate both detailed and simplified versions of the SWTORS

Figure 84. CORA Scores for SWCB/SWCSI model components

Test ID	**Direction**	**WC**	**Tiedown**	**CORA Head Acc**	**CORA Chest Acc**
AW2102	Front	SWCB	UDIG	76.4%	77.7%
WC1602	Front	SWCB	Simple SWTORS	79.2%	82.4%
WC1602	Front	SWCB	Detailed SWTORS	92.4%	95.7%
WX2205	Nearside	SWCB	Qstraint docking	70.5%	73.6%
WX2207	Nearside	SWCB	SWTORS	67.3%	63.8%
WX2306	Nearside (center)	SWCSI	SWTORS	75.3%	80.7%
WX2203	Rear	SWCB	UDIG	71.3%	52.5%

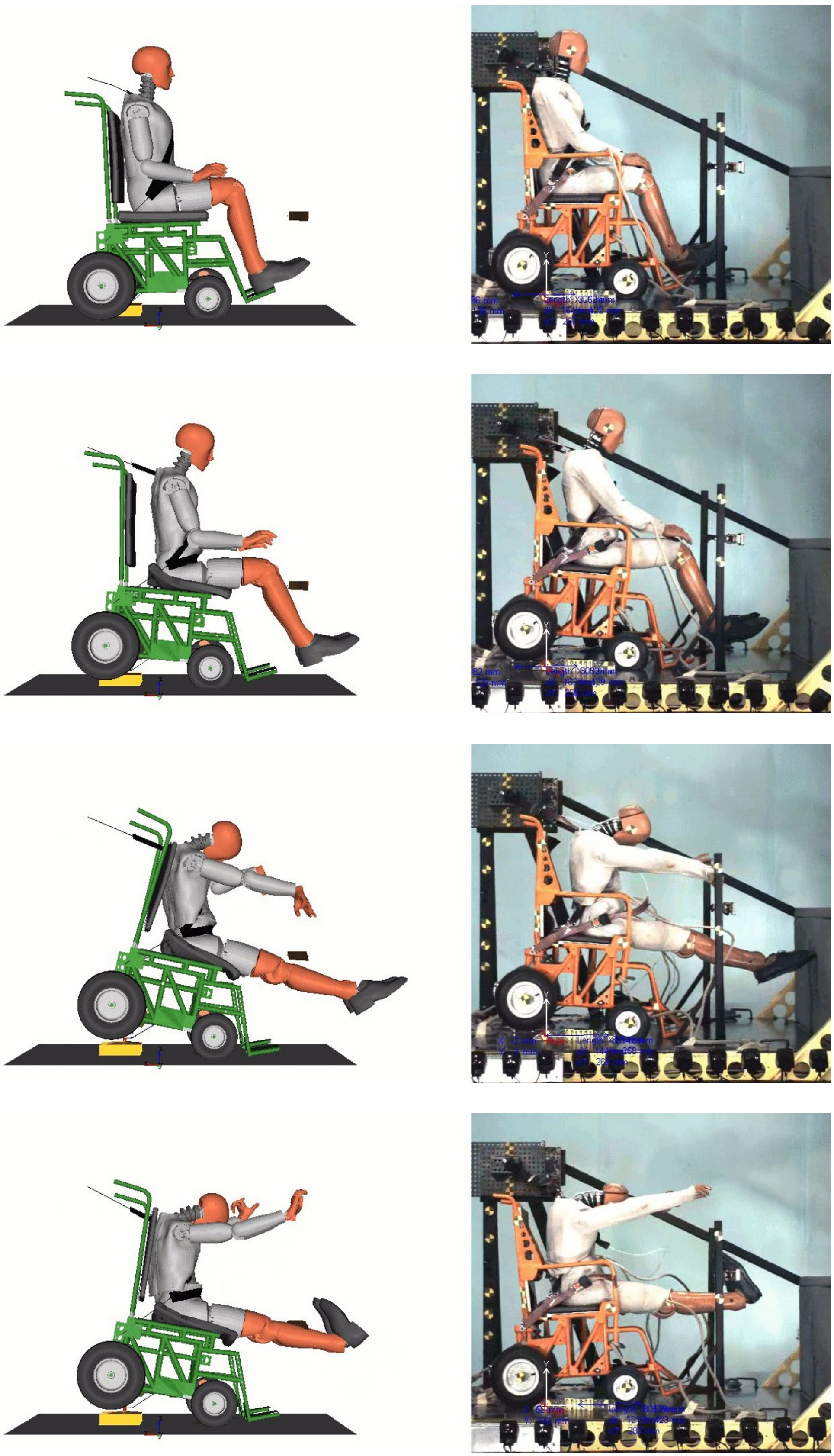


Figure 85. Comparison of model and test kinematics for SWCB/SWC, secured by traditional docking, under frontal impact, at 30, 60, 90, 120 ms.

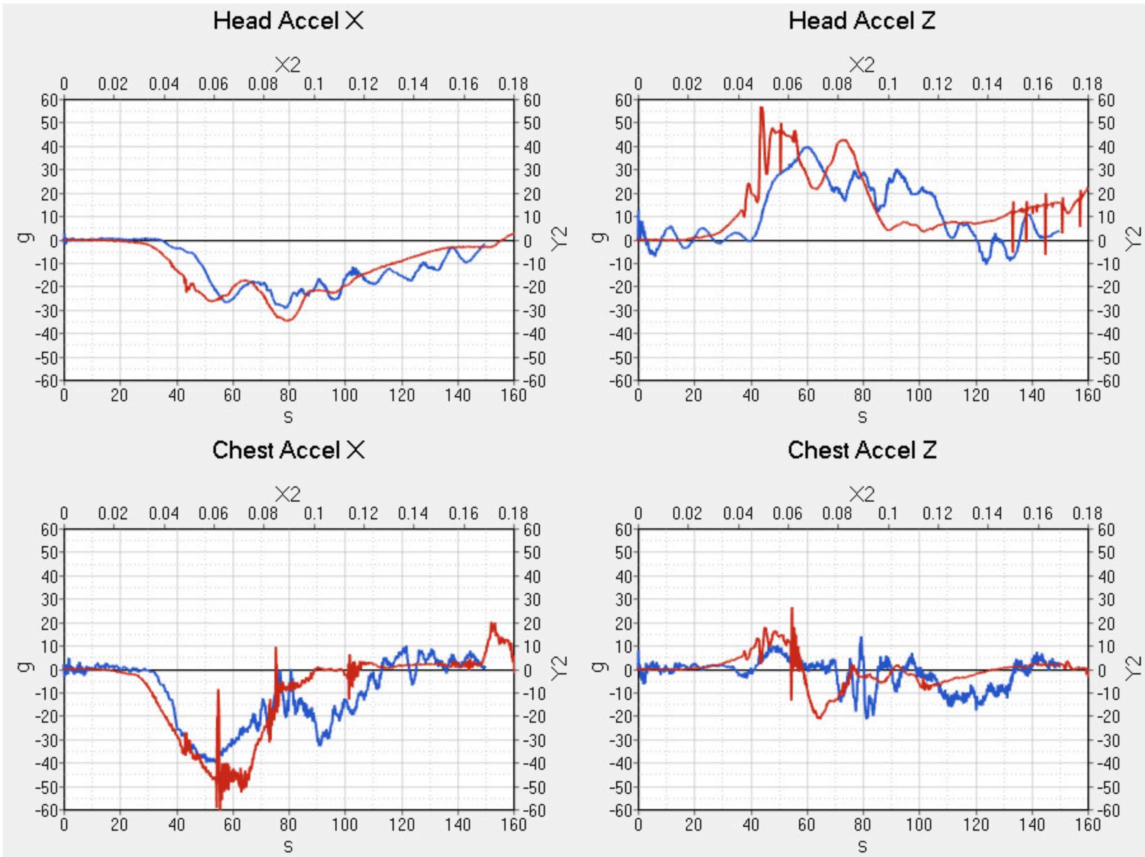


Figure 86. Comparison of test (red) and model (blue) SWCB/SWC, secured by traditional docking,, under frontal impact.

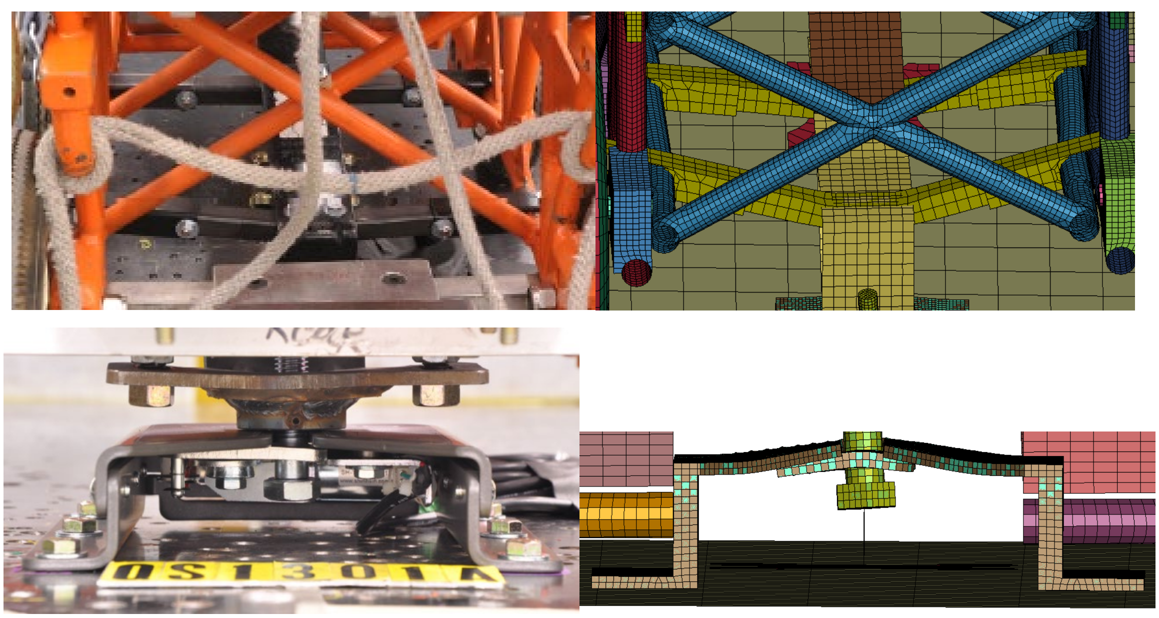
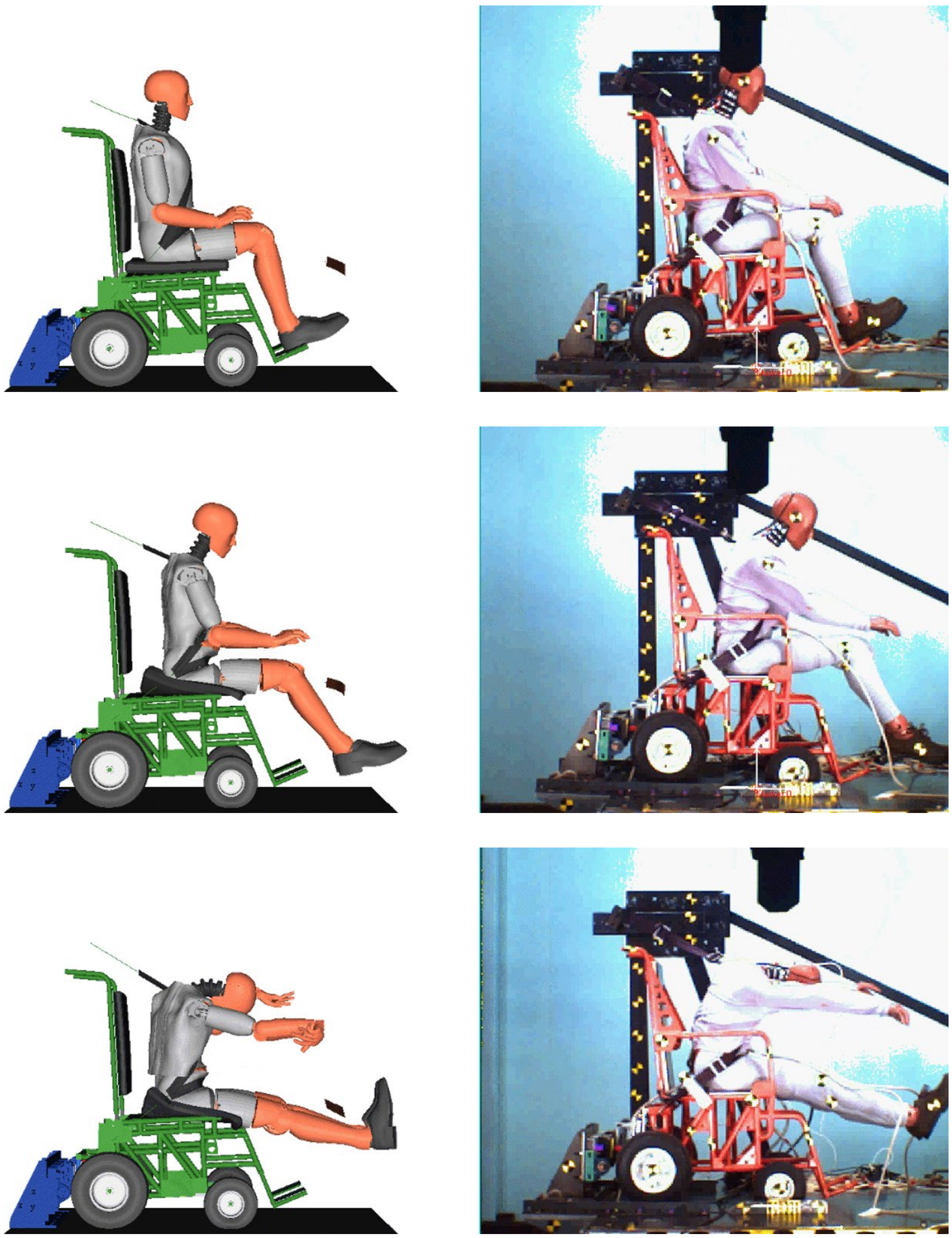


Figure 87. Comparison of anchor deformation in test and model under frontal impact.



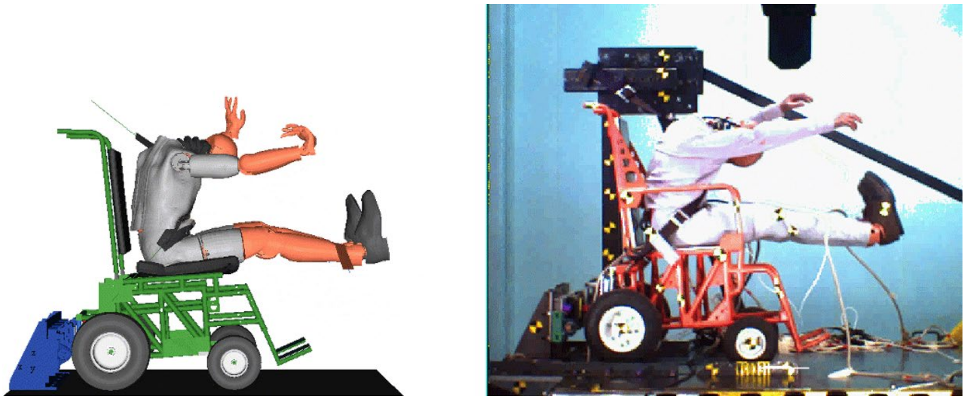


Figure 88. Comparison of model and test kinematics for SWCB, secured by UDIG, at 30, 60, 90, 120 ms.

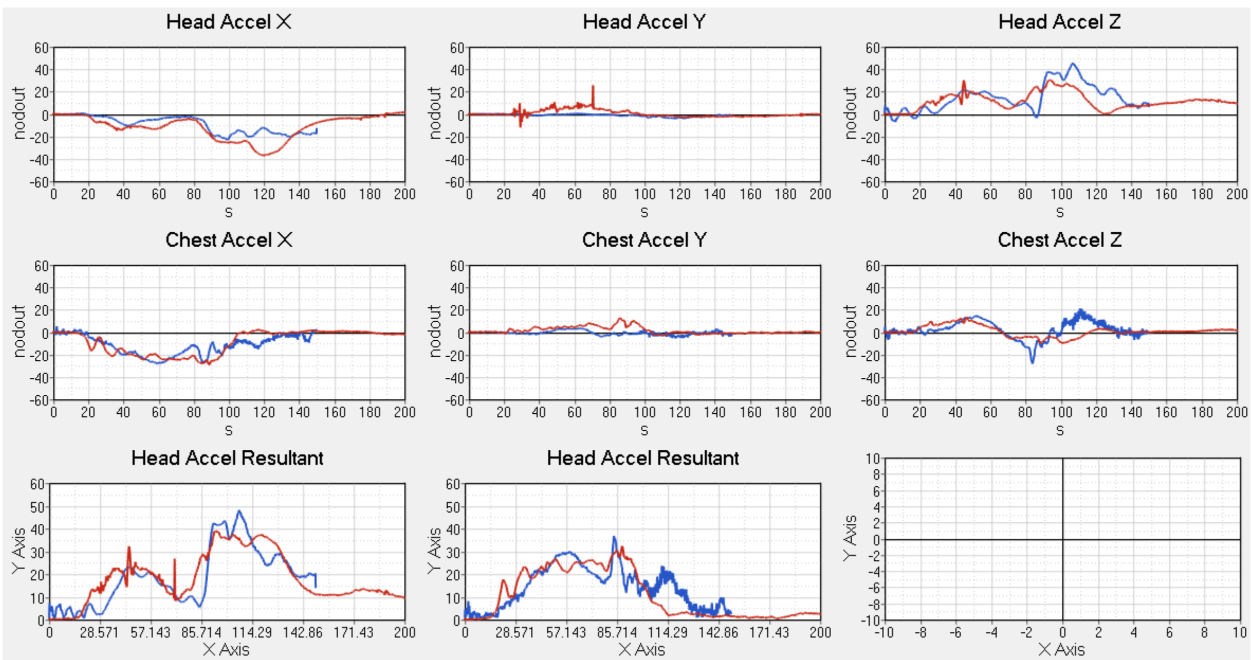


Figure 89. Comparison of test (red) and model (blue) data for SWCB, secured by UDIG, under frontal impact.

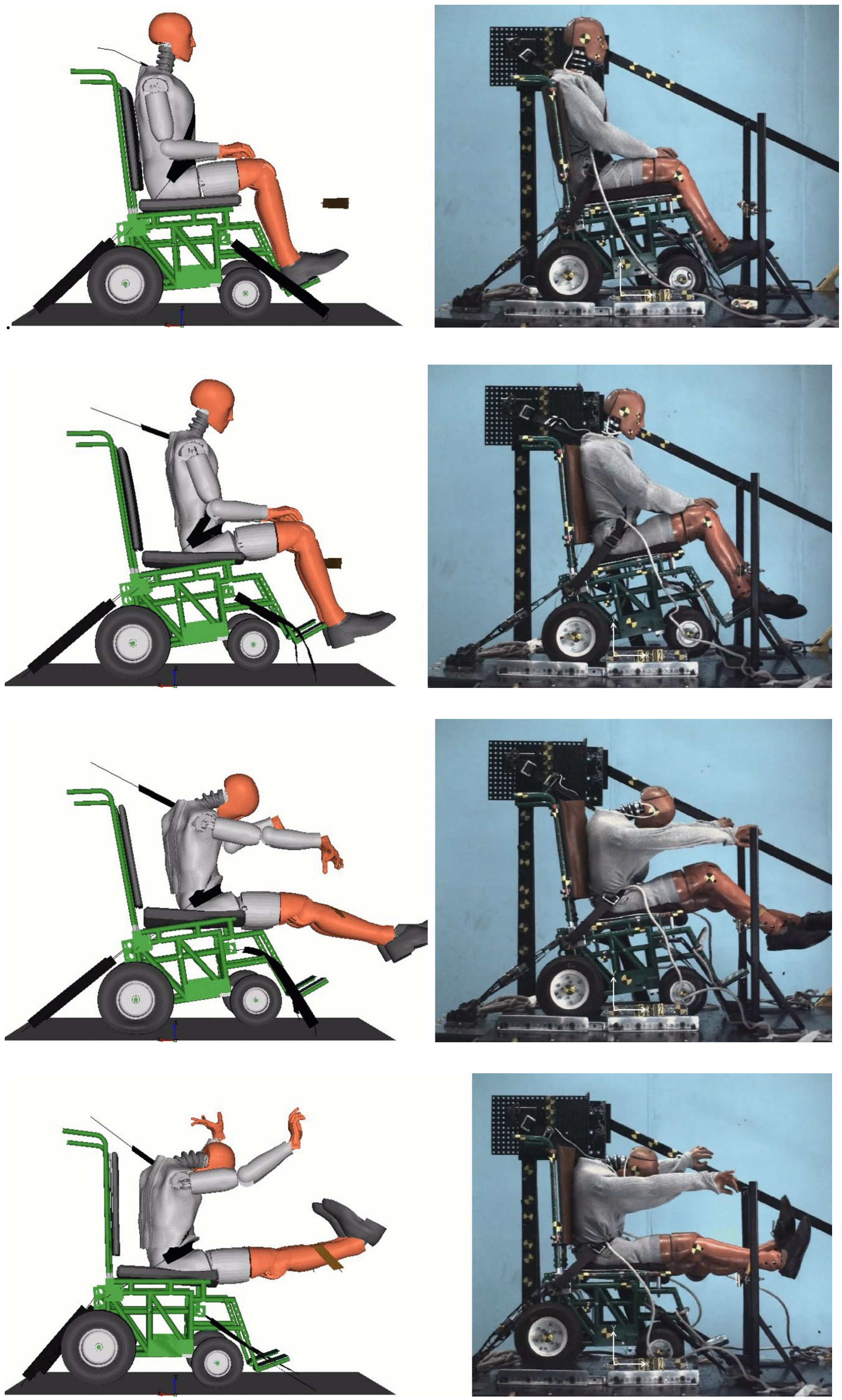


Figure 90. Comparison of model and test kinematics for SWCB with simple SWTORS, under frontal impact, at 30, 60, 90, 120 ms.

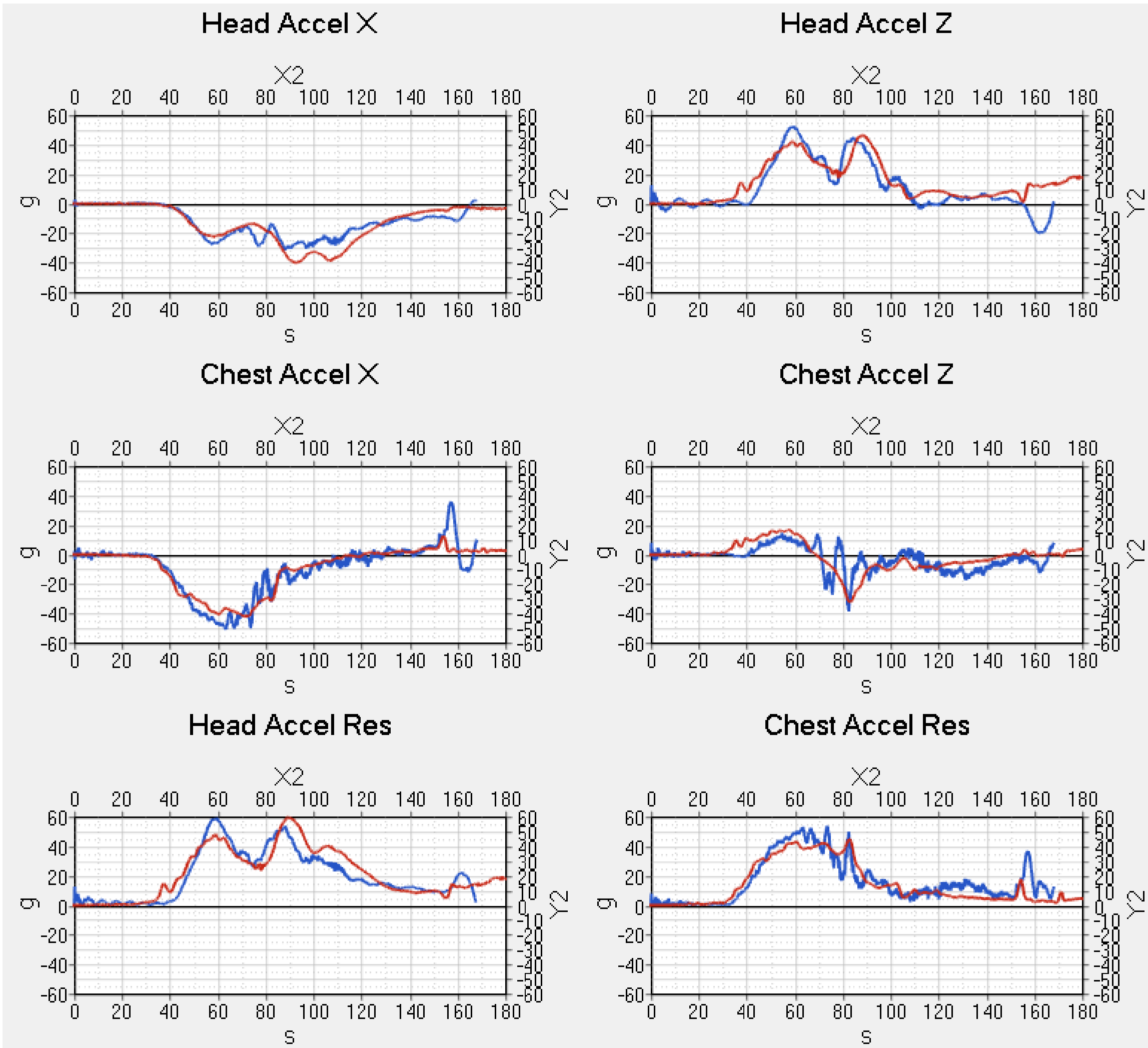


Figure 91. Comparison of test (red) and model (blue) data for SWCB with simple SWTORS, under frontal impact

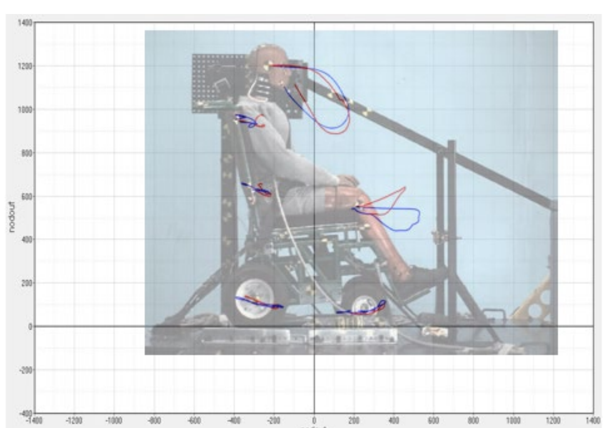
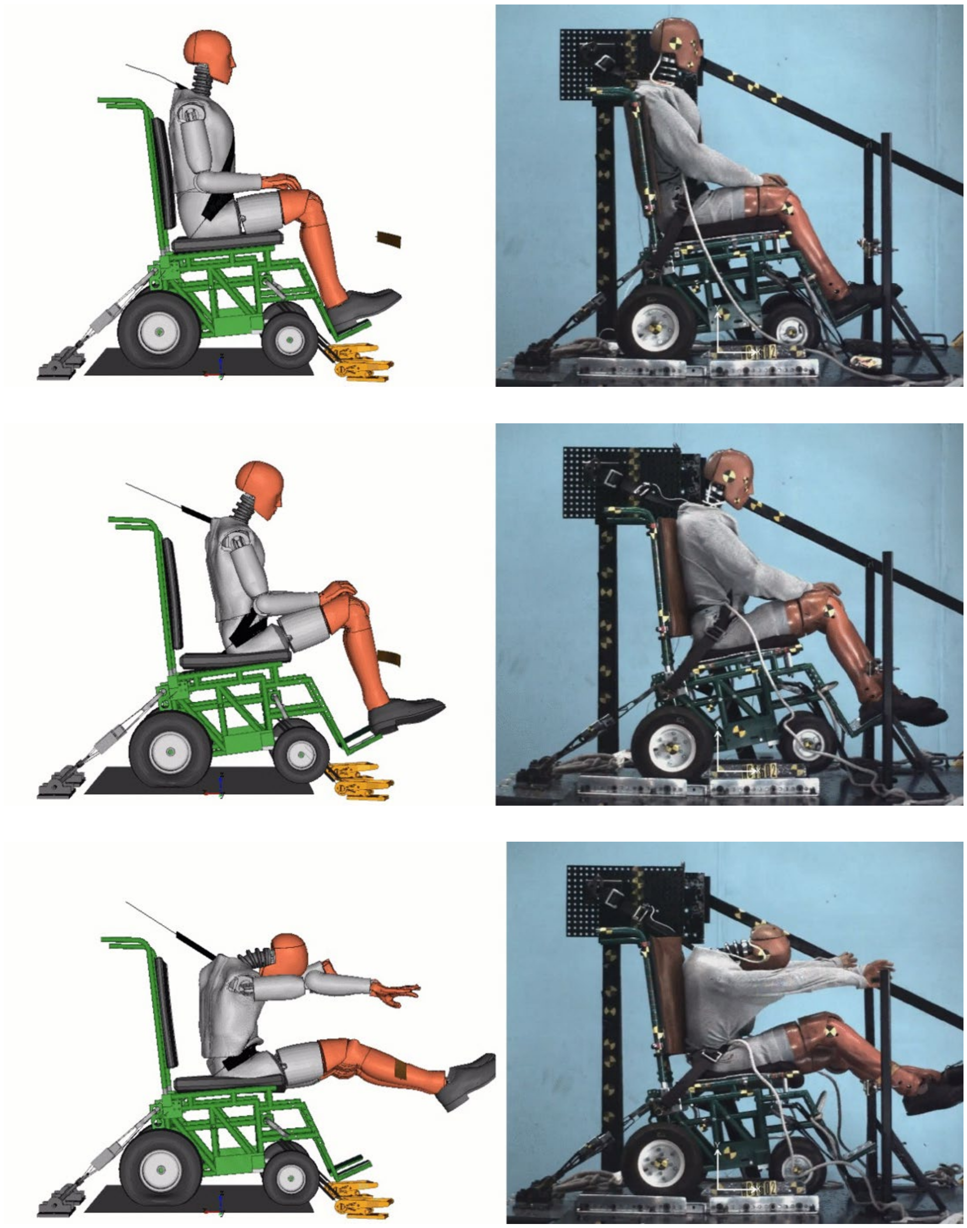


Figure 92. Comparison of test (red) and model (blue) excursion data for SWCB with simple SWTORS, under frontal impact.



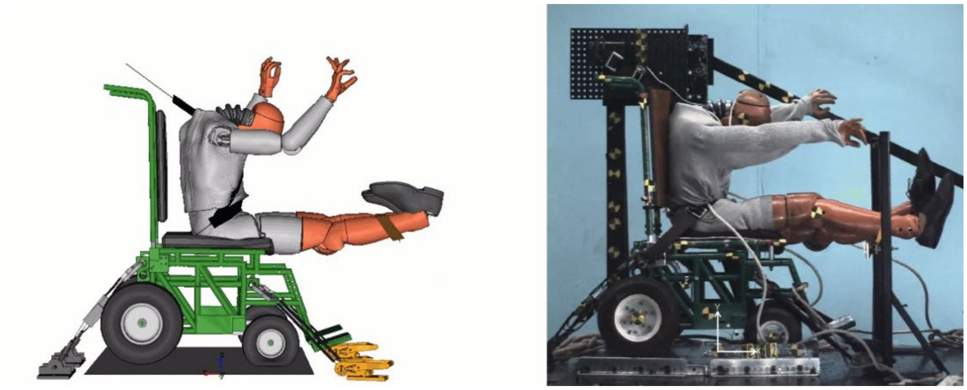


Figure 93. Comparison of model and test kinematics for SWCB with detailed SWTORS, under frontal impact, at ~ 30, 60, 90, 120 ms.

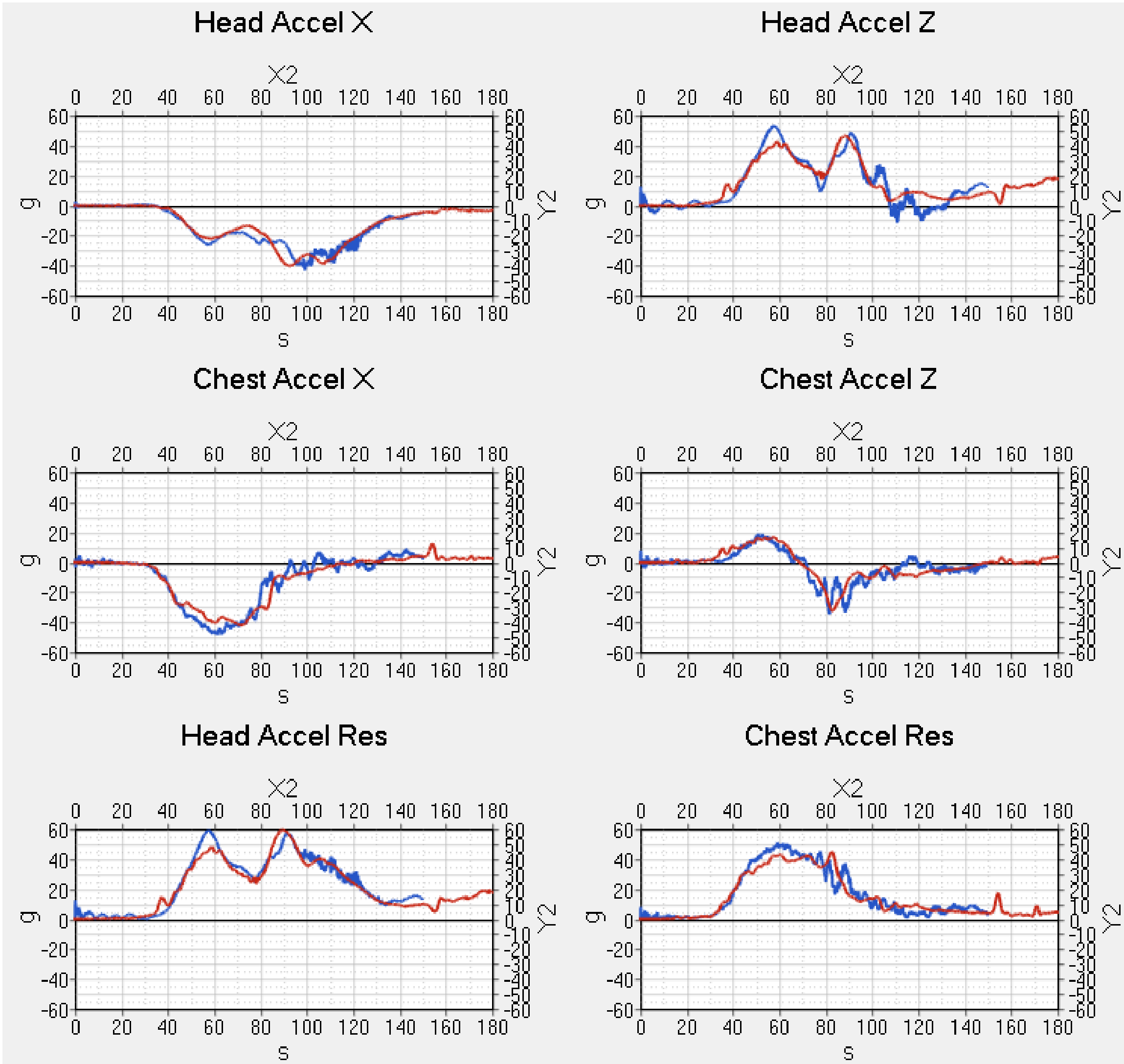


Figure 94. Comparison of test (red) and model (blue) data for SWCB with detailed SWTORS, under frontal impact.

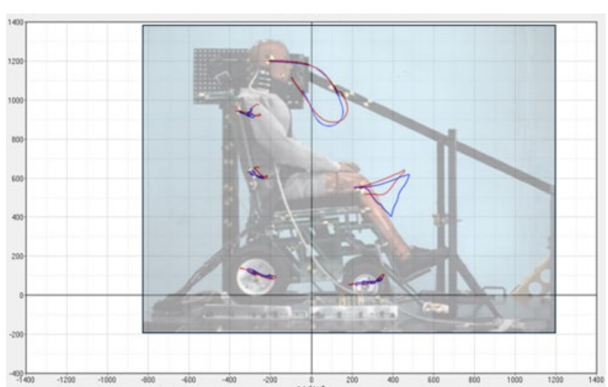


Figure 95. Comparison of test (red) and model (blue) excursion data for SWCB with detailed SWTORS, under frontal impact.

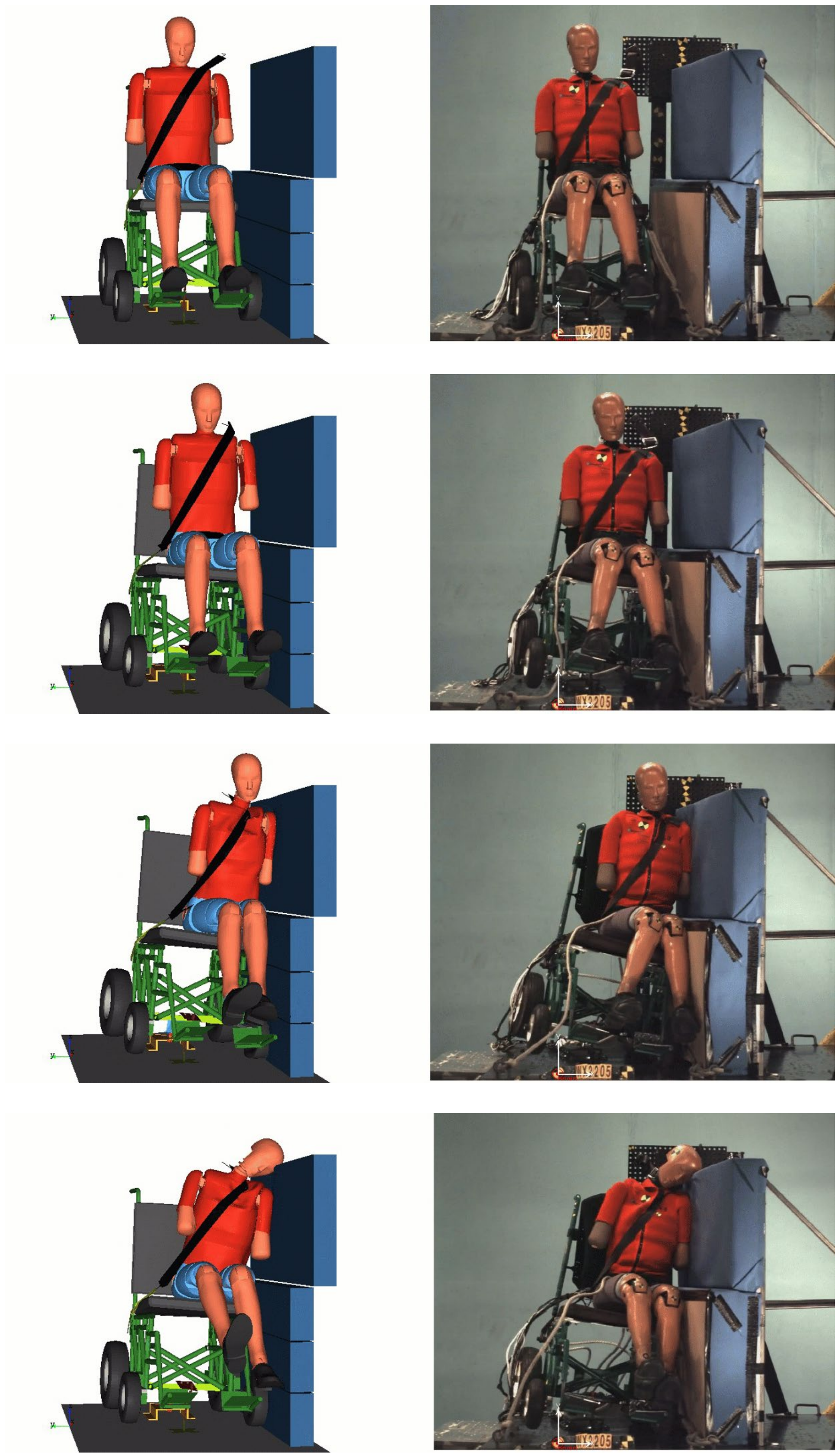


Figure 96. Comparison of model and test kinematics for SWCB with traditional docking, under nearside impact, at 30, 60, 90, 120 ms.

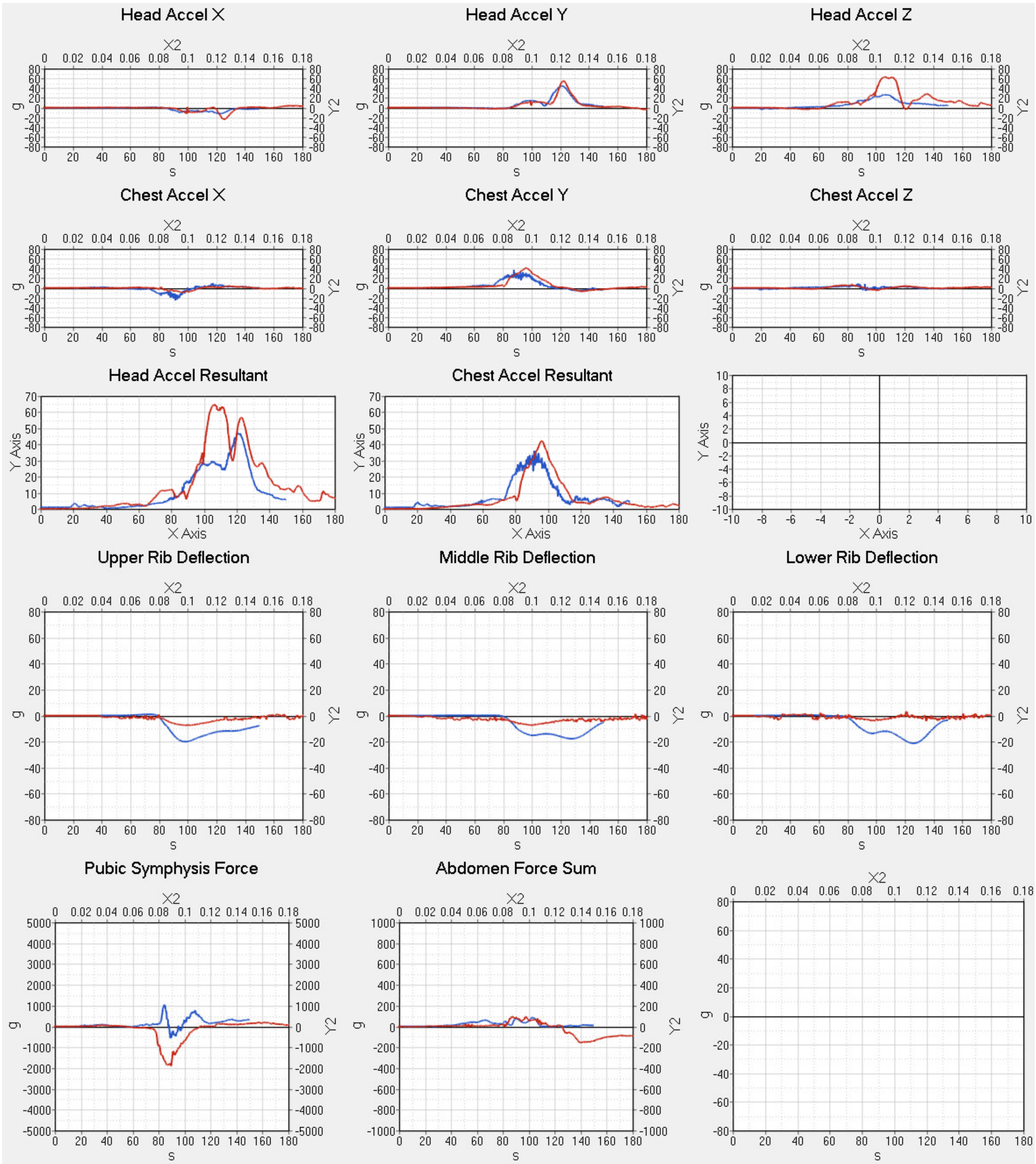


Figure 97. Comparison of test (red) and model (blue) data for SWCB with traditional docking, under nearside impact.

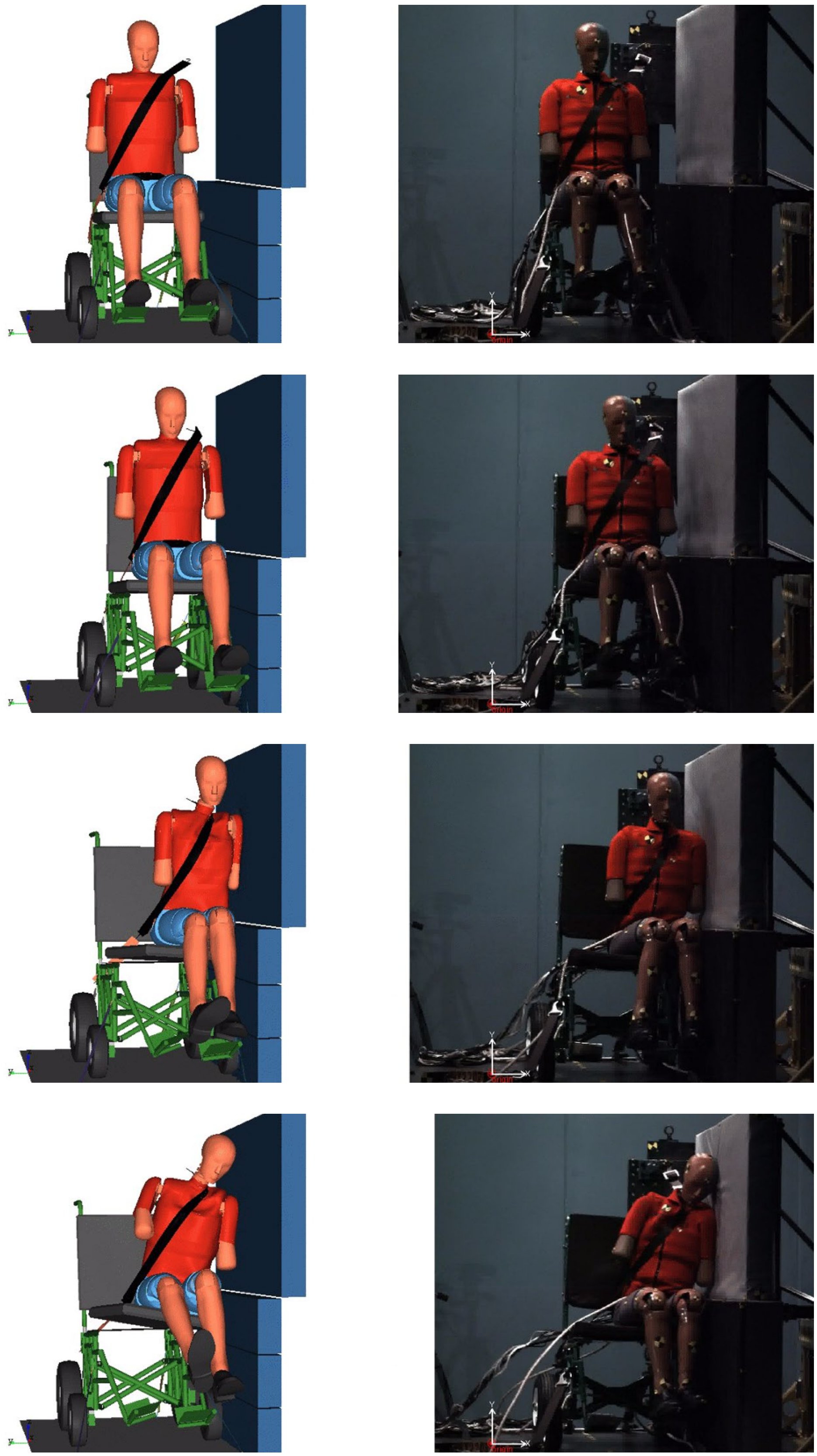


Figure 98. Comparison of model and test kinematics for SWCB with SWTORS, under nearside impact, at ~ 30, 60, 90, 120 ms.

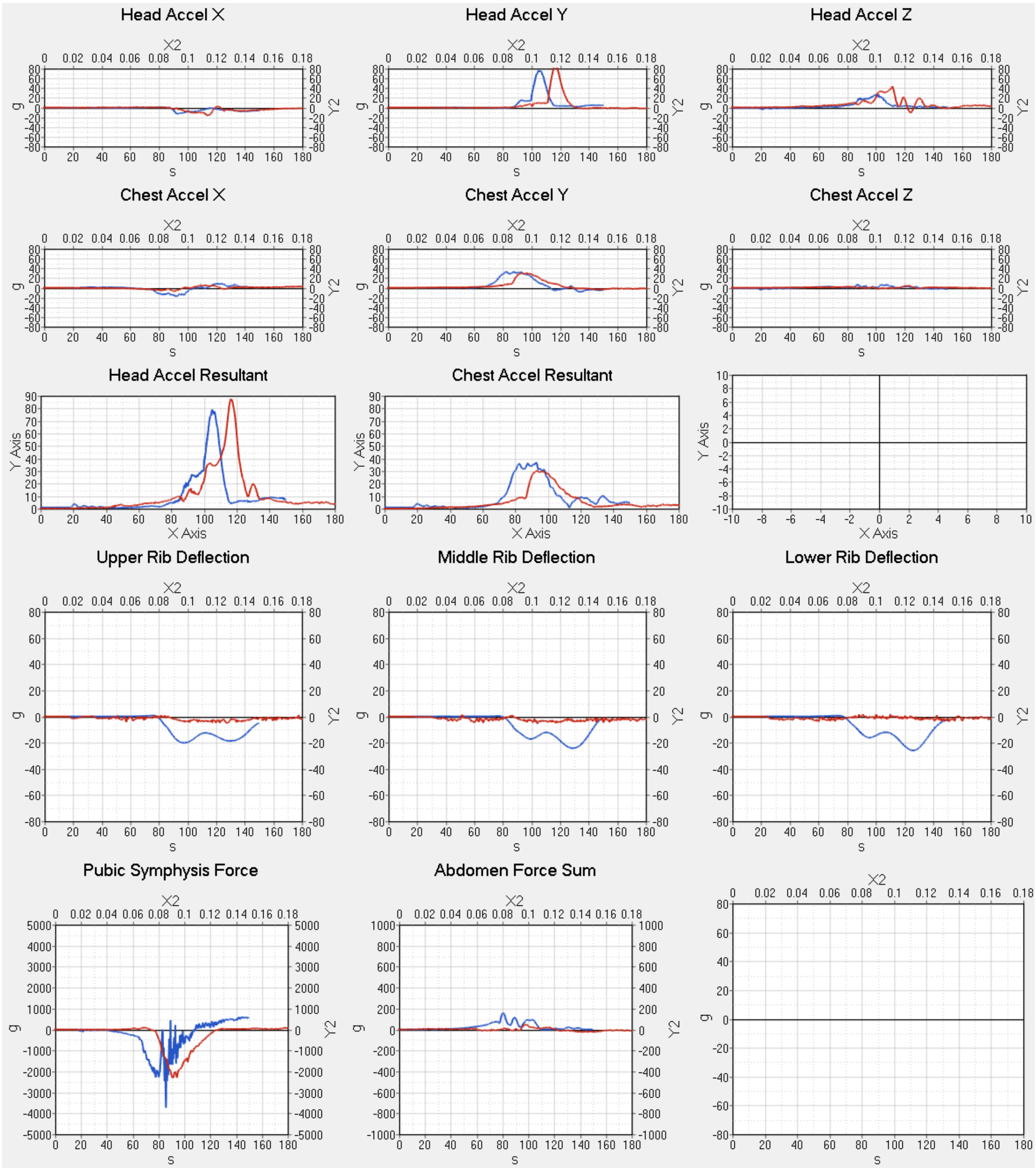


Figure 99. Comparison of test (red) and model (blue) data for SWCB with SWTORS, under nearside impact.

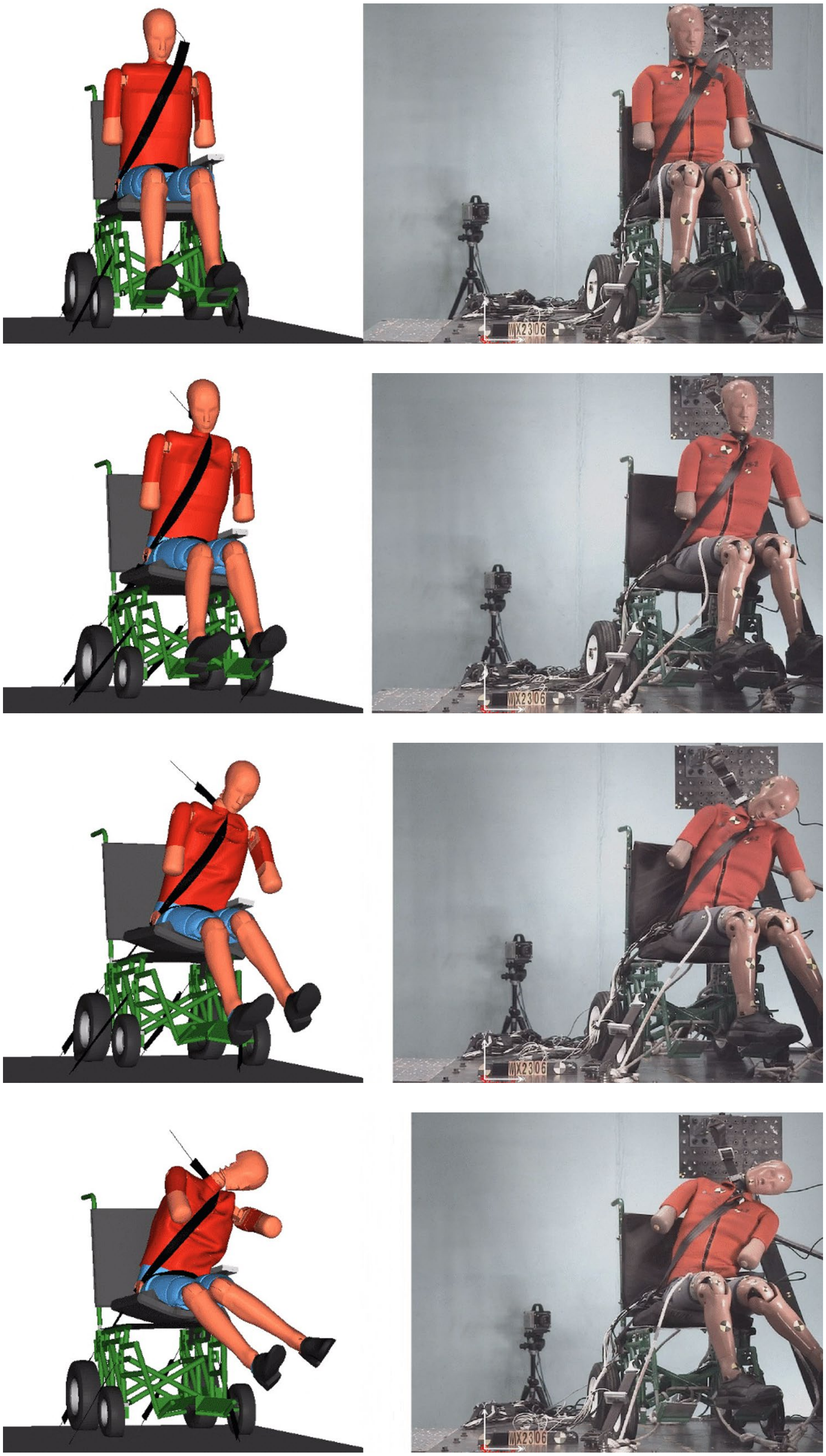

MX2306

Figure 100. Comparison of model and test kinematics for SWCSI with SWTORS, under nearside (center) impact, at 60, 90, 120, 150 ms.

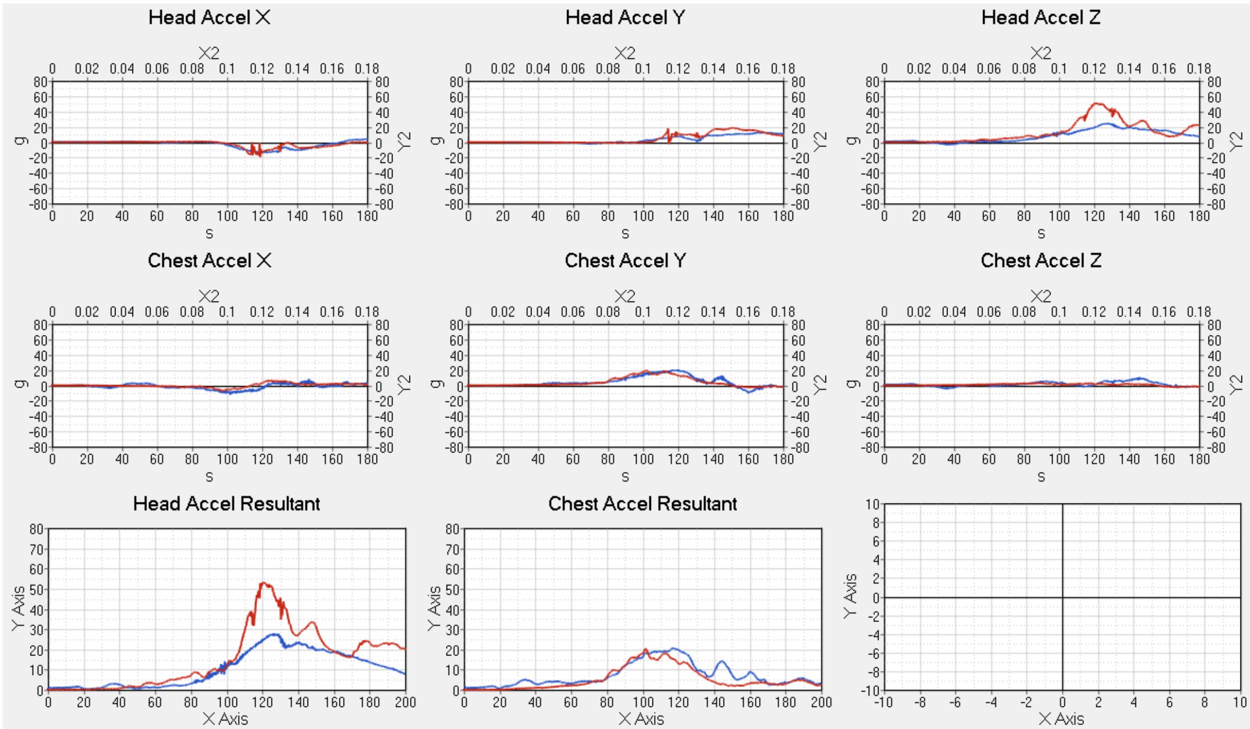


Figure 101. Comparison of test (red) and model (blue) data for SWCSI with SWTORS, under nearside (center) impact.

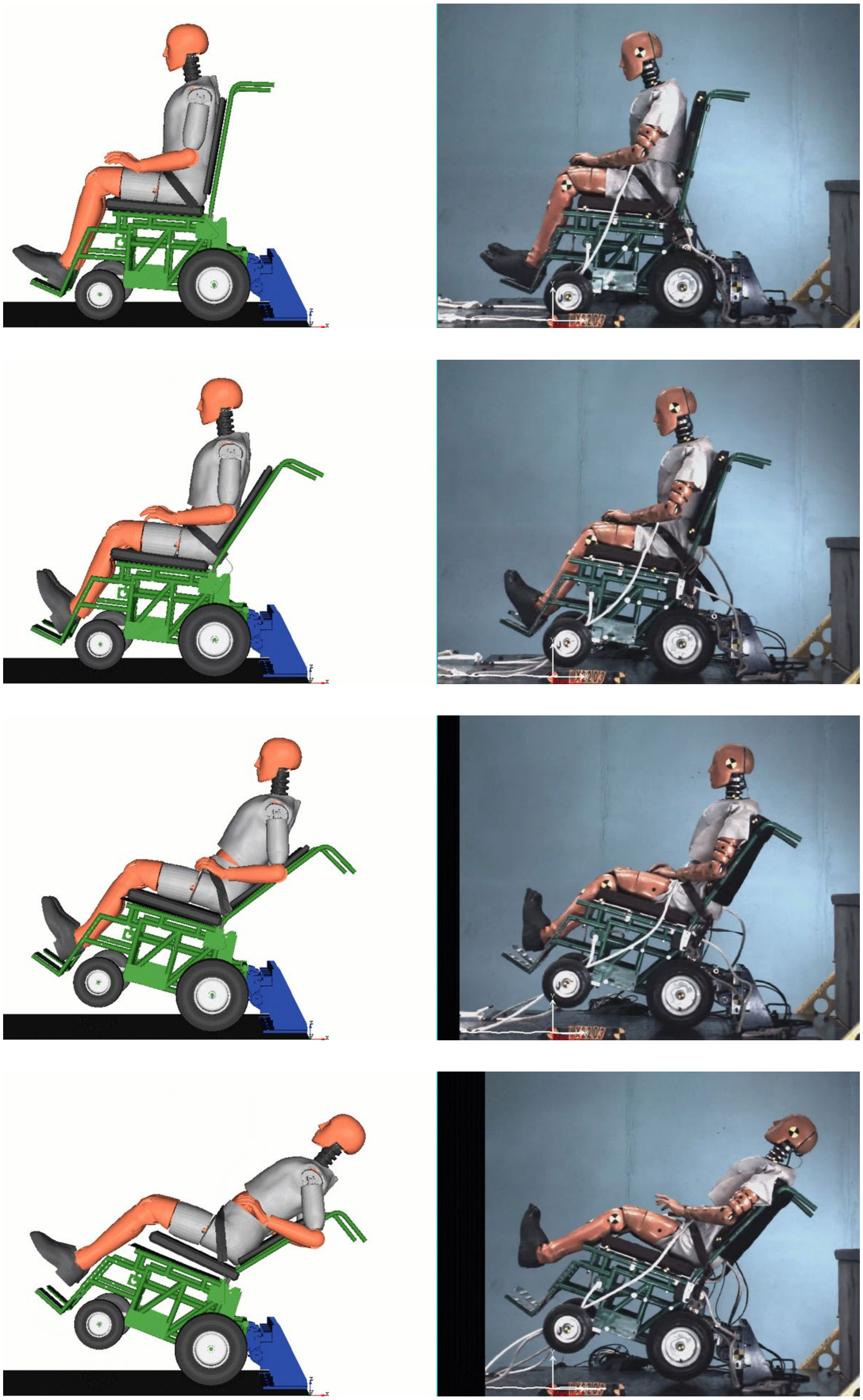


Figure 102. Comparison of model and test kinematics for SWCB with UDIG, under rear impact, at 30, 60, 90, 120 ms.

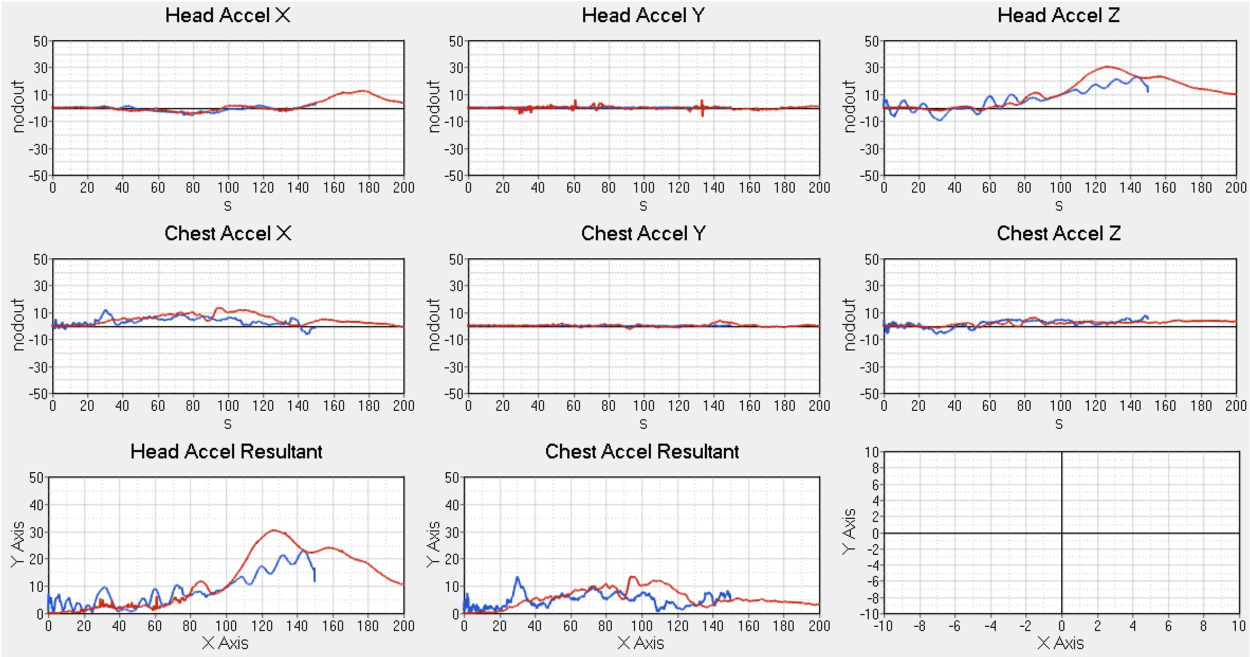


Figure 103. Comparison of test (red) and model (blue) data for SWCB with UDIG, under rear impact.

Appendix C: Power Wheelchair Model

A finite element (FE) model of a Quantum Rehab Q6 Edge 2.0 with Synergy Seating, shown in Figure 104, was created as part of project funded by the National Highway Traffic Safety Administration to develop side impact test procedures for evaluating wheelchairs, wheelchair tiedowns and occupant restraint systems (WTORS), and vehicle occupant protection systems for wheelchair seating stations. The project deliverables include a publicly available FE model of a power wheelchair that could be used to improve safety for people who travel while seated in their wheelchairs. We thank Pride Mobility providing data on the characteristics of the wheelchair spring and damper.

Figure 104. Photo of power wheelchair and labeled components.

Components purchased to assemble this wheelchair (in 2022) were:

- Q6 Edge 2.0 3SP-SS
- NF22 Nano Silica Interceptor 2
- Tru-Balance 3 Power Tilt
- Transit Kit Occupied
- Comfort Plus Headrest Pad, 10 inch
- Removable Headrest Hardware
- Lap Belt 60 inch
- Legrest Assy Cntr Mnt Foot Platform
- Large Calf Pads
- Stealth Cushion Assy Simplicity General Use 18x18

The wheelchair was disassembled, and each component was weighed and measured to create a CAD model of the geometry shown in Figure 105. Views of the FE model generated from this geometry are shown in Figure 106. Figure 107 compares the mass of key physical components to the masses in the FE model.

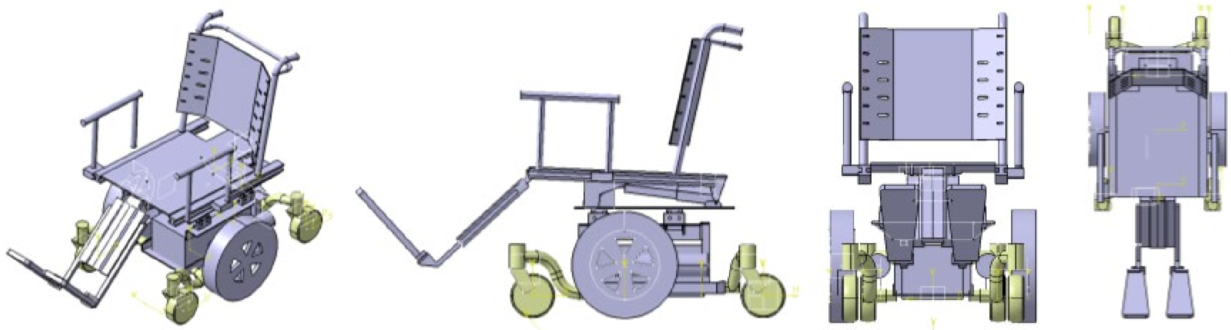


Figure 105. CAD geometry used to create power wheelchair model.

Figure 106. FE mesh of power wheelchair model.

Figure 107. Comparison of physical and model masses for power wheelchair model

Component	Physical mass (kg)	Model mass (kg)
Base (without batteries)	58.5	58.6
Batteries	34.0	34.0
Connection from base to seating	15.3	12.2
Seating System	42.2	44.6
Total	150.0	149.4

Figure 108 lists the dynamic sled tests used to validate the model. Videos, setup details, and data measured for the rear and side impacts are available to the public in the NHTSA Biomechanics Database. Figure 110 through Figure 119 show comparisons between the signals measured in the tests and those generated in the simulations, as well as a visual comparison between the test and simulation at several timesteps. Figure 109 shows CORA scores for each pair of signals. For the first frontal simulation, there may have been changes to the wheelchair hardware from the 2016 test used to validate and the version purchased in 2022 to create the model. For the second frontal test, scores are low likely because a SCARAB airbag was used in the test and not the model.

Figure 108. Tests used to validate power wheelchair model

Test ID	**Direction**	**Tiedown**	**Occupant Restraint**	Average accel (g)	Delta V (km/h)
PM1602	Front	SWTORS	WC-mounted lap belt and vehicle-mounted shoulder belt	-19.8	48.0
AW2115	Front	UDIG	Vehicle mounted 3PB, SCARAB	-20.9	47.7
WX2204	Nearside	SWTORS	WC-mounted lap belt and vehicle-mounted shoulder belt	-11.5	19.7
WX2111	Nearside	Q'Straint Docking	WC-mounted lap belt and vehicle-mounted shoulder belt	-10.9	21.6
WX2202	Rear	AMF Bruns 4-point tiedowns	WC-mounted lap belt only	-15.3	29.1

Figure 109. CORA scores for power wheelchair model

Test ID	**Direction**	**CORA Head Acc**	**CORA Chest Acc**
PM1602	Front	74.4%	68.6%
AW2115	Front	52.1%	66.7%
WX2204	Nearside	63.9%	55.5%
WX2111	Nearside	73.5%	79.5%
WX2202	Rear	62.7%	51.4%

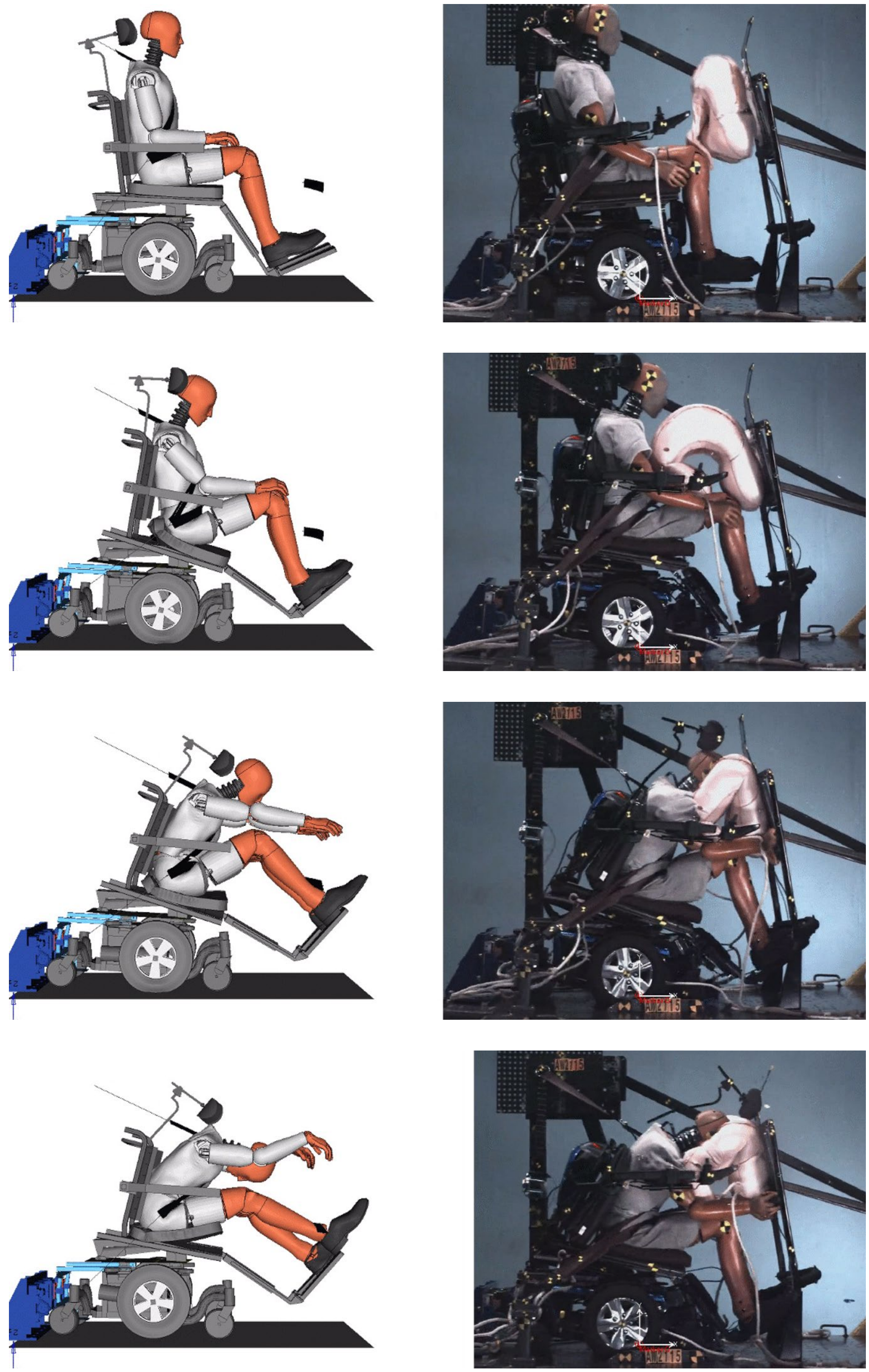


Figure 110. Comparison of model and test kinematics for power wheelchair, secured by UDIG, under frontal impact, at 30, 60, 90, 120 ms.

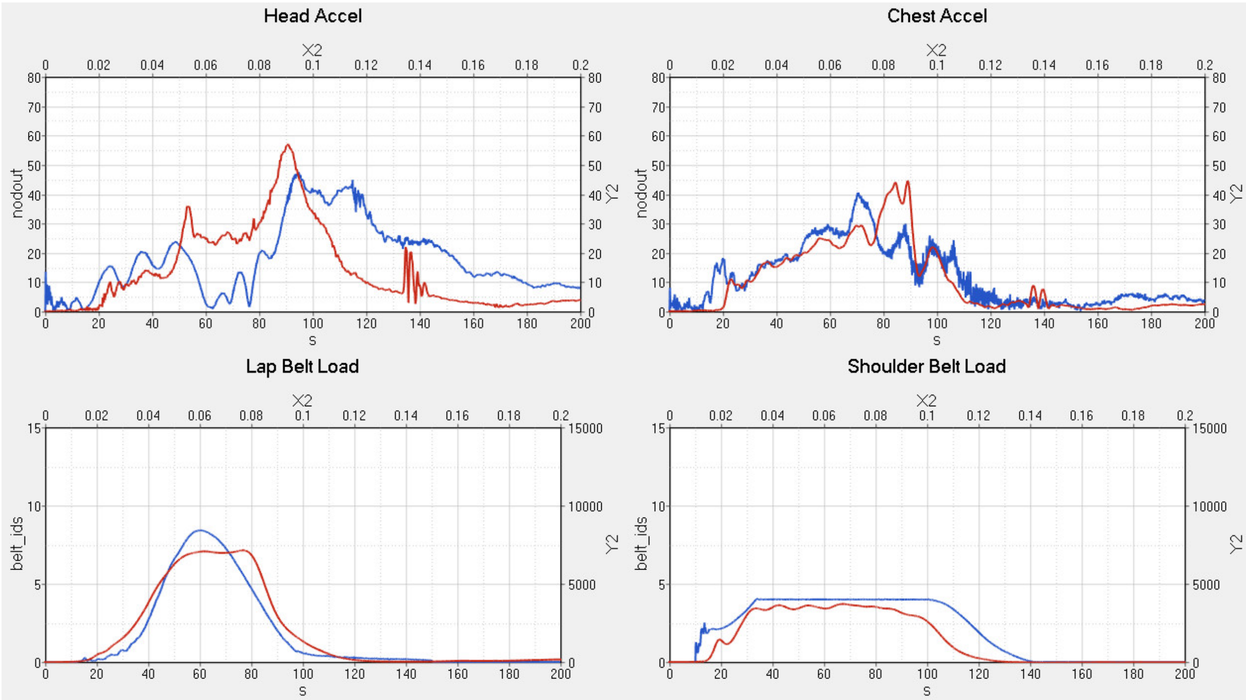


Figure 111. Comparison of test (red) and model (blue) data for power wheelchair, secured by UDIG, under frontal impact; no airbag in simulation.

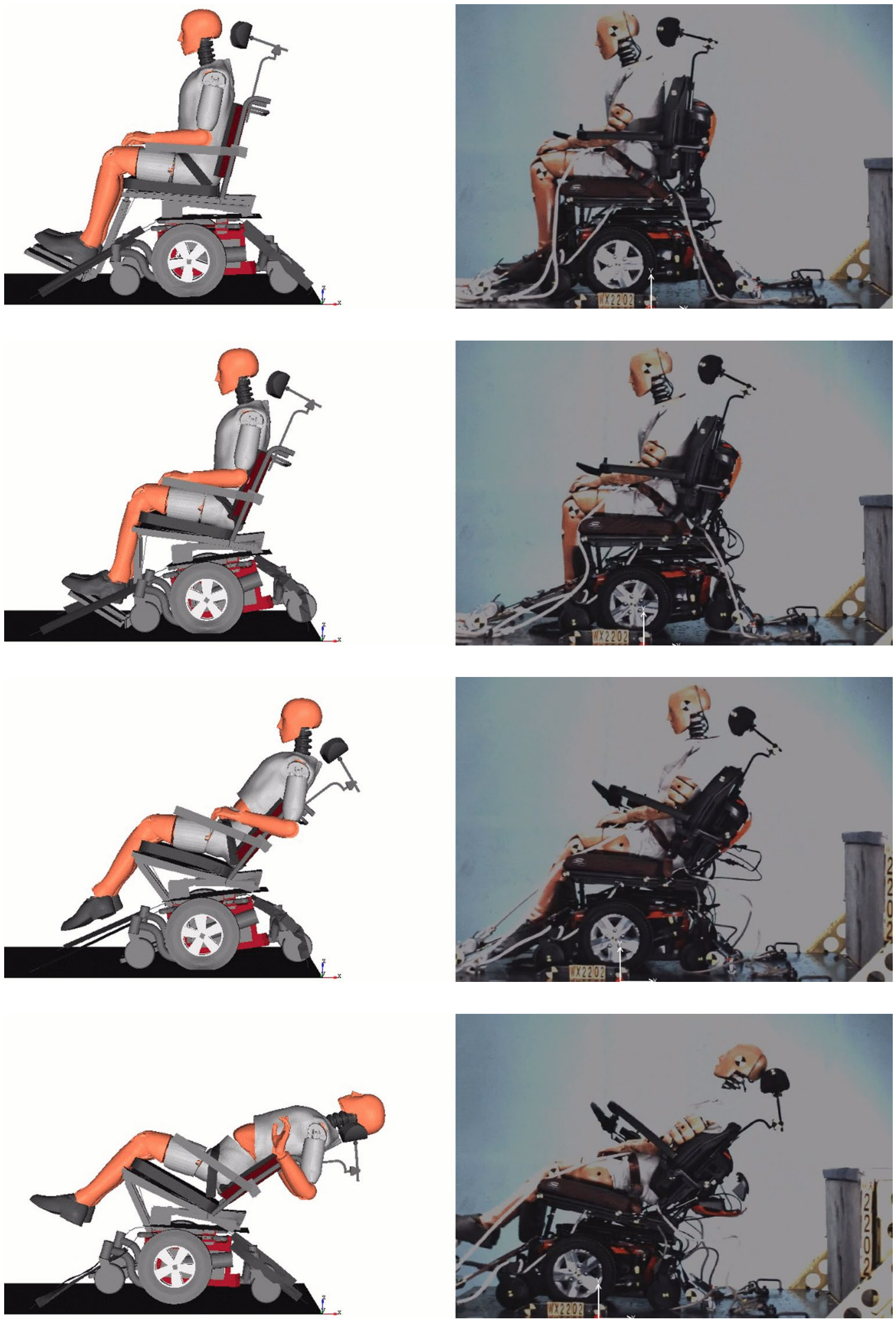


Figure 112. Comparison of model and test kinematics for power wheelchair, secured by commercial 4-point strap tiedowns, under rear impact, at 30, 60, 90, 120 ms.

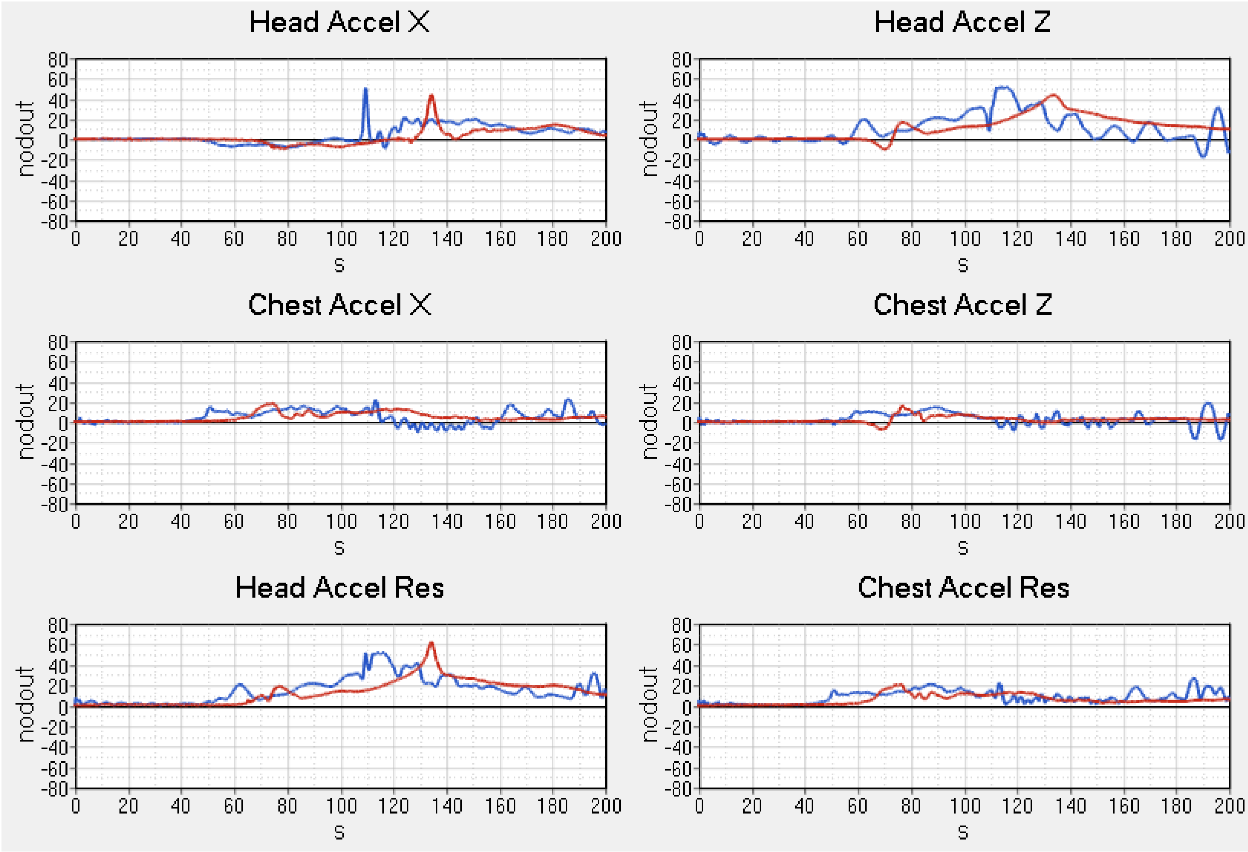
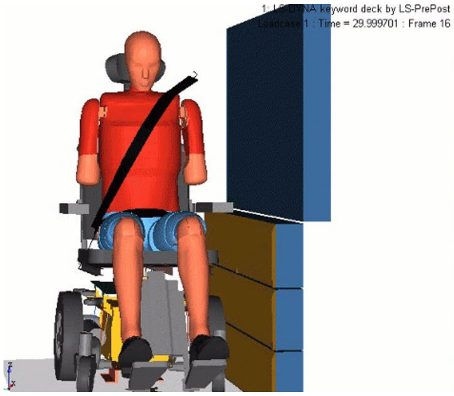
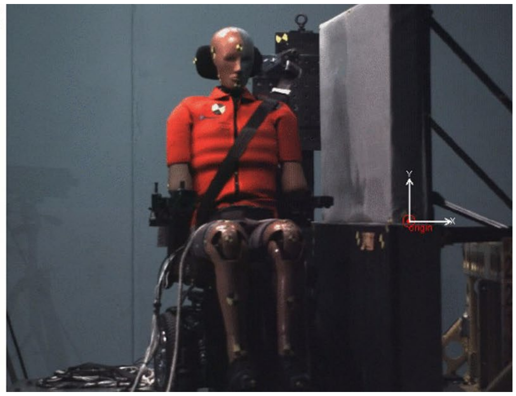
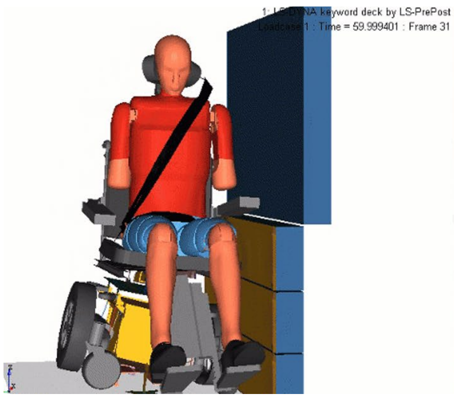


Figure 113. Comparison of test (red) and model (blue) data for power wheelchair, secured by commercial 4-point strap tiedowns, under rear impact.

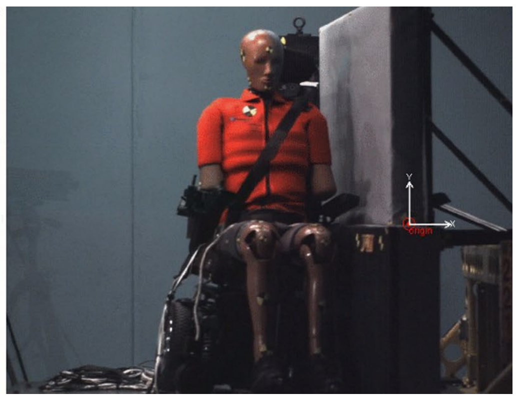


1: LS-DYNA keyword deck by LS-PrePost
Loadcase 1 : Time = 29.999701 : Frame 16





1: LS-DYNA keyword deck by LS-PrePost
Loadcase 1 : Time = 59.999401 : Frame 31



1: LS-DYNA keyword deck by LS-PrePost
Loadcase 1 : Time = 89.999107 : Frame 46

1: LS-DYNA keyword deck by LS-PrePost
Loadcase 1 : Time = 119.999702 : Frame 61

Figure 114. Comparison of model and test kinematics for power wheelchair, secured by traditional docking, under nearside impact, at 30, 60, 90, 120 ms.

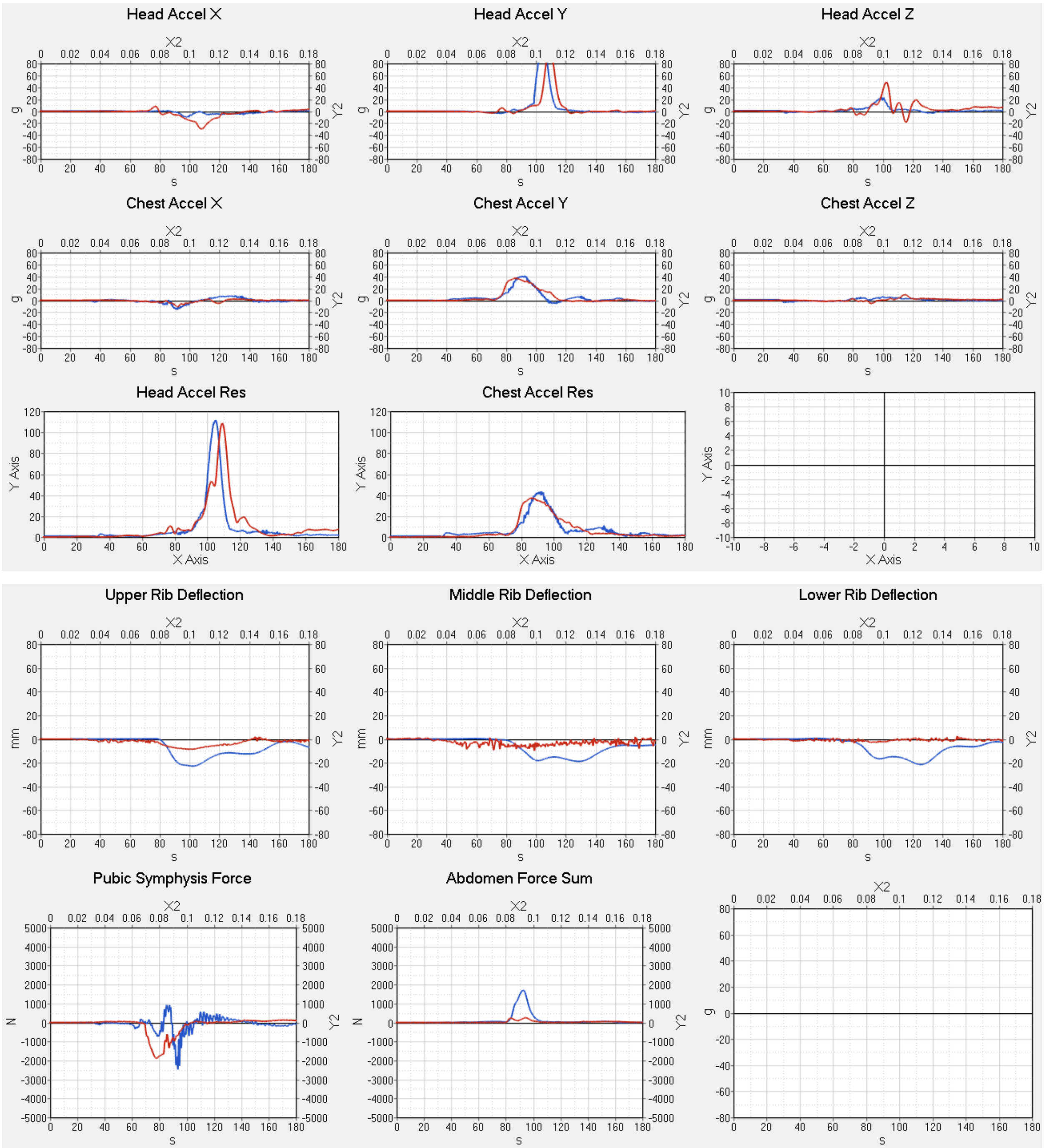


Figure 115. Comparison of test (red) and model (blue) data for power wheelchair, secured by traditional docking, under nearside impact.

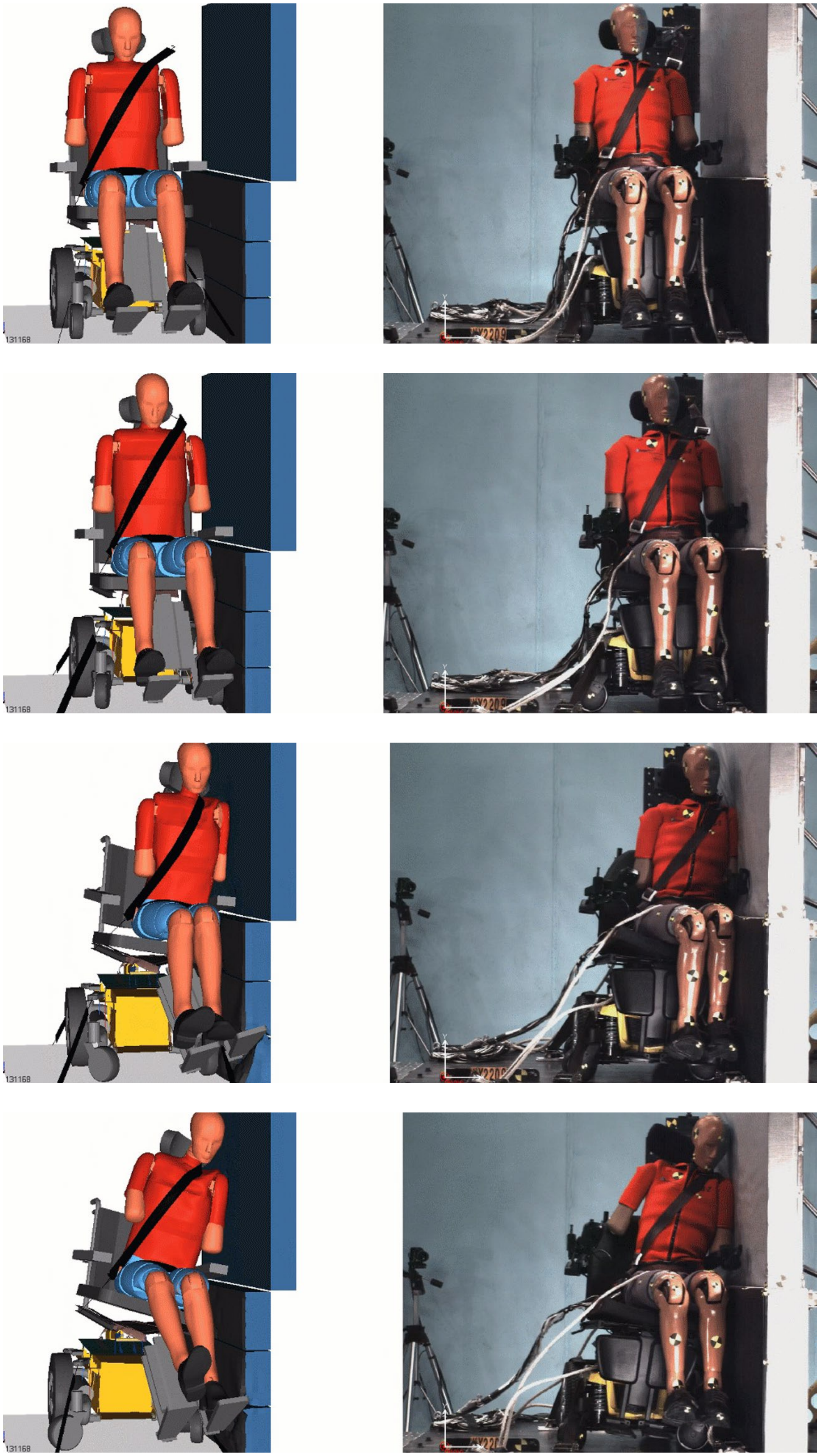


Figure 116. Comparison of model and test kinematics for power wheelchair, secured by commercial 4-point tiedowns, under nearside impact, at 30, 60, 90, 120 ms.

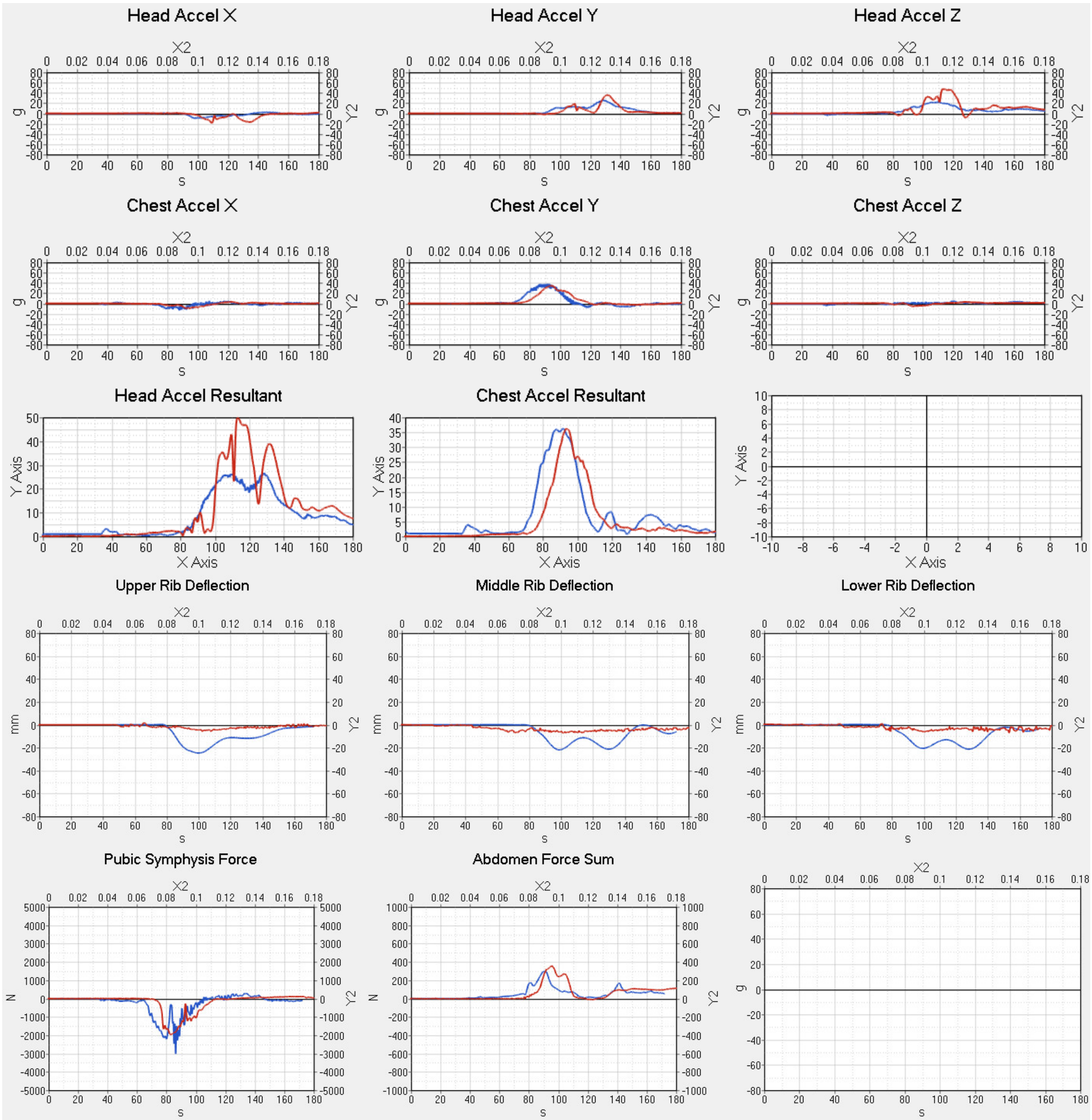


Figure 117. Comparison of test (red) and model (blue) data for power wheelchair, secured by commercial 4-point tiedowns, under nearside impact.

Appendix D: Manual Wheelchair Model

A finite element (FE) model of a Ki Mobility Catalyst 5, shown in Figure 120 was created as part of project funded by the National Highway Traffic Safety Administration to develop side impact test procedures for evaluating wheelchairs (WTORS), wheelchair tiedowns and occupant restraint systems, and vehicle occupant protection systems for wheelchair seating stations. The project deliverables include a publicly available FE model of a manual wheelchair that could be used to improve safety for people who travel while seated in their wheelchairs. We thank Ki Mobility for allowing us to use one of their tests for frontal validation.

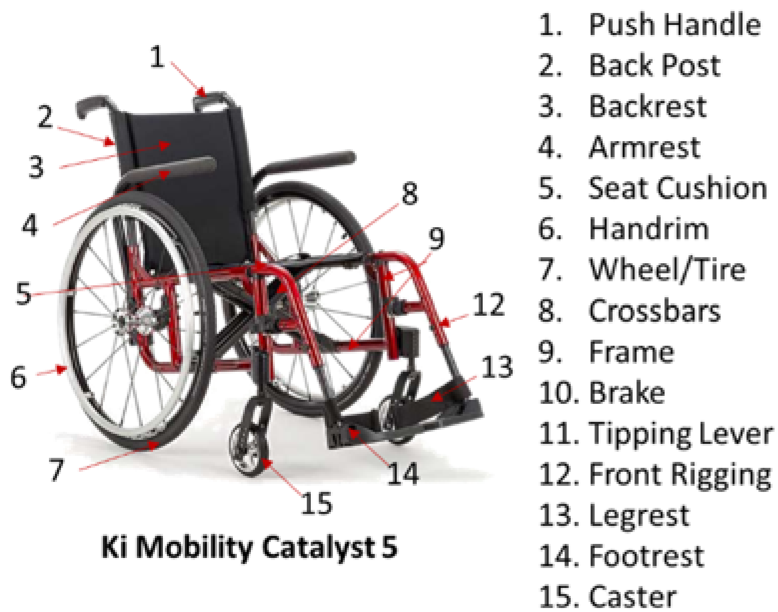


Figure 118. Photo of Ki Mobility Catalyst 5 and numbered components.

The wheelchair parts ordered (in 2022) to assemble the wheelchair as modeled are:

- Catalyst 5 Manual Chair C50101902
- Transit System
- Armrest, Heigh Adj, T Arm Full
- Anti Tipper
- Pos Belt 1 ½ in Auto Buckle
- Axiom G Cushion 18x18

The wheelchair was disassembled, and each component was weighed and measured to create a CAD model of the geometry shown in Figure 121. Views of the FE model generated from this geometry are shown in Figure 122. Table 1 compares the mass of key physical components to the masses in the FE model.

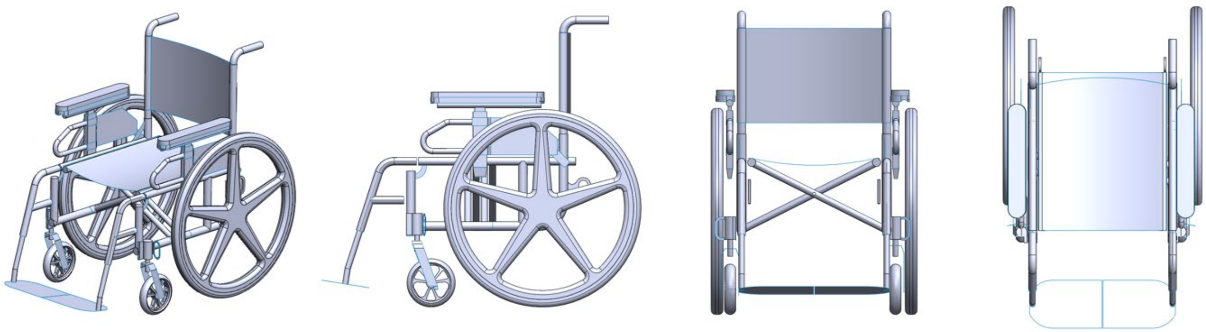


Figure 119. CAD geometry used to create manual wheelchair model.

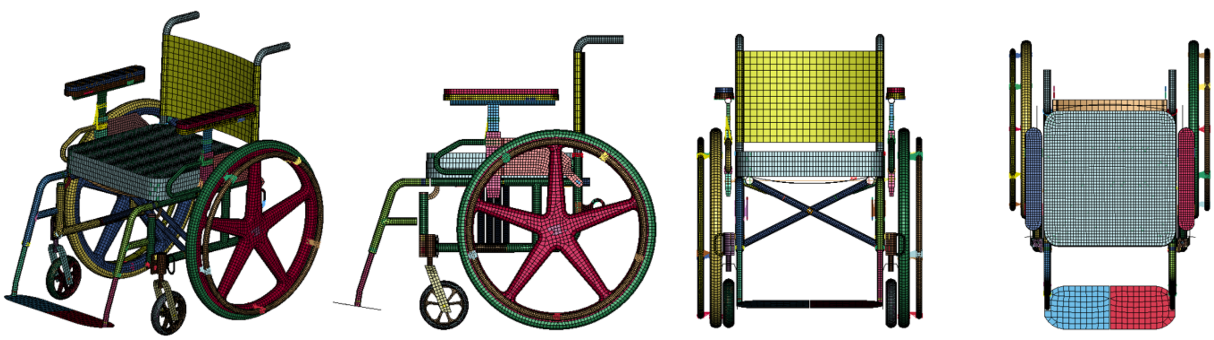


Figure 120. FE mesh of manual wheelchair model.

Table 6. Comparison of physical and model masses for power wheelchair model

Component	Physical mass (kg)	Model mass (kg)
Footrests	1.28	1.36
Armrests	2.16	1.90
Front wheels	1.52	2.83
Rear wheels	4.64	5.68
Main structure and seat	7.40	5.09
Total	17.0	16.86

Figure 123 lists the dynamic sled tests used to validate the model. Videos, setup details, and data measured for the rear and side impacts are available to the public in the NHTSA Biomechanics Database. Figure 125 through Figure 130 show a visual comparison between the test and simulation at several timesteps, as well as plots comparing the signals measured in the tests and those generated in the simulations. In addition, Figure 131 shows a images of the residual deformation in the mounting bracket for the test and model, with good level of agreement. Figure 124 shows CORA scores for each pair of signals.

Figure 121. Test conditions used to validate manual wheelchair model.

Test ID	Direction	Securement	Occupant Restraint
KM0901	Front	SWTORS	WC-mounted lap belt and vehicle-mounted shoulder belt
WX2210	Nearside	UDIG	WC-mounted lap belt and vehicle-mounted shoulder belt
WX2201	Rear	Qstraint docking	WC-mounted lap belt only

Figure 122. CORA scores for manual wheelchair model.

Test ID	Direction	Securement	CORA Head Acc	CORA Chest Acc
KM0901	Front	SWTORS	87%	83%
WX2210	Nearside	UDIG	69%	84%
WX2201	Rear	Qstraint docking	90%*	73%*

*Up to 160 ms

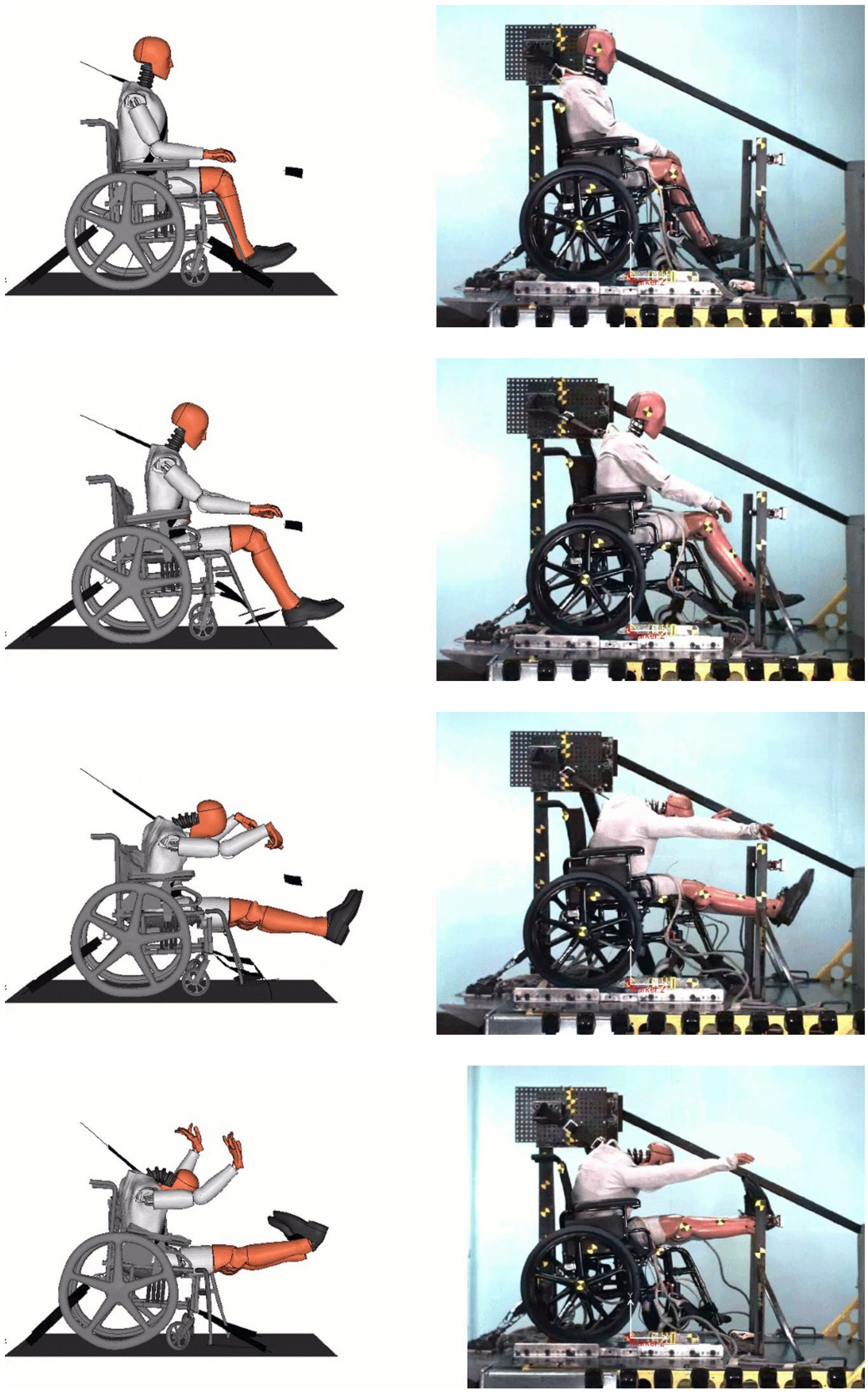


Figure 123. Comparison of model and test kinematics for manual wheelchair, secured by SWTORS, under frontal impact, at 30, 60, 90, 120 ms.

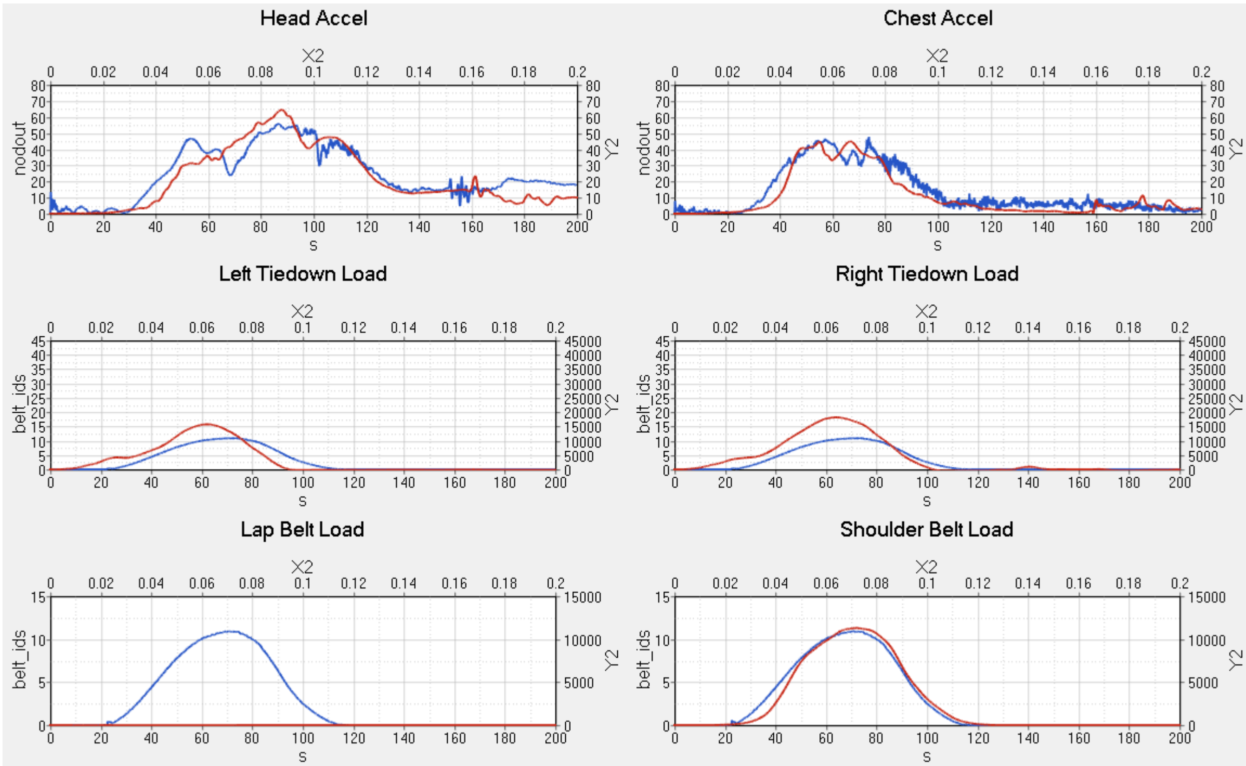


Figure 124. Comparison of test (red) and model (blue) data for manual wheelchair, secured by SWTORS, under frontal impact.


131168
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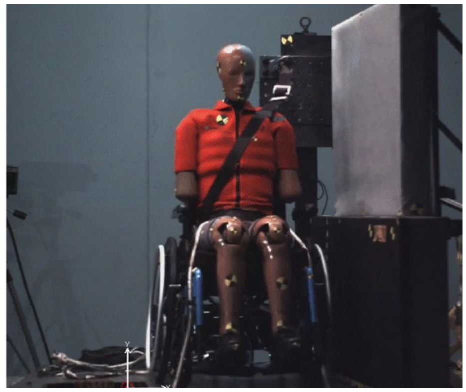
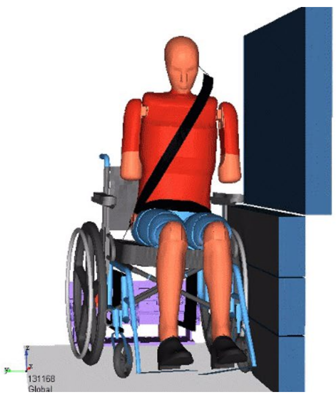
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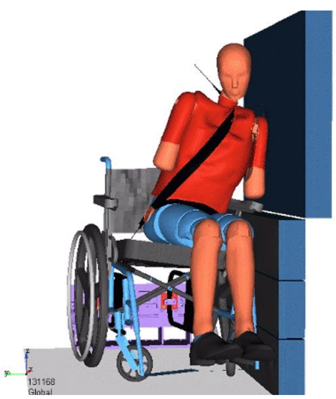
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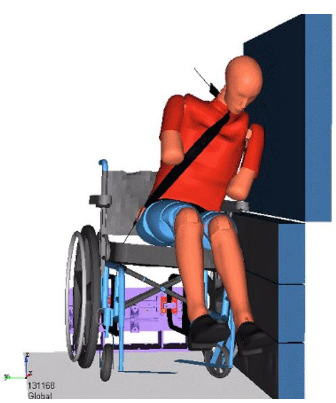
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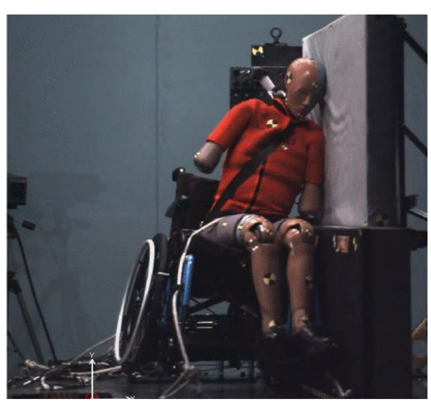


Figure 125. Comparison of model and test kinematics for manual wheelchair, secured by UDIG, under nearside impact, at ~30, 60, 90, 120 ms.

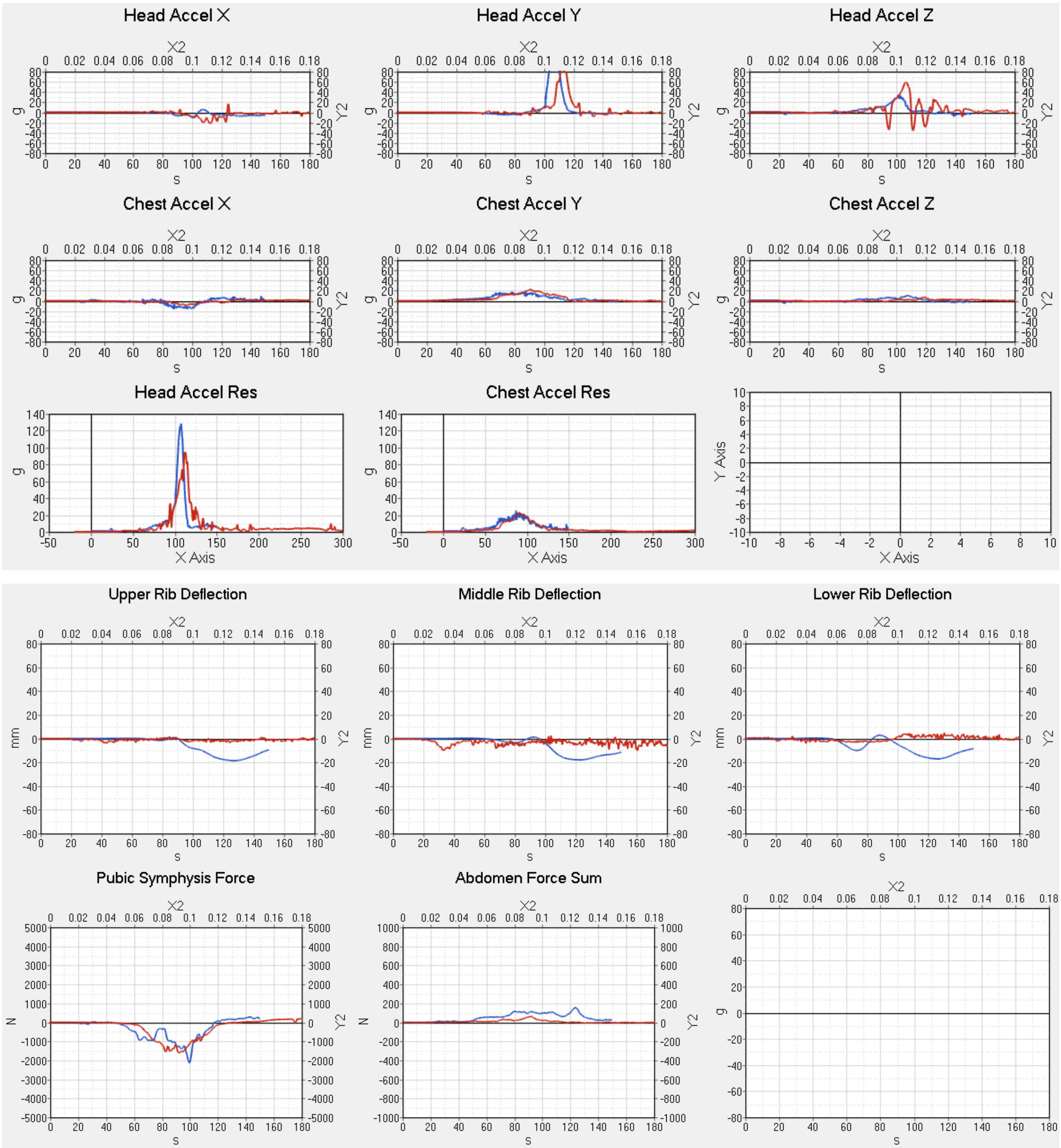


Figure 126. Comparison of test (red) and model (blue) data for manual wheelchair, secured by UDIG, under nearside impact.

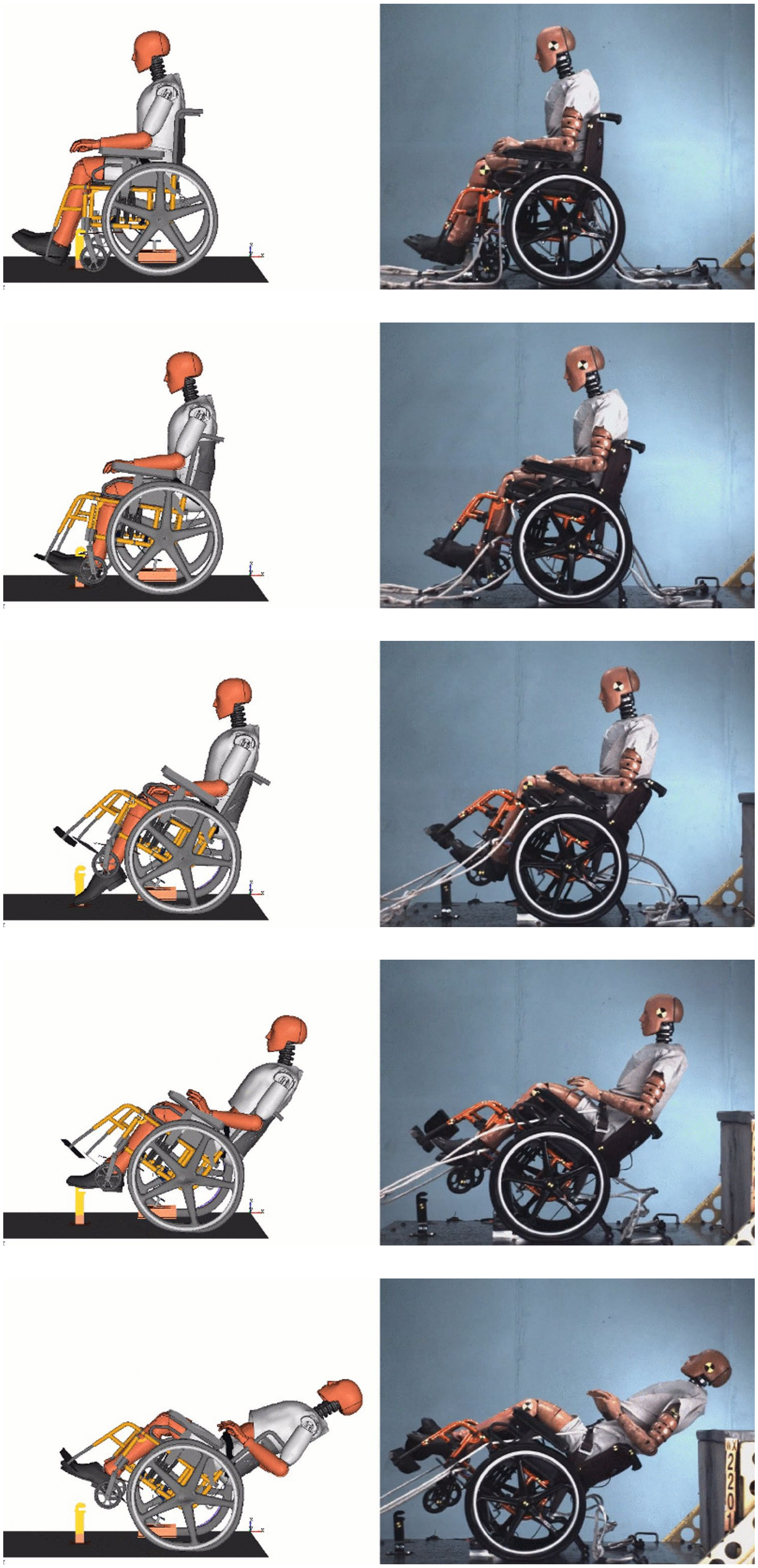


Figure 127. Comparison of model and test kinematics for manual wheelchair, secured by Q'Straint docking, under rear impact, at 30, 60, 90, 120, 150 ms.

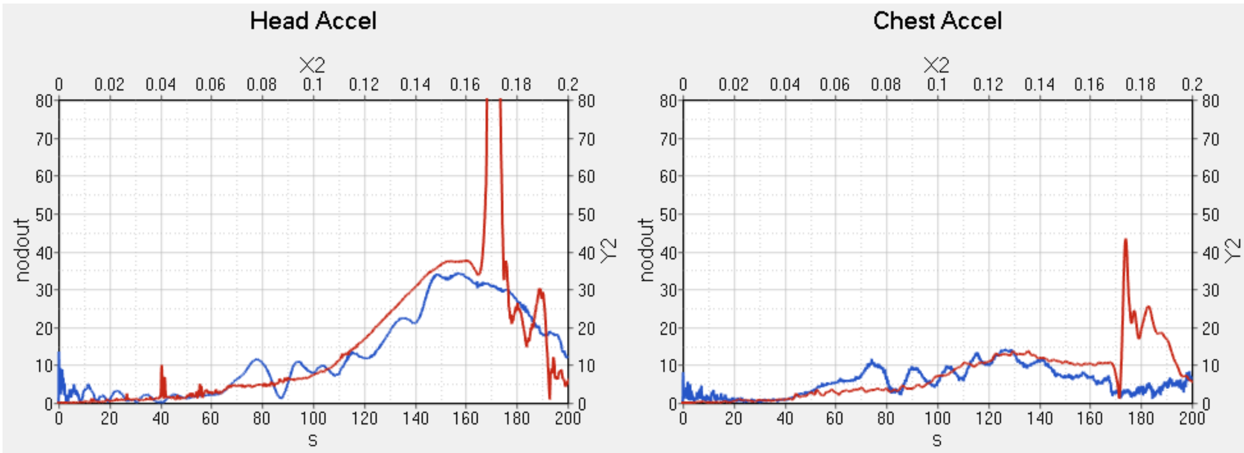


Figure 128. Comparison of test (red) and model (blue) data for manual wheelchair, secured by Q'Straint docking, under rear impact.

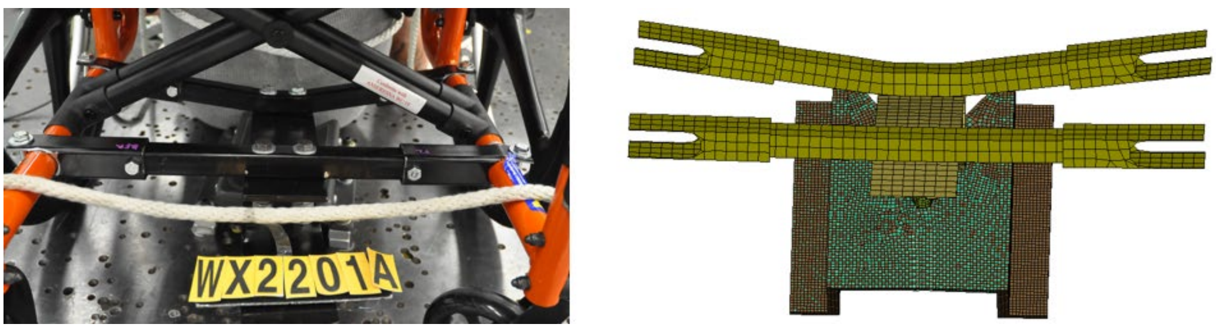


Figure 129. Comparison of residual deformation in anchor bracket for test (left) and model (right) for manual wheelchair in rear impact.

Appendix E: Test Procedures

Introduction

These procedures were developed to provide improved safety in side impact crashes for people who travel while seated in their wheelchairs. The procedures will allow testing and development of:

- Wheelchairs that remain intact and keep the occupant positioned relative to the airbag under lateral loading
- Tiedowns that effectively secure wheelchairs under lateral loading
- Vehicle occupant protection systems for people using wheelchairs as vehicle seating in nearside and farside impact

The test procedures and tools address the different needs of wheelchair manufacturers, wheelchair tiedowns and occupant restraint systems (WTORS) manufacturers, and vehicle manufacturers, while also considering how to maximize both independence and safety of wheelchair users. While wheelchairs are designed for a variety of different user sizes, these initial procedures focus on testing products suitable for use by a midsized male occupant.

The design and performance requirements, and associated test methods, have been adapted from RESNA WC-4:2017 for use under side impact test conditions.

These procedures can be used to evaluate wheelchair performance in a 10-*g*, 13-mph lateral impact. Figure 1 shows the velocity versus time plot for this crash event. The test fixtures orient the wheelchair and tiedowns 80 degrees laterally (rotated 10 degrees toward frontal from a full 90-degree lateral impact), to account for the frontal component present in most side impact crashes. The test severity was developed by reviewing the FMVSS 214 and US Side NCAP acceleration profiles of passenger vehicles that can be converted for wheelchair use, generally vans, minivans, and SUVs. The profile of the loading wall used during wheelchair evaluation was also derived from these tests to represent the residual deformation seen in side impacts of these types of vehicles.

Three similar but separate procedures have been developed to reflect the different test goals for the three commercial items tested: WTORS, wheelchairs, and vehicle occupant protection systems.

In side impact, the WTORS purpose is to limit motion of the wheelchair and maintain the wheelchair in an upright position while remaining intact and not creating sharp edges or projectiles. WTORS should be tested to determine their strength under lateral loading. This is best accomplished using a sled test without a representation of a lateral wall to maximize the load on the tiedown elements. Since the test is primarily of strength and there are no lateral vehicle elements to interact with, the mass of the ATD is important but its ability to assess injury risk in side impacts is not. To maximize the tiedown loads, a wheelchair-anchored lap belt is used. The commercial WTORS is tested with a surrogate representation of a wheelchair and a mid-size male ATD.

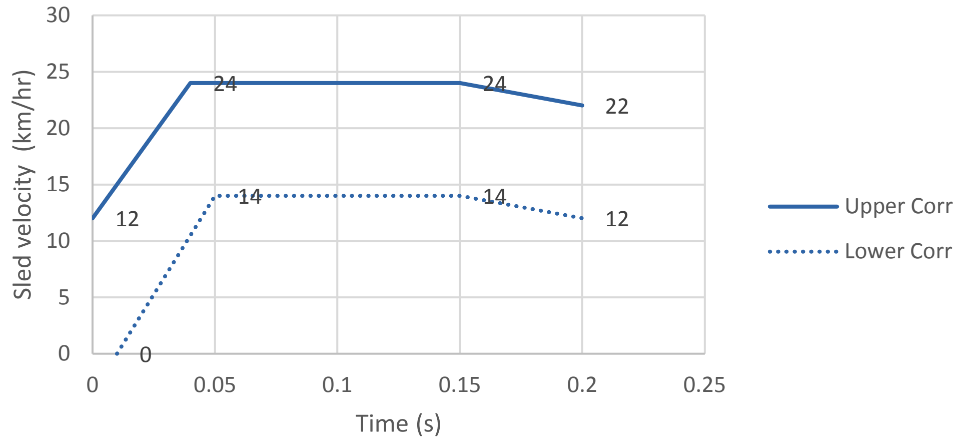


Figure 1. Side impact velocity corridor.

In side impact, the wheelchair should fill the role of a vehicle seat. The wheelchair should maintain the occupant in an upright seated position and maintain its essential size and shape, despite impact with vehicle interior elements. The wheelchair should stay intact and not create dangerous projectiles or sharp edges that can be contacted by vehicle occupants. To assess these qualities, the wheelchair is tested with a sled test that includes a surrogate WTORS and a generic representations of the deformed vehicle sidewall.

Much of the protection afforded to vehicle occupants in side impact comes from the vehicle environment and the built-in occupant protection systems. The anchoring of the occupant belts, characteristics of the vehicle side wall, and deployment parameters of the side airbags are all key factors that are determined by the vehicle manufacturer. These systems should be tested using a fidelic representation of the vehicle, such as sled testing (or simulations) with a body in white or a full vehicle side impact test, per FMVSS 214 or US Side NCAP. In these cases, the vehicle manufacturer may or may not know the characteristics of the WTORS that will be used, but they will need to plan to protect a wide range of occupants using many different wheelchair models. These vehicle systems are best evaluated using either a commercial (if known) or surrogate WTORS, a surrogate wheelchair, and a side impact ATD such as the ES2-re.

To accomplish these three distinct sets of target outcomes, three procedures are proposed.

Side Impact Test Procedures for WTORS

Objective

This procedure describes the tools and methods for sled testing using simulated side impact loading conditions that WTORS would experience in a 10-*g*, 13-mph side impact event when securing a wheelchair that faces forward in the vehicle (toward the primary direction of vehicle travel). In this procedure, the WTORS is evaluated for dynamic strength, structural integrity, and the system's ability to maintain the wheelchair and occupant in an upright seated position, so the occupant can benefit from vehicle features that mitigate side impact related loading and injury. WTORS that are designed to work with a wide range of wheelchairs are tested with a surrogate wheelchair base and a midsize male ATD. These same procedures can be used with WTORS systems that are designed for use by one specific wheelchair model. In the latter case, the commercial wheelchair could be used for testing.

WTORS Test Methods

Equipment

The equipment needed to conduct this testing includes:

- A complete commercial WTORS that complies with ANSI/RESNA WC18
- A dynamic sled with a flat rigid mounting surface capable of the 10-*g*, 13-mph test pulse shown in Figure 1.
- Rigid fixturing where the upper shoulder anchor point can be attached. This anchor point fixture should not have any structural elements that extend into the head excursion area.
- Calibrated instrumentation to verify the tested pulse with a data collection system that complies with SAE J211
- A midsized male ATD
- A surrogate wheelchair base meeting the description found in Annex B of ANSI/RESNA WC20
- Two high speed digital video cameras capable of recording images at 500 fps or higher
- A means to accurately measure back support post angle with respect to vertical, lateral wheelchair and ATD excursions from the recorded video views.

Prior to conducting the test, make sure the sled instrumentation has been calibrated per the manufacturer in the past 12 months. Inspect the ATD for damage and adjust the joints to a resistance of 1 *g*. Dress the ATD in snug fitting cotton clothing as specified for federal crash testing requirements. Verify that the surrogate wheelchair base is in good working order and the tires are inflated per manufacturer specifications.

Test Procedures

1. Define a wheelchair station on the sled platform that is at least 76 cm (30 in) wide and 123 cm (48 in) long.
2. Orient the centerline of the wheelchair station so that in the plan (overhead) view, the centerline of the station is rotated 80 degrees clockwise from the primary direction of sled travel, as shown in Figure 2.

3. Install the WTORS per the manufacturer's instructions using the provided commercial anchorages and fasteners. In absence of manufacturer's instructions to the contrary, install the WTORS:
    a. For strap-type tiedown systems, choose anchor points that are:
        i. Symmetrically located with respect to the wheelchair center line (aka the wheelchair reference plane).
        ii. At least 123 cm (48 in) apart from front to rear of the wheelchair
        iii. Installed so that the rear anchorages are directly behind the wheelchair securement points and the rear tiedown straps are parallel to the wheelchair centerline when viewed from overhead.
        iv. Installed so that the front tiedown points are outboard of the front wheelchair securement points, but not further apart than 76 cm (30 in).
    b. For docking systems follow the manufacturers installation instructions.
4. Secure the wheelchair with the WTORS per the manufacturer's instructions.
5. Place the ATD into the wheelchair making sure the ATD is seated symmetrically with the torso upright and the back and legs pushed into and in contact with the wheelchair back support and seat.
6. Position the seat belt on the ATD with the lap belt routed at the junction of the pelvis/thigh and route the shoulder belt so that it diagonally crosses the collarbone, sternum and meets the lap belt at the hip. The shoulder belt anchor point should be located 300 mm ± 15 mm (11.8 in. ± 0.6 in.) behind the front edge of the ATD shoulder ('clavicle'), 300 mm ± 15 mm (11.8 in. ± 0.6 in.) lateral from ATD head center, and 50 mm ± 15 mm (6.9 in. ± 0.6 in.) above the top of the ATD's head.
7. Apply high contrast targets on the front corners of the wheelchair seatpan (to calculate excursion from overhead camera) and at the top and bottom of the seatback centerline (visible from rear camera) to allow calculation of angle.
8. Measure and record the WTORS anchorage locations, tiedown strap angles and seat belt angles.
9. Conduct the sled test.

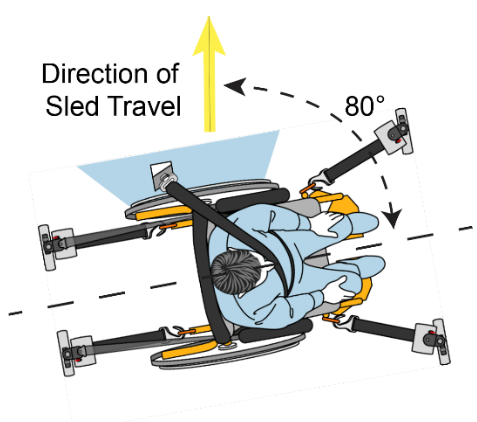


Figure 2. Overhead view of wheelchair station placement.

WTORS Performance criteria

Examine the WTORS, ATD, and test wheelchair, and analyze the test films or videos to determine, measure, and/or calculate compliance with the criteria below:

1. The ATD should be in a seated posture in the wheelchair at the end of the test, with the ATD torso leaning less than 45° from the vertical when viewed from all directions,
2. The test wheelchair shall remain upright on the test platform,
3. Primary load-carrying parts and components of a WTORS shall not completely fail in the absence of a backup component or structural member without signs of failure,
4. Components of the WTORS that may contact the wheelchair-seated occupant or other nearby occupants shall not fragment or separate in a manner that produced sharp edges with a radius of less than 2 mm (0.08 in.),
5. Rigid components of the WTORS greater than 150 g (5.3 oz) shall not completely detach,
6. The wheelchair and ATD can be removed from the tiedown/securement system without the use of tools,
7. The maximum angle of the WC back support posts, relative to the vertical, shall not exceed 12 degrees, and
8. The lateral excursion of the right edge of the wheelchair seatpan near point-P shall not exceed 275 millimeters measured perpendicular to the initial wheelchair centerline.

Side Impact Test Procedures for Wheelchairs

Objective

This procedure describes the tools and methods for a sled test to simulated side impact loading conditions that wheelchairs would experience in a 10-*g*, 13-km/hr side impact event while traveling facing forward in the vehicle (toward the primary direction of vehicle travel). In this procedure, the wheelchair is evaluated for dynamic strength, structural integrity, and the wheelchair's ability to stay upright and maintain the occupant in an upright seated position, so the occupant can benefit from vehicle features that mitigate side impact related loading and injury. A staggered surrogate vehicle sidewall is used to represent the intruding vehicle wall at peak intrusion. This wall allows realistic loading between the vehicle and wheelchair frame. Wheelchairs are tested with a surrogate WTORS, and the procedure is suitable for testing products designed for an occupant the size of a midsized male ATD.

Wheelchair Test Methods

Equipment

The equipment needed to conduct this testing includes:

- A complete commercial wheelchair that complies with ANSI/RESNA WC19.
- A dynamic sled with a flat rigid mounting surface capable of the 10-*g*, 13-km/hr test pulse shown in Figure 1.
- Rigid fixturing where the upper shoulder anchor point can be attached. This anchor point fixture should not have any structural elements that extend into the head excursion area.
- The side impact wall described in Annex A.
- Calibrated instrumentation to verify the tested pulse with a data collection system that complies with SAE J211
- A midsized male ATD.
- A surrogate WTORS meeting the description of Annex D of ANSI/RESNA WC19.
- Two high speed digital video cameras capable of recording images at 500 fps

Prior to conducting the test, make sure the sled instrumentation has been calibrated per the manufacturer in the previous 12 months. Inspect the ATD for damage and adjust the joints to a resistance of 1 g. Clothe the ATD in snug fitting cotton clothing as specified in federal crash testing standards. Verify that the surrogate wheelchair is in good working order and the tires are inflated per manufacturer's specifications.

Test Procedures

1. Define a wheelchair station on the sled platform that is at least 76 cm (30 in) wide and 123 (48 in) long.
2. Orient the centerline of the wheelchair station so that in the plan (overhead) view, the centerline of the station is rotated 80 degrees from the primary direction of sled travel, as shown in Figure 2.
3. Shift and secure the loading wall so it is parallel to the wheelchair centerline and positioned 50 $\pm$ 1 cm (20 in $\pm$ 0.5 in) away from the closest point on the wheelchair.

4. The wheelchair should be adjusted to fit the ATD per the manufacturer's instructions and all adjustment mechanisms should be tightened per the user manual.
5. Adjustable elements of the seat (such as tilt and recline) should be in a middle position rather than at the end of adjustment travel.
6. The seat back support angle should be between 5 and 30 degrees from vertical when measured unloaded at the seatback centerline.
7. The seat pan angle should be between 5 and 30 degrees from horizontal when measured unloaded at the seat centerline.
8. Install the SWTORS so that the anchor points are:
    a. Symmetrically located with respect to the wheelchair center line (aka the wheelchair reference place).
    b. At least 48 inches apart from front to rear of the wheelchair.
    c. Installed so that the rear anchorages are directly behind the wheelchair securement points and the rear tiedown straps are parallel to the wheelchair centerline when viewed from overhead.
    d. Installed so that the front tiedown points are outboard of the front wheelchair securement points, but not further apart than 76 cm (30 in).
9. Secure the wheelchair with the SWTORS.
    a. While maintaining the wheelchair reference plane within 3° of the centerline of the wheelchair station, adjust the fore/aft position of the wheelchair while tensioning the tiedown straps to between 100 N and 200 N (about 22 lbf and 44 lbf), to achieve a side-view projected angle of the rear tiedown straps of 45° ± 3° to the horizontal.
    b. If a rear tiedown-strap angle in this range cannot be achieved with a tiedown-strap length of at least 495 mm (19.5 in.), adjust the length of the rear tiedown strap assemblies to between 495 mm and 508 mm (19.5 in. and 20 in.), and measure the resulting side-view projected angle of the rear tiedown straps.
10. Place the ATD into the wheelchair making sure the ATD is seated symmetrically with the torso upright and the back and legs pushed into and in contact with the wheelchair back support and seat.
11. Position seat belt on the ATD with the lap belt routed at the junction of the pelvis/thigh and route the shoulder belt so that it diagonally crosses the collarbone, sternum and meets the lap belt at the hip. The shoulder belt anchor point should be located 300 mm ± 15 mm (11.8 in. ± 0.6 in.) behind and 173 mm ± 15 mm (6.9 in. ± 0.6 in.) above the top of the ATD's shoulder.
12. Measure and record the SWTORS anchorage locations, tiedown strap angles, seat belt angles, the wheelchair width at the seat rails, the ATD H-point height, wheelchair back support angle, and wheelchair seat pan angle.
13. Conduct the sled test.

Wheelchair Performance Criteria

When tested according to the procedures in this document, the wheelchair should meet the following requirements:

1. The wheelchair securement point structural components shall not fail completely.
2. The wheelchair securement points shall not deform such that the hooks of the four-point, strap-type surrogate tiedown system cannot be disengaged and removed.
3. The wheelchair should be in an upright position at the end of the test.
4. The ATD should be in a seated posture in the wheelchair at the end of the test, with the ATD torso leaning less than 45° from the vertical when viewed from all directions.
5. No rigid components, parts, equipment, or accessories with a mass greater than 150 grams (5.3 oz) should detach from the wheelchair during the test.
6. Wheelchair components that could contact the occupant seated in a wheelchair or nearby occupants should not break or separate in a manger that produces sharp edges with a radius of less than 2 mm (0.08 in.).
7. Locking mechanisms of tilt seating systems shall not have structural components that completely fail during the test. Shifting of seating-system orientation from release or slipping of a friction clamp are allowed if the sideview angle of the seating surface does not rotate below horizontal.
8. At the end of the test, the average height of the left and right ATD H-points relative to the wheelchair ground plane shall not have decreased by more than 20% from the pre-test average height.
9. At the end of the test, the average wheelchair width, measured at the seat rails shall not have decreased by more than 20% from the pre-test width.
10. Seats and back supports shall not separate or detach from the wheelchair or wheelchair frame unless there is a backup at the same point that remains functional.
11. No webbing of the surrogate wheelchair tiedown and occupant restraint system (SWTORS) or commercial WTORS shall completely fail due to interaction with the wheelchair or its components during a test.
12. All securement hooks of the SWTORS or commercial tiedown shall remain attached to the wheelchair securement points throughout the test.
13. Wheelchair-anchored belt restraints shall not become detached at anchorages, disconnected at buckles, or show complete webbing failure.
14. Batteries of power wheelchairs or their surrogate replacement parts shall:
    - i) not move completely outside the wheelchair footprint,
    - ii) remain attached or tethered to the battery compartment throughout the test, and
    - iii) shall not contact the ATD

Method for positioning wheelchairs, WTORS, and ATDs for in-vehicle testing and simulation

These procedures adapt the methods for evaluating wheelchair dynamic performance on a sled using the procedures of WC19 so they can be used to evaluate occupant protection systems in vehicles through computational modeling or vehicle crash testing. The WC19 procedures were inspired by FMVSS 208 seating procedures.

Wheelchair Adjustment

1) For wheelchairs with seats that adjust from front-to-back, adjust to the midpoint of the range, or to the location recommended by the wheelchair manufacturer for the size of ATD being tested.
2) For wheelchairs with multiple anchor points for belt restraints, choose the midpoint of the range, or the location recommended by the wheelchair manufacturer for the size of ATD being tested.
3) If desired, replace electronic components with substitutes having the same dimensions, mass, and center of gravity. For batteries, electrolyte fluid can be replaced with water. Batteries or their substitutes should represent the heaviest allowed for use with the wheelchair.
4) Inflate tires to the midpoint of the manufacturer's suggested pressure range.
5) If using, install the wheelchair-anchored lap belt or 5-point harness.
6) For wheelchairs with reclining seatbacks, adjust the seatback angle to 10 degrees rearward of vertical, measured along the centerline of the unloaded seatback.
7) For wheelchairs with adjustable seat cushions, or tilt seating systems, adjust to 10 degrees above horizontal, measured at the centerline of the seat cushion.
8) Tighten and lock any adjustments according to manufacturer's directions.
9) Apply the wheelchair brakes, if present.

Wheelchair Securement

When securing a wheelchair using commercial tiedowns, follow the WTORS manufacturer's instructions for use. The following directions are for use when securing a wheelchair using four surrogate wheelchair tiedowns, defined in WC19, in a vehicle or simulation.

1) Vehicle anchor points should be symmetric about the longitudinal centerline of the wheelchair station. The wheelchair centerline should be aligned with the longitudinal centerline of the wheelchair station within +/- 3 degrees.
2) The fore-aft distance between front and rear anchor points should be 1220 +/- 12 mm (48 +/- 0.5 in). An alternative fore-aft distance of 1296 +/- 12 mm (51 in +/- 0.5) is allowed to accommodate larger wheelchairs (or if trying to comply with ISO test procedures).
3) Laterally, the rear anchor points should be within +/- 25 mm of the rear securement points on the wheelchair.
4) Laterally, the front anchor points should be aligned with or outboard relative to the front securement points on the wheelchair. Lateral distance should range from 300 to 760 mm (12 to 30 in).
5) Adjust the surrogate tiedown length to 495 mm (19.5 in). Attach the surrogate tiedowns to the four securement points on the wheelchair. With the rear tiedowns taut, measure the side-

view angle of the rear tiedown straps between the anchor points on the floor and the hooks at the wheelchair.

   a. If the angle is below 45 degrees, the strap adjustment is good.
   b. If this angle is above 45 degrees, lengthen the rear tiedown straps until the tiedown straps are within 45 +/- 3 degrees when secured to the rear anchor points.

6) When the desired length is achieved, tension the front tiedown using the ratchet mechanisms to a tension between 100 and 200 N (22 to 44 lbf).

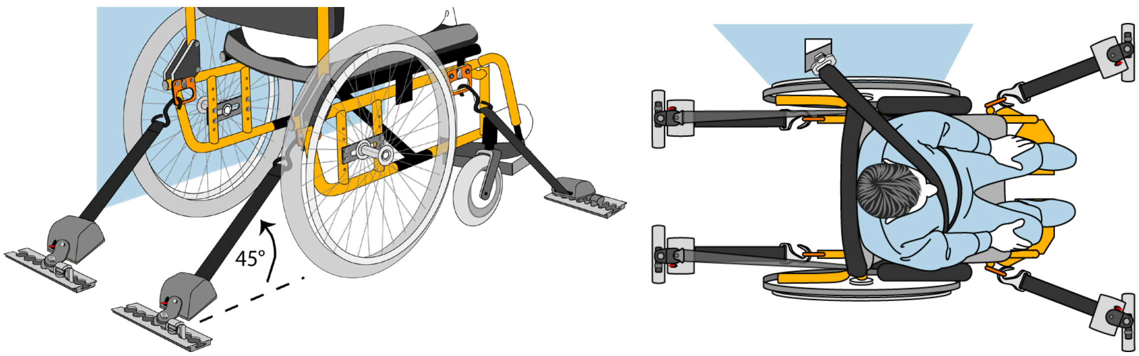


Figure 3. Illustration of ideal sideview tiedown angle between 30-45 degrees and lateral positions of tiedowns.

ATD Positioning

1) Adjust joints of ATD to 1 g setting as directed in ATD user's manual. The ATD should wear snug fitting cotton clothing as specified in federal standards for crash testing.
2) Position the ATD in the wheelchair sitting upright and symmetrically about the wheelchair longitudinal centerline. The back of the pelvis/buttocks should be as close as possible to the bottom of the back support.
3) Position the feet on the footrests.
4) Place the elbows on the wheelchair arm supports (if provided) and prop the hands on the ATD thighs, so that the upper torso is supported in an upright position.
5) Place high-contrast targets on the ATD's knee joint and head CG.

Seatbelt Placement using Add-On Occupant Restraints

1) Attach the floor anchorages of the seatbelt restraint to the floor so that they are located longitudinally between the rear tiedown anchorages and the wheelchair and laterally within 50 mm (2 in) of the wheelchair side frames to achieve sideview pelvic-belt angles between 30° and 75° to the horizontal.
2) The lap belt should be placed low across the front of the pelvis on the upper thighs, not on the abdomen. When possible, the lap belt should be angled between 45° and 75° to the horizontal when viewed from the side. Some wheelchair features, like armrests, can interfere with good belt fit. To avoid placing the lap belt over the armrest and to keep the lap belt low on the pelvis, it may be necessary to pivot the armrests out of position, insert the belt between the armrest and the seatback, or through openings between the backrest and seat.

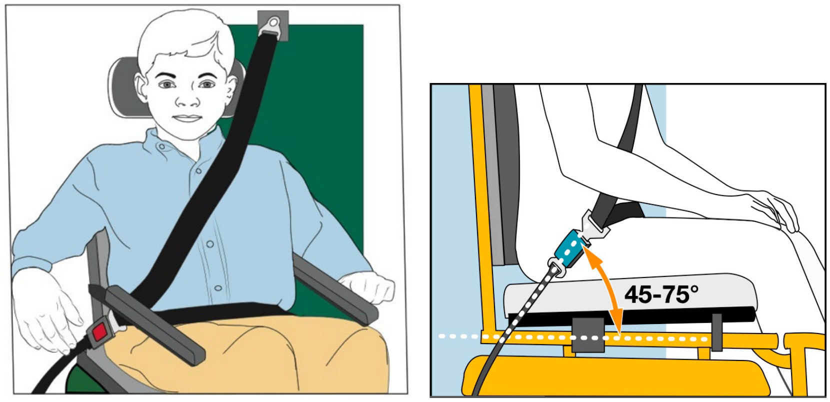


Figure 4. Illustration of recommended belt fit.

3) When using adjustable shoulder belt anchor point hardware, the diagonal shoulder belt should cross the middle of the shoulder and the center of the chest, and should connect to the lap belt near the hip of the wheelchair rider. The upper shoulder-belt anchor point or guide should be anchored above and behind the top of the occupant's shoulder, so that the belt is in good contact with the shoulder and chest while traveling. A side-view angle of 30° ± 5° is achieved with the anchor point located 300 mm ± 15 mm (11.8 in. ± 0.6 in.) behind and 173 mm ± 15 mm (6.9 in. ± 0.6 in.) above the top of the ATD's shoulder.

References

1. RESNA WC-4:2017, Section 18: Wheelchair tiedown and occupant restraint systems for use in
2. motor vehicles
3. RESNA WC-4:2017, Section 19: Wheelchairs used as seating in motor vehicles
4. RESNA WC-4:2017, Section 20: Wheelchair seating systems for use in motor vehicles
5. SAE Recommended Practice J211 Instrumentation for impact tests
6. Federal Motor Vehicle Safety Standard 214 (FMVSS 214) 49 CFR Part 571.214 Side impact protection

Annex A: Drawings of Side Impact Wall Structure

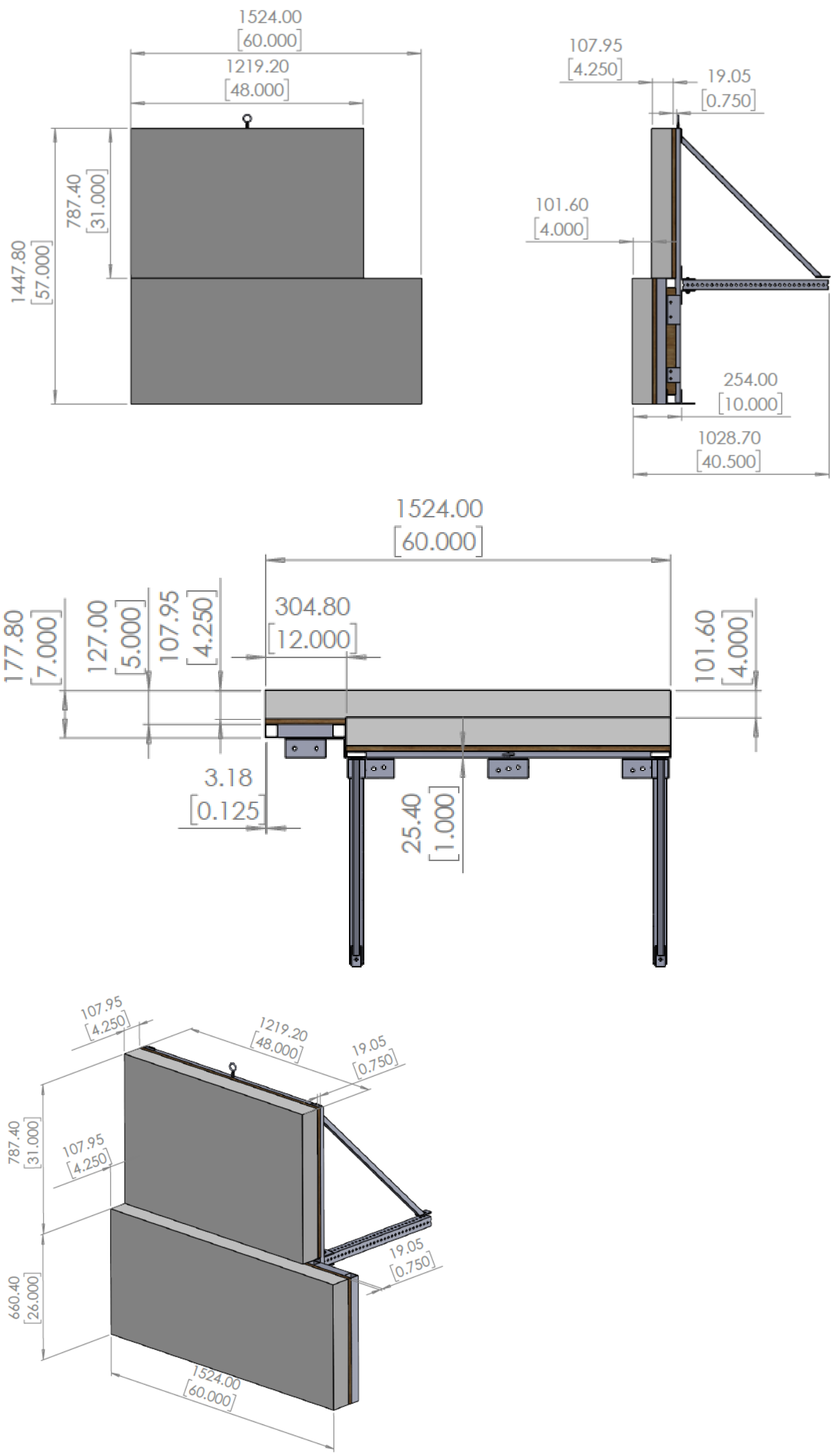


Figure 130. CAD images of side impact testing wall (drawings available to download at https://wc-transportation-safety.umtri.umich.edu/wheelchair-side-impact-test-procedure/).

Annex B: Wheelchair & WTORS Performance Criteria Evaluation Forms

SUMMARY OF WHEELCHAIR PERFORMANCE IN SIDE IMPACT

SLED TEST WX2204 – Q6 Edge 2.0 Power WC + Commercial 4-PT #1 + Wall

Proposed Requirement	**Notes**	**Pass/Fail**
Structural components of the WC securement points shall not completely fail	Securement points did not fail.	Pass
Deformation of WC securement points must not prevent disengagement of hook	Securement points did not deform.	Pass
WC upright and on test platform	WC upright	Pass
ATD must be in WC seat with torso leaning not more than 45˚	ATD in seat with torso upright	Pass
Detached hardware cannot exceed 150 g	No hardware detached	Pass
WC must not have sharp edges with potential for occupant contact	No sharp edges observed	Pass
Locking mechanisms of tilt seating cannot release or completely fail.	No tilt release.	Pass
Post-test height of ATD H-point shall be >= 20% of pretest height	Post-test H-pt height did not decrease from pre-test height.	Pass
Average WC width shall not decrease by more than 20% of pretest width	Post-test width did not decrease from pre-test width.	Pass
Seating system cannot break free from WC at any attachment point.	Seating stayed attached	Pass
WC cannot cause complete failure of the surrogate WTORS.	No WTORS failure	Pass
Tiedown hooks of WTORS shall remain engaged with WC securement points.	No tiedown hooks disengaged.	Pass
WC-anchored belt restraints shall not detach or completely fail.	WC-anchored lap belt intact and attached.	Pass
Batteries must be within WC footprint	Batteries remained within footprint	Pass
Batteries must remain attached to battery compartment	Batteries remained attached	Pass
Batteries cannot contact ATD	Batteries did not contact ATD	Pass

SUMMARY OF WHEELCHAIR PERFORMANCE

SLED TEST WX2206 – Ki Mobility Manual + UDIG + Wall

Proposed Requirement	**Notes**	**Pass/Fail**
Structural components of the WC securement points shall not completely fail	UDIG attachments did not fail	Pass
Deformation of WC securement points must not prevent disengagement of hook	UDIG attachments did not fail and prevent disengagement	Pass
WC upright and on test platform	WC upright	Pass
ATD must be in WC seat with torso leaning not more than 45˚	ATD in seat with torso reclined 10 degrees	Pass
Detached hardware cannot exceed 150 g	No hardware detached	Pass
WC must not have sharp edges with potential for occupant contact	No sharp edges observed	Pass
Locking mechanisms of tilt seating cannot release or completely fail.	No tilt release	Pass
Post-test height of ATD H-point shall be >= 20% of pretest height	Post-test H-pt height did not decrease from pre-test height	Pass
Average WC width shall not decrease by more than 20% of pretest width	Post-test width did not decrease from pre-test width	Pass
Seating system cannot break free from WC at any attachment point.	Seating stayed attached	Pass
WC cannot cause complete failure of the surrogate WTORS.	No UDIG failure	Pass
Tiedown hooks of WTORS shall remain engaged with WC securement points.	NA	NA
WC-anchored belt restraints shall not detach or completely fail.	WC-anchored lap belt intact and attached.	Pass
Batteries must be within WC footprint	NA - no batteries	NA
Batteries must remain attached to battery compartment	NA - no batteries	NA
Batteries must not contact ATD	NA - no batteries	NA

SUMMARY OF WHEELCHAIR PERFORMANCE

SLED TEST WX2208 – Quickie 2 Manual + SWTORS + Wall

Proposed Requirement	**Notes**	**Pass/Fail**
Structural components of the WC securement points shall not completely fail	Securement points did not fail.	Pass
Deformation of WC securement points must not prevent disengagement of hook	Securement points did not deform.	Pass
WC upright and on test platform	WC upright	Pass
ATD must be in WC seat with torso leaning not more than 45˚	ATD in seat with torso reclined 10 degrees	Pass
Detached hardware cannot exceed 150 g	No hardware detached	Pass
WC must not have sharp edges with potential for occupant contact	No sharp edges observed	Pass
Locking mechanisms of tilt seating cannot release or completely fail.	No tilt release	Pass
Post-test height of ATD H-point shall be >= 20% of pretest height	Post-test H-pt height did not decrease from pre-test height	Pass
Average WC width shall not decrease by more than 20% of pretest width	Post-test width did not decrease from pre-test width	Pass
Seating system cannot break free from WC at any attachment point.	Seating stayed attached	Pass
WC cannot cause complete failure of the surrogate WTORS.	No WTORS failure	Pass
Tiedown hooks of WTORS shall remain engaged with WC securement points.	No hooks detached	Pass
WC-anchored belt restraints shall not detach or completely fail.	WC-anchored lap belt intact and attached.	Pass
Batteries must be within WC footprint	NA - no batteries	NA
Batteries must remain attached to battery compartment	NA - no batteries	NA
Batteries must not contact ATD	NA - no batteries	NA

SUMMARY OF WHEELCHAIR PERFORMANCE

SLED TEST WX2209 – Q6 Edge 2.0 Power WC + SWTORS + Wall

Proposed Requirement	**Notes**	**Pass/Fail**
Structural components of the WC securement points shall not completely fail	Securement points did not fail.	Pass
Deformation of WC securement points must not prevent disengagement of hook	Securement points did not deform.	Pass
WC upright and on test platform	WC upright	Pass
ATD must be in WC seat with torso leaning not more than 45˚	ATD in seat with torso leaning 5 degrees to the left	Pass
Detached hardware cannot exceed 150 g	A plastic cupholder detached but <150g	Pass
WC must not have sharp edges with potential for occupant contact	No sharp edges observed	Pass
Locking mechanisms of tilt seating cannot release or completely fail.	No tilt release	Pass
Post-test height of ATD H-point shall be >= 20% of pretest height	Post-test H-pt height did not decrease from pre-test height	Pass
Average WC width shall not decrease by more than 20% of pretest width	Post-test width did not decrease from pre-test width	Pass
Seating system cannot break free from WC at any attachment point.	Seating stayed attached	Pass
WC cannot cause complete failure of the surrogate WTORS.	No WTORS failure	Pass
Tiedown hooks of WTORS shall remain engaged with WC securement points.	No hooks detached	Pass
WC-anchored belt restraints shall not detach or completely fail.	WC-anchored lap belt intact and attached.	Pass
Batteries must be within WC footprint	Batteries remained within footprint	Pass
Batteries must remain attached to battery compartment	Batteries remained attached	Pass
Batteries must not contact ATD	Batteries did not contact ATD	Pass

SUMMARY OF WHEELCHAIR PERFORMANCE

SLED TEST WX2210 – Ki Mobility Manual + UDIG + Wall

Proposed Requirement	**Notes**	**Pass/Fail**
Structural components of the WC securement points shall not completely fail	UDIG attachments did not fail	Pass
Deformation of WC securement points must not prevent disengagement of hook	UDIG attachments did not fail and prevent disengagement	Pass
WC upright and on test platform	WC upright	Pass
ATD must be in WC seat with torso leaning not more than 45˚	ATD in seat with torso upright	Pass
Detached hardware cannot exceed 150 g	No hardware detached	Pass
WC must not have sharp edges with potential for occupant contact	No sharp edges observed	Pass
Locking mechanisms of tilt seating cannot release or completely fail.	No tilt release	Pass
Post-test height of ATD H-point shall be >= 20% of pretest height	Post-test H-pt height did not decrease from pre-test height	Pass
Average WC width shall not decrease by more than 20% of pretest width	Post-test width did not decrease from pre-test width	Pass
Seating system cannot break free from WC at any attachment point.	Seating stayed attached	Pass
WC cannot cause complete failure of the surrogate WTORS.	No UDIG failure	Pass
Tiedown hooks of WTORS shall remain engaged with WC securement points.	NA	NA
WC-anchored belt restraints shall not detach or completely fail.	WC-anchored lap belt intact and attached.	Pass
Batteries must be within WC footprint	NA - no batteries	NA
Batteries must remain attached to battery compartment	NA - no batteries	NA
Batteries must not contact ATD	NA - no batteries	NA

SUMMARY OF WHEELCHAIR PERFORMANCE
SLED TEST WX2211 – Q6 Edge 2.0 Power WC + Dock #1 + Wall

Proposed Requirement	Notes	Pass/Fail
Structural components of the WC securement points shall not completely fail	Securement adaptor did not fail.	Pass
Deformation of WC securement points must not prevent disengagement of hook	Dock was able to release	Pass
WC upright and on test platform	WC upright	Pass
ATD must be in WC seat with torso leaning not more than 45˚	ATD in seat with torso leaning 40 degrees to the right	Pass
Detached hardware cannot exceed 150 g	No hardware detached	Pass
WC must not have sharp edges with potential for occupant contact	No sharp edges observed	Pass
Locking mechanisms of tilt seating cannot release or completely fail.	No tilt release	Pass
Post-test height of ATD H-point shall be >= 20% of pretest height	Post-test H-pt height did not decrease from pre-test height	Pass
Average WC width shall not decrease by more than 20% of pretest width	Post-test width did not decrease from pre-test width	Pass
Seating system cannot break free from WC at any attachment point.	Seating stayed attached	Pass
WC cannot cause complete failure of the surrogate WTORS.	No WTORS failure	Pass
Tiedown hooks of WTORS shall remain engaged with WC securement points.	NA	NA
WC-anchored belt restraints shall not detach or completely fail.	WC-anchored lap belt intact and attached.	Pass
Batteries must be within WC footprint	Batteries remained within footprint	Pass
Batteries must remain attached to battery compartment	Batteries remained attached	Pass
Batteries must not contact ATD	Batteries did not contact ATD	Pass

SUMMARY OF WHEELCHAIR PERFORMANCE

SLED TEST WX2212 – Ki Mobility Manual WC + SWTORS + Wall

Proposed Requirement	Notes	Pass/Fail
Structural components of the WC securement points shall not completely fail	Securement points did not fail.	Pass
Deformation of WC securement points must not prevent disengagement of hook	Securement points did not deform.	Pass
WC upright and on test platform	WC upright	Pass
ATD must be in WC seat with torso leaning not more than 45˚	ATD in seat with torso upright	Pass
Detached hardware cannot exceed 150 g	No hardware detached	Pass
WC must not have sharp edges with potential for occupant contact	No sharp edges observed	Pass
Locking mechanisms of tilt seating cannot release or completely fail.	No tilt release	Pass
Post-test height of ATD H-point shall be >= 20% of pretest height	Post-test H-pt height did not decrease from pre-test height	Pass
Average WC width shall not decrease by more than 20% of pretest width	Post-test width did not decrease from pre-test width	Pass
Seating system cannot break free from WC at any attachment point.	Seating stayed attached	Pass
WC cannot cause complete failure of the surrogate WTORS.	No WTORS failure	Pass
Tiedown hooks of WTORS shall remain engaged with WC securement points.	No hooks detached	Pass
WC-anchored belt restraints shall not detach or completely fail.	WC-anchored lap belt intact and attached.	Pass
Batteries must be within WC footprint	NA - no batteries	NA
Batteries must remain attached to battery compartment	NA - no batteries	NA
Batteries must not contact ATD	NA - no batteries	NA

SUMMARY OF WHEELCHAIR PERFORMANCE

SLED TEST WX2302 – Leggero Enzo WC + SWTORS + Wall

Proposed Requirement	Notes	Pass/Fail
Structural components of the WC securement points shall not completely fail	Securement points did not fail.	Pass
Deformation of WC securement points must not prevent disengagement of hook	Securement points did not deform.	Pass
WC upright and on test platform	WC upright	Pass
ATD must be in WC seat with torso leaning not more than 45˚	ATD in seat with torso upright	Pass
Detached hardware cannot exceed 150 g	Front left frame portion detached >150 g	Fail
WC must not have sharp edges with potential for occupant contact	The front left lateral frame broke with a sharp edge exposed.	Fail
Locking mechanisms of tilt seating cannot release or completely fail.	No tilt release	Pass
Post-test height of ATD H-point shall be >= 20% of pretest height	Post-test H-pt height decreased by 4% from pre-test height	Pass
Average WC width shall not decrease by more than 20% of pretest width	Post-test width did not decrease from pre-test width	Pass
Seating system cannot break free from WC at any attachment point.	Seating stayed attached	Pass
WC cannot cause complete failure of the surrogate WTORS.	No WTORS failure	Pass
Tiedown hooks of WTORS shall remain engaged with WC securement points.	No hooks detached	Pass
WC-anchored belt restraints shall not detach or completely fail.	WC-anchored lap belt intact and attached.	Pass
Batteries must be within WC footprint	NA - no batteries	NA
Batteries must remain attached to battery compartment	NA - no batteries	NA
Batteries must not contact ATD	NA - no batteries	NA

SUMMARY OF WTORS PERFORMANCE

SLED TEST WX2305 – SWCSI + 4-PT #1

Proposed Requirement	Notes	Pass/Fail
ATD must be in WC seat with torso leaning not more than 45˚	ATD in seat with torso upright	Pass
WC upright and on test platform	WC upright	Pass
Primary load-carrying parts and components of a WTORS shall not completely fail in the absence of a backup component or structural member without signs of failure	No failure of WTORS	Pass
WTORS must not have sharp edges with potential for occupant contact	No sharp edges	Pass
Detached hardware cannot exceed 150 g	No hardware detached	Pass
WC and ATD can be removed from WTORS without the use of tools	No tools needed	Pass
WC point-P excursion cannot exceed 275 mm	270 mm	Pass
WC back support post angle wrt vertical cannot exceed 12˚	5˚	Pass

SUMMARY OF WTORS PERFORMANCE

SLED TEST WX2307 – SWCSI + 4-PT #2

Proposed Requirement	Notes	Pass/Fail
ATD must be in WC seat with torso leaning not more than 45˚	ATD in seat with torso leaning 5˚ to the left	Pass
WC upright and on test platform	WC upright	Pass
Primary load-carrying parts and components of a WTORS shall not completely fail in the absence of a backup component or structural member without signs of failure	No failure of WTORS	Pass
WTORS must not have sharp edges with potential for occupant contact	No sharp edges	Pass
Detached hardware cannot exceed 150 g	No hardware detached	Pass
WC and ATD can be removed from WTORS without the use of tools	No tools needed	Pass
WC point-P excursion cannot exceed 275 mm	239 mm	Pass
WC back support post angle wrt vertical cannot exceed 12˚	4˚	Pass

SUMMARY OF WTORS PERFORMANCE

SLED TEST WX2308 – SWCSI + Dock #1

Proposed Requirement	**Notes**	**Pass/Fail**
ATD must be in WC seat with torso leaning not more than 45˚	ATD in seat with torso leaning 5˚ to the left	Pass
WC upright and on test platform	WC upright	Pass
Primary load-carrying parts and components of a WTORS shall not completely fail in the absence of a backup component or structural member without signs of failure	No failure of WTORS	Pass
WTORS must not have sharp edges with potential for occupant contact	No sharp edges	Pass
Detached hardware cannot exceed 150 g	No hardware detached	Pass
WC and ATD can be removed from WTORS without the use of tools	No tools needed	Pass
WC point-P excursion cannot exceed 275 mm	136 mm	Pass
WC back support post angle wrt vertical cannot exceed 12˚	14˚	Fail

SUMMARY OF WTORS PERFORMANCE

SLED TEST WX2309 – SWCSI + Dock #2

Proposed Requirement	**Notes**	**Pass/Fail**
ATD must be in WC seat with torso leaning not more than 45˚	ATD in seat with torso leaning 10˚ to the left	Pass
WC upright and on test platform	WC upright	Pass
Primary load-carrying parts and components of a WTORS shall not completely fail in the absence of a backup component or structural member without signs of failure	No failure of WTORS	Pass
WTORS must not have sharp edges with potential for occupant contact	No sharp edges	Pass
Detached hardware cannot exceed 150 g	No hardware detached	Pass
WC and ATD can be removed from WTORS without the use of tools	No tools needed	Pass
WC point-P excursion cannot exceed 275 mm	161 mm	Pass
WC back support post angle wrt vertical cannot exceed 12˚	17˚	Fail

Appendix F: SWCSI Design Testing Results

Figure 131. Kinematics for WX2212, Ki Mobility+SWTORS, nearside with wall, from -20 to 120 ms every 20 ms.

Figure 132. Kinematics for WX2208, Quickie 2+SWTORS, nearside with wall, from -20 to 120 ms every 20 ms.

Figure 133. Kinematics for WX2302, Leggero+SWTORS, nearside with wall, from -20 to 120 ms every 20 ms.

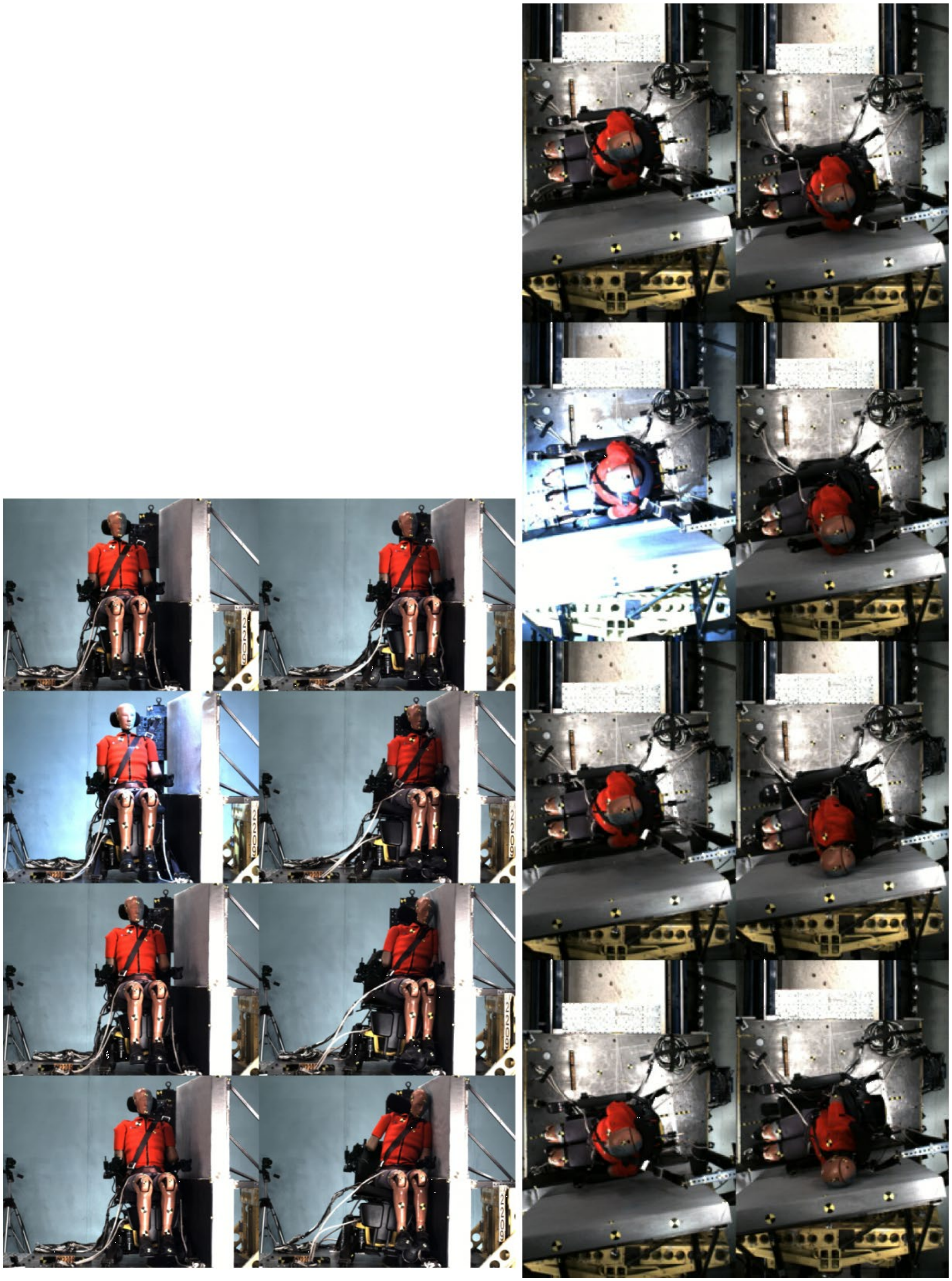


Figure 134. Kinematics for WX2209, Quantum Edge+SWTORS, nearside with wall, from -20 to 120 ms every 20 ms.

Figure 135. Kinematics for WX2207, SWCB+SWTORS, nearside with wall, from -20 to 120 ms every 20 ms.

Figure 136. Kinematics for WX2303, SWCSI+SWTORS, nearside with wall, from 0 to 140 ms every 20 ms.

Figure 137. Kinematics for WX2213, Ki Mobility+SWTORS, nearside (center) without wall, from -20 to 120 ms every 20 ms.

Figure 138. Kinematics for WX2214, Quickie 2+SWTORS, nearside (center) without wall, from -20 to 120 ms every 20 ms.

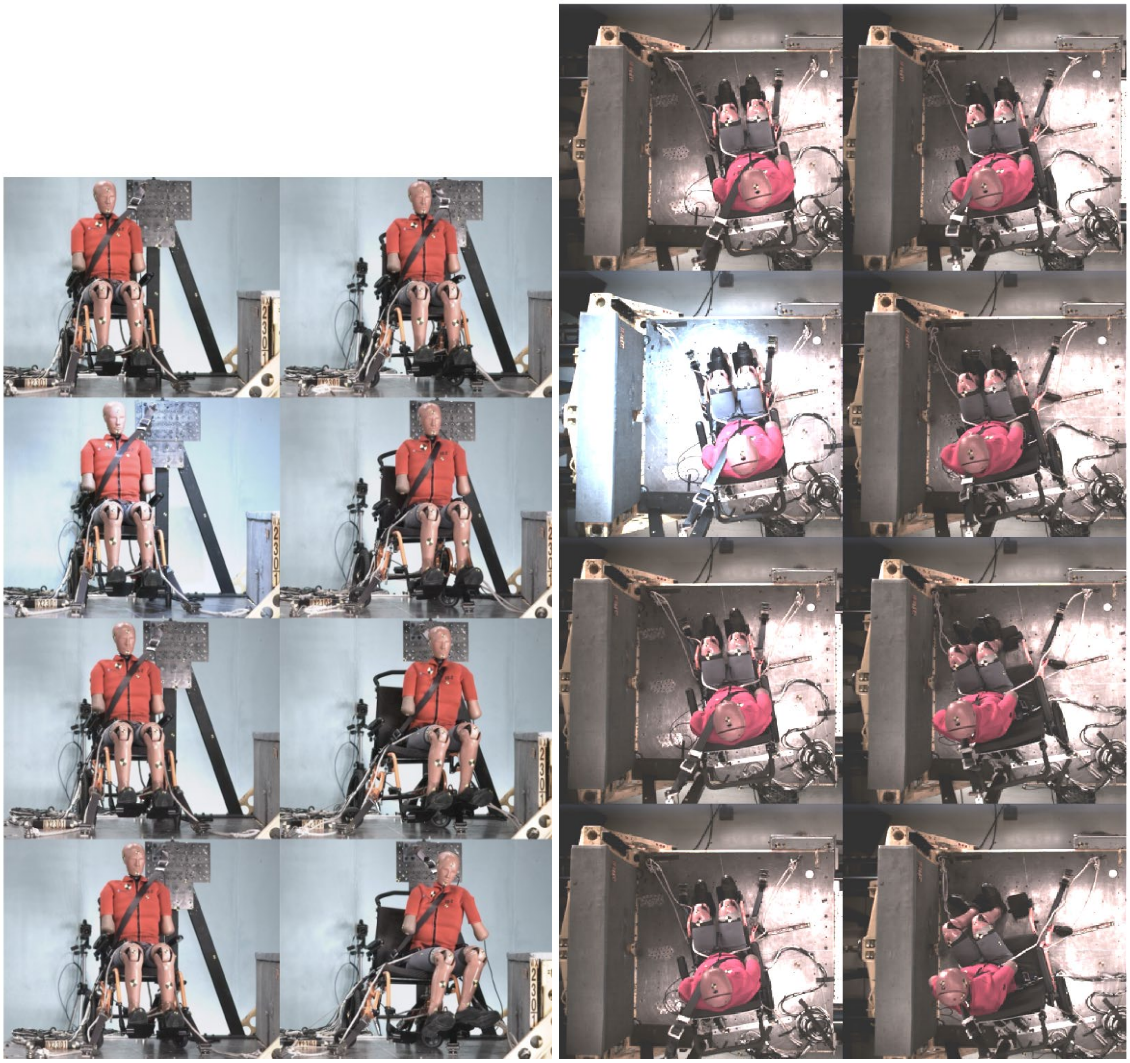


Figure 139. Kinematics for WX2301, Leggero+SWTORS, nearside (center) without wall, from -20 to 120 ms every 20 ms.

Figure 140. Kinematics for WX2310, SWCB+SWTORS, nearside (center) without wall, from -20 to 120 ms every 20 ms.

Figure 141. Kinematics for WX2304, SWCSI+SWTORS, nearside (center) without wall, from -20 to 120 ms every 20 ms.

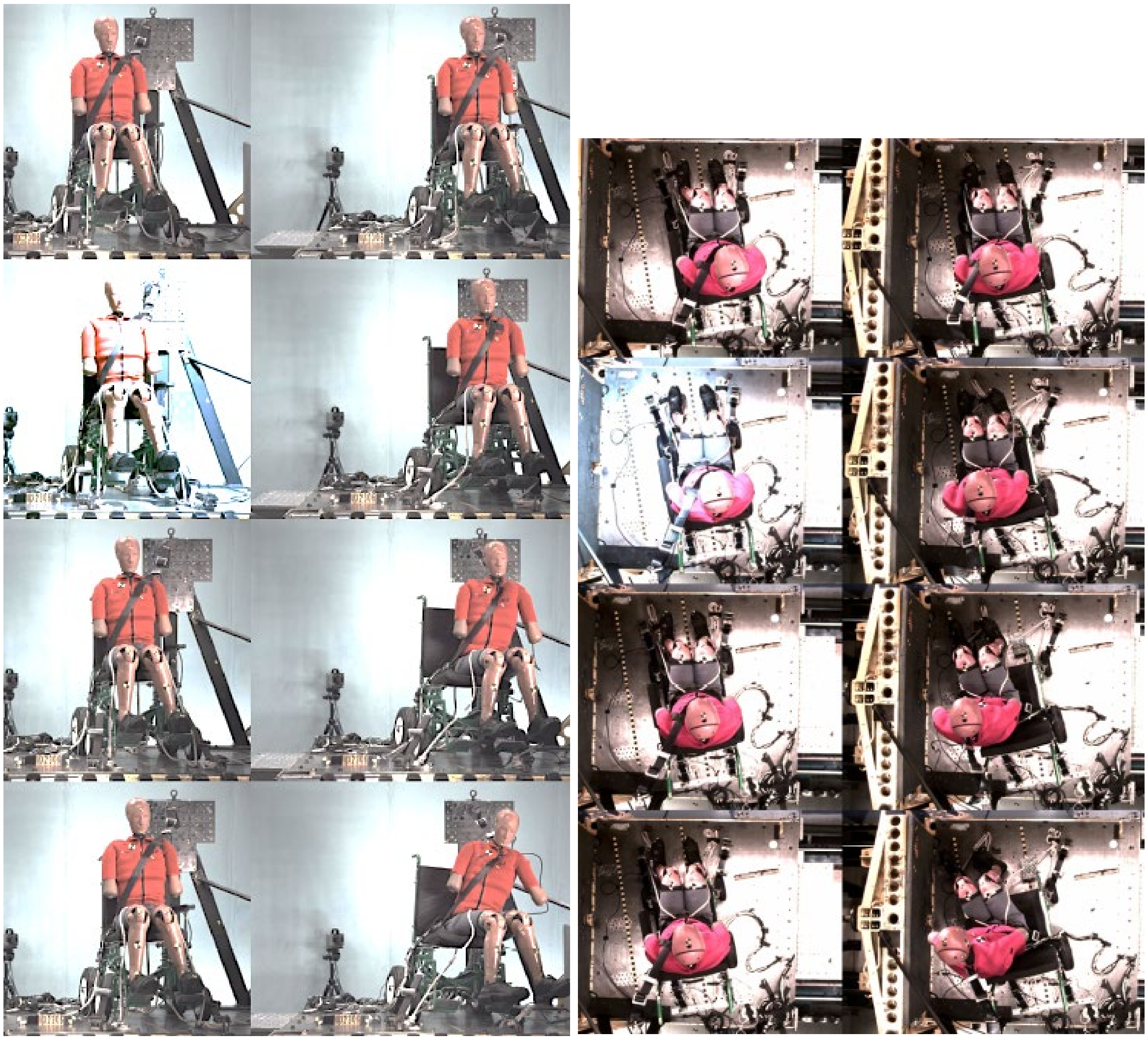


Figure 142. Kinematics for WX2306, SWCSI+SWTORS, nearside (center) without wall, from -20 to 120 ms every 20 ms.

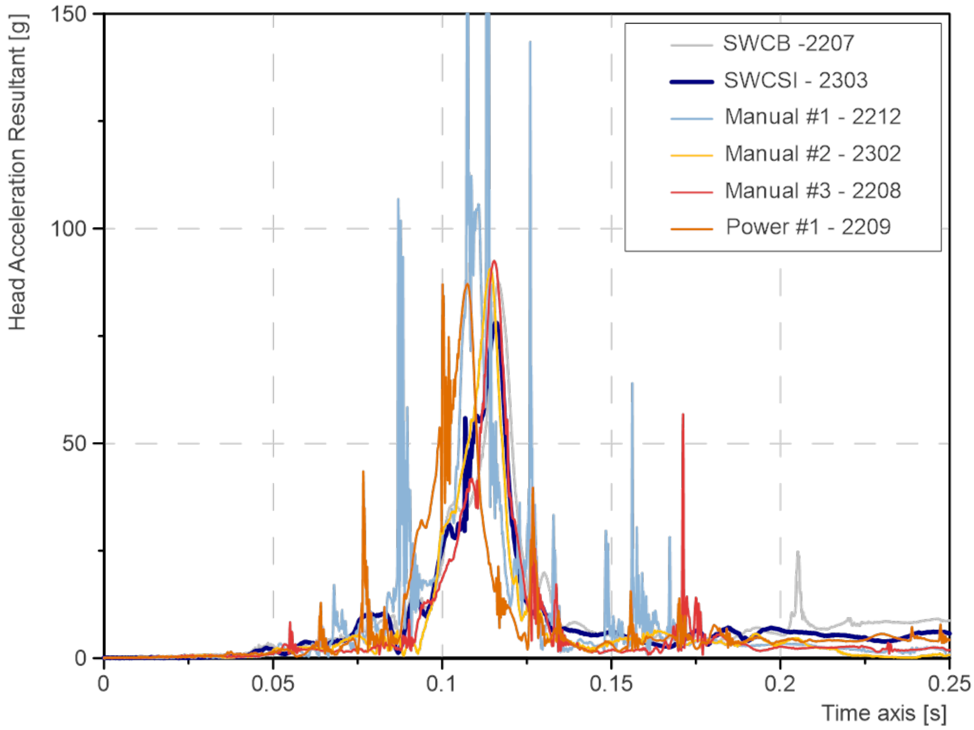


Figure 143. Head resultant accelerations in nearside tests with wall of SWCB, SWCSI, and commercial wheelchair tests secured by SWTORS.

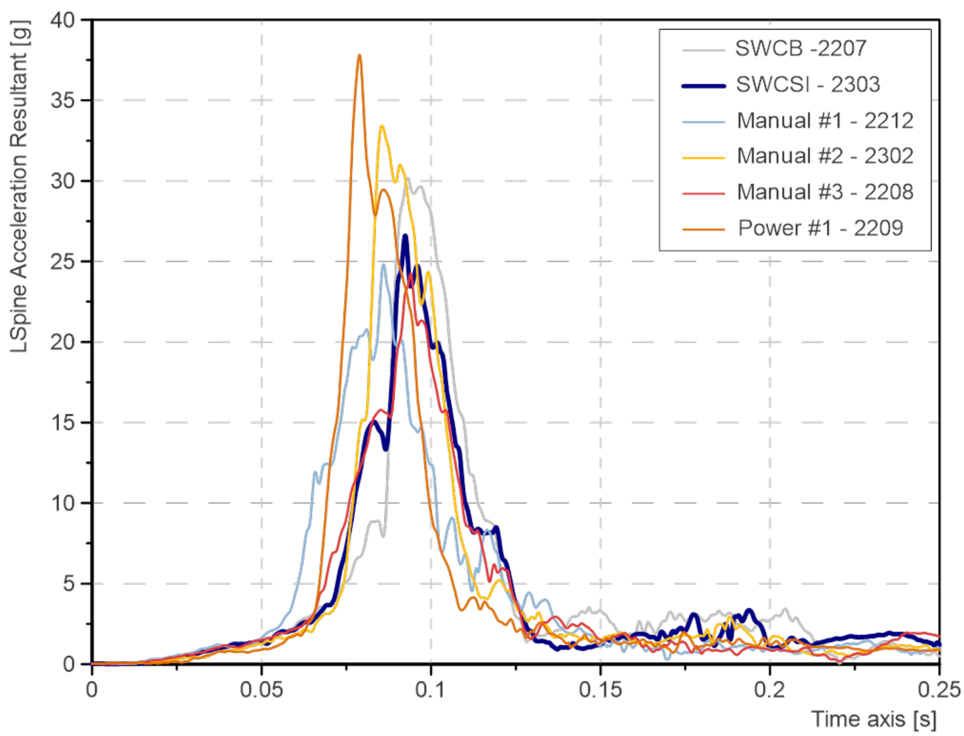


Figure 144. Spine resultant accelerations in nearside tests with wall of SWCB, SWCSI, and commercial wheelchair tests secured by SWTORS.

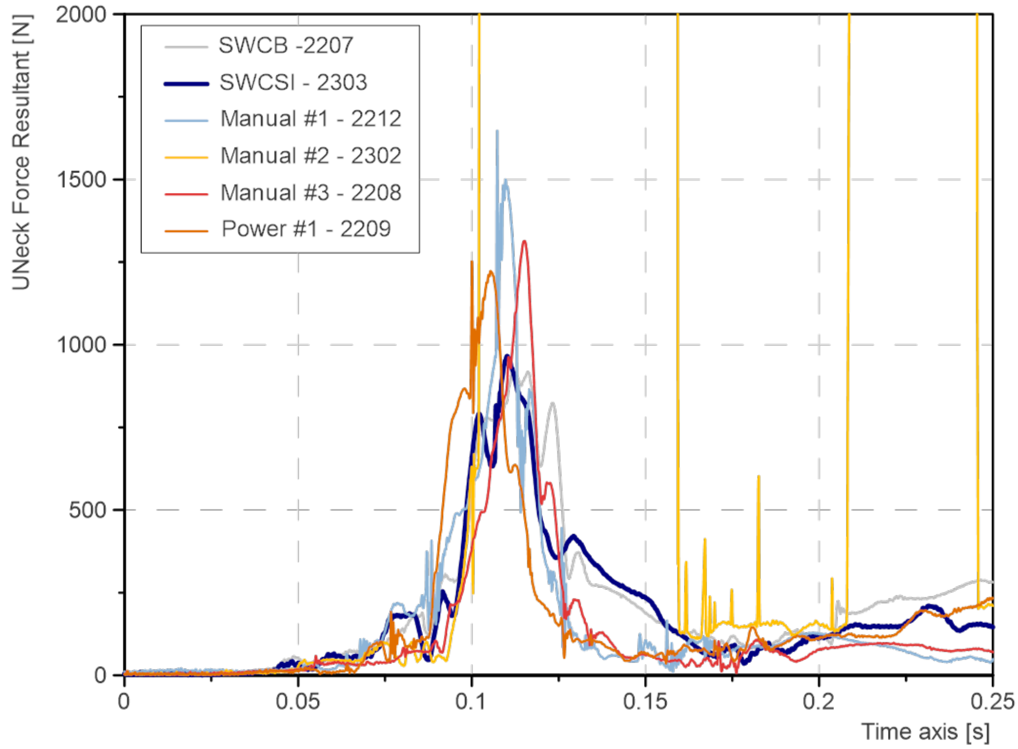


Figure 145. Upper neck resultant force in nearside tests with wall of SWCB, SWCSI, and commercial wheelchair tests secured by SWTORS.

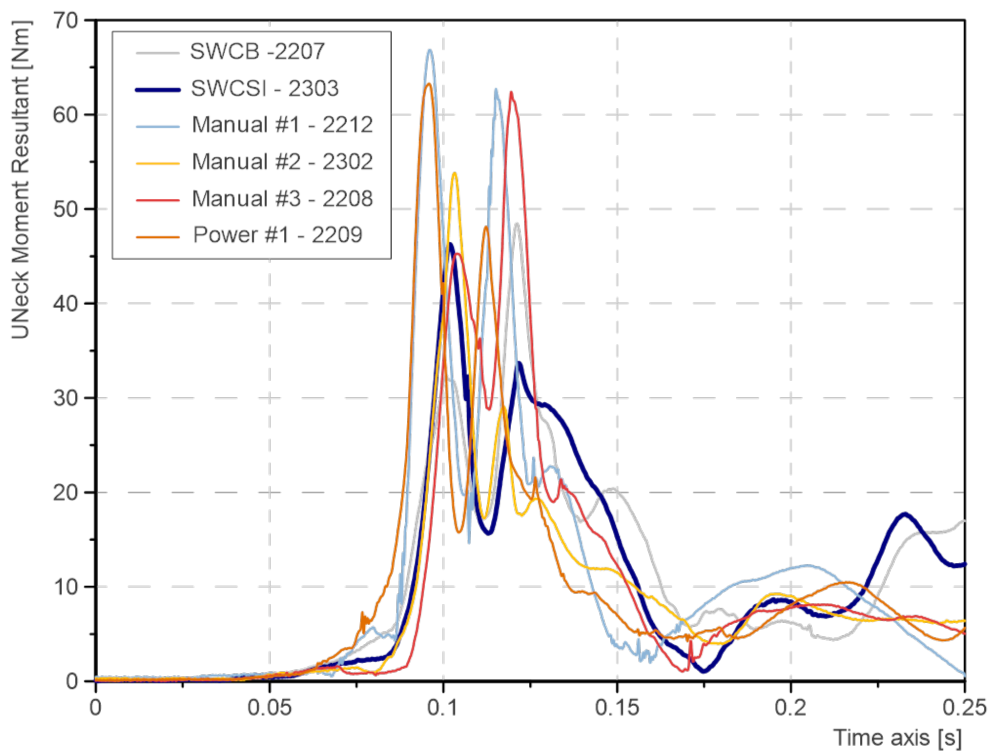


Figure 146. Upper neck resultant moment in nearside tests with wall of SWCB, SWCSI, and commercial wheelchair tests secured by SWTORS.

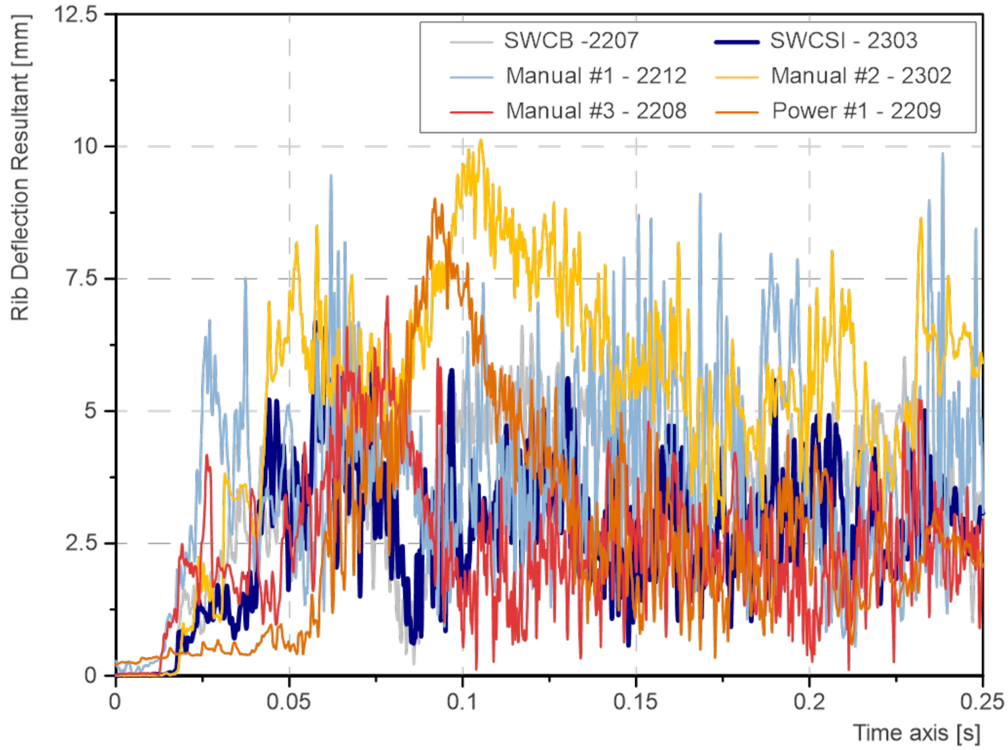


Figure 147. Rib resultant deflection in nearside tests with wall of SWCB, SWCSI, and commercial wheelchair tests secured by SWTORS.

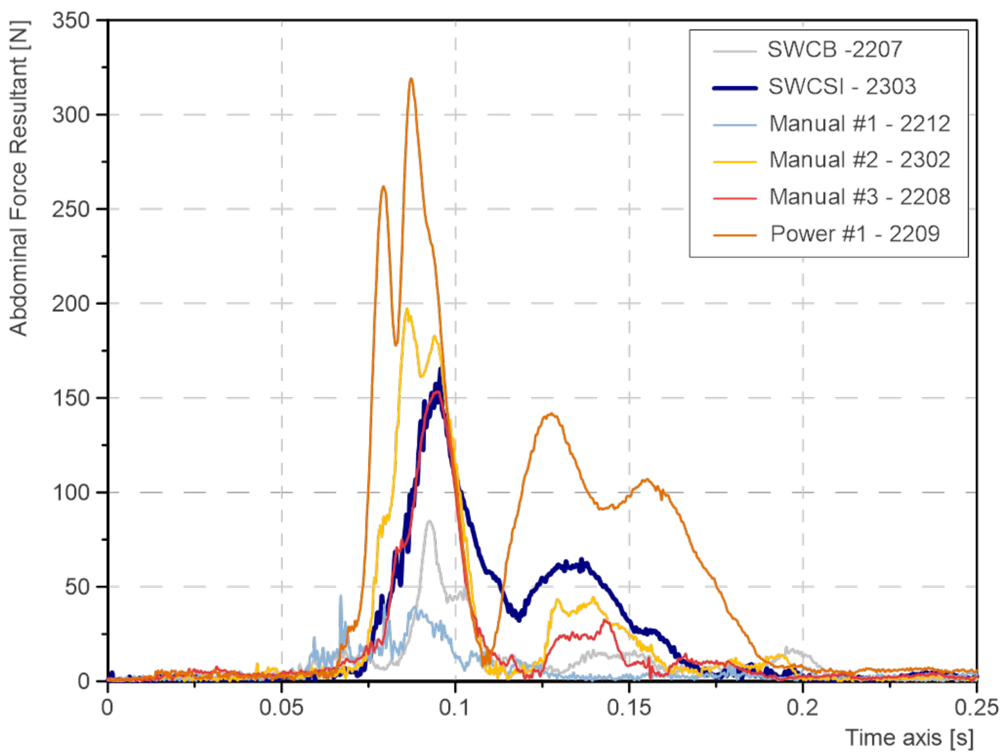


Figure 148. Abdomen resultant force in nearside tests with wall of SWCB, SWCSI, and commercial wheelchair tests secured by SWTORS.

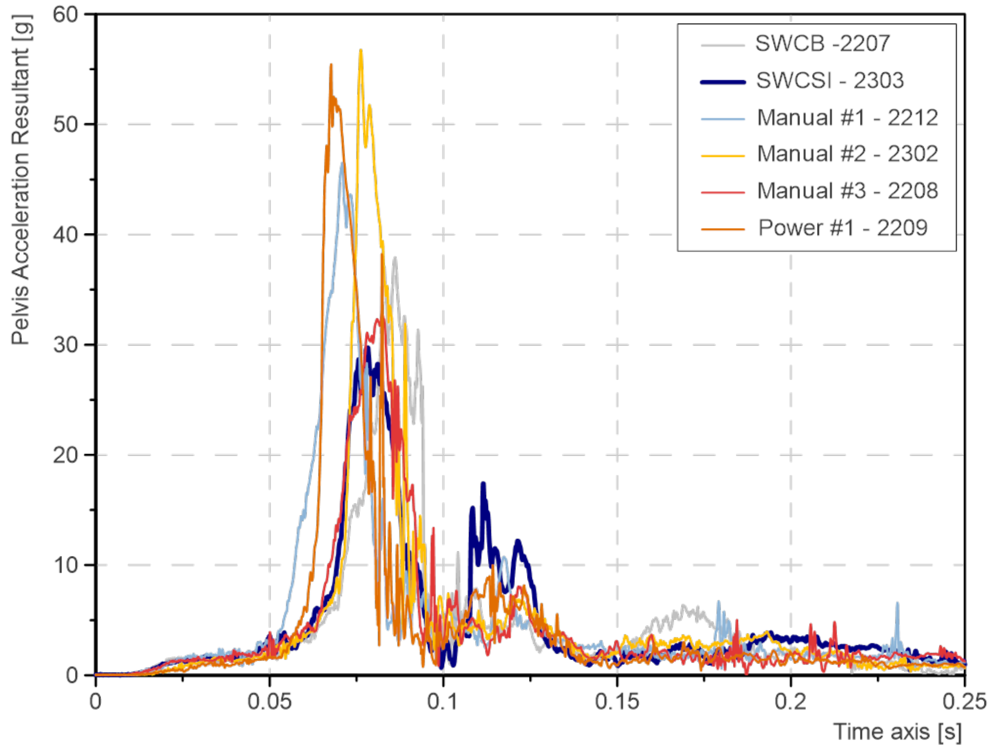


Figure 149. Pelvis resultant acceleration in nearside tests with wall of SWCB, SWCSI, and commercial wheelchair tests secured by SWTORS.

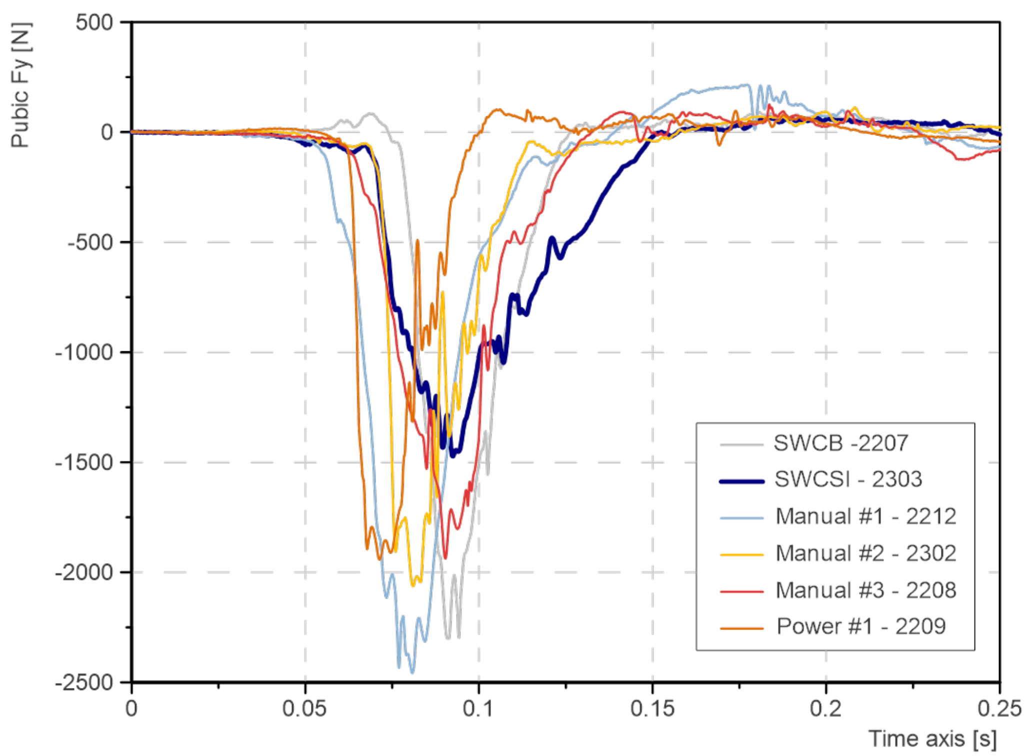


Figure 150. Pubic Y-Force in nearside tests with wall of SWCB, SWCSI, and commercial wheelchair tests secured by SWTORS.

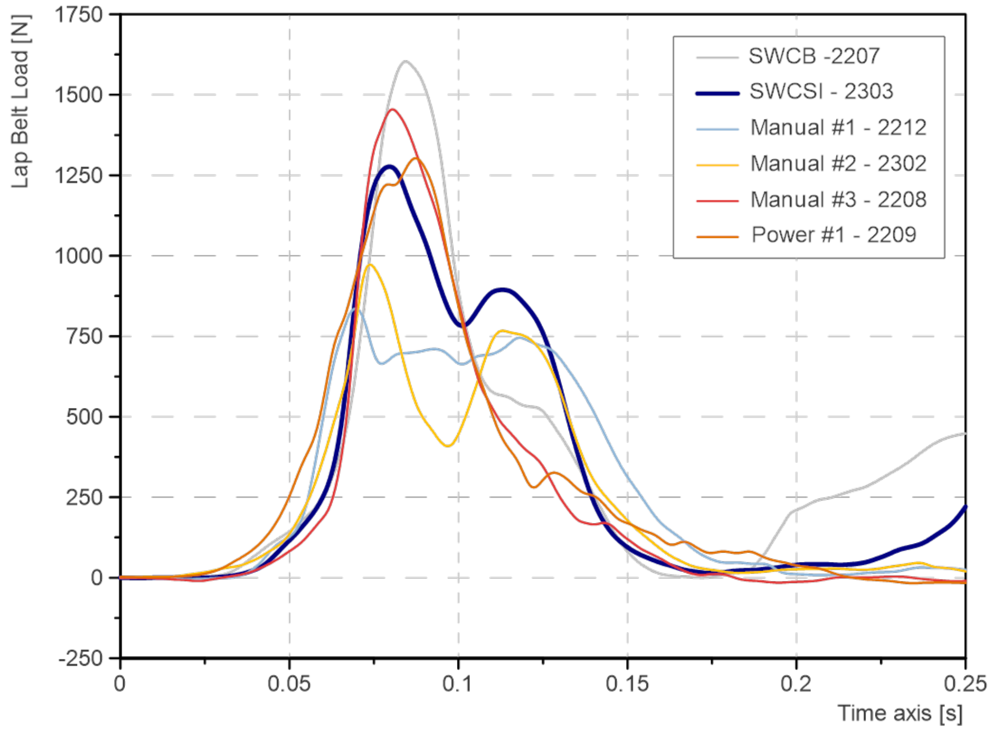


Figure 151. Lap belt load in nearside tests with wall of SWCB, SWCSI, and commercial wheelchair tests secured by SWTORS.

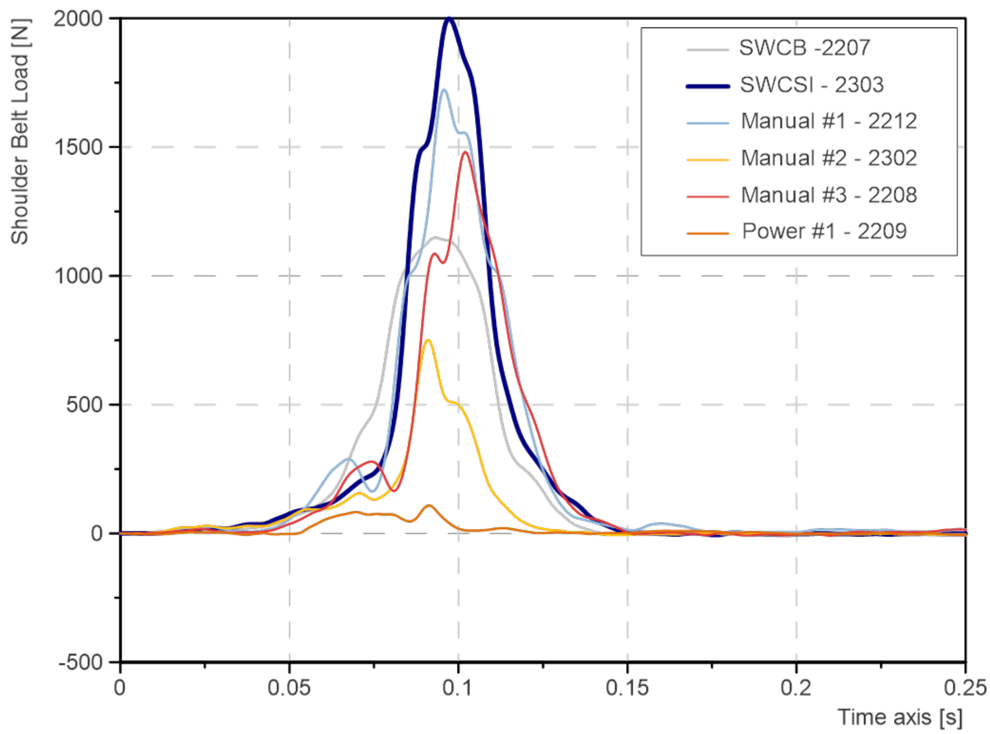


Figure 152. Shoulder belt load in nearside tests with wall of SWCB, SWCSI, and commercial wheelchair tests secured by SWTORS.

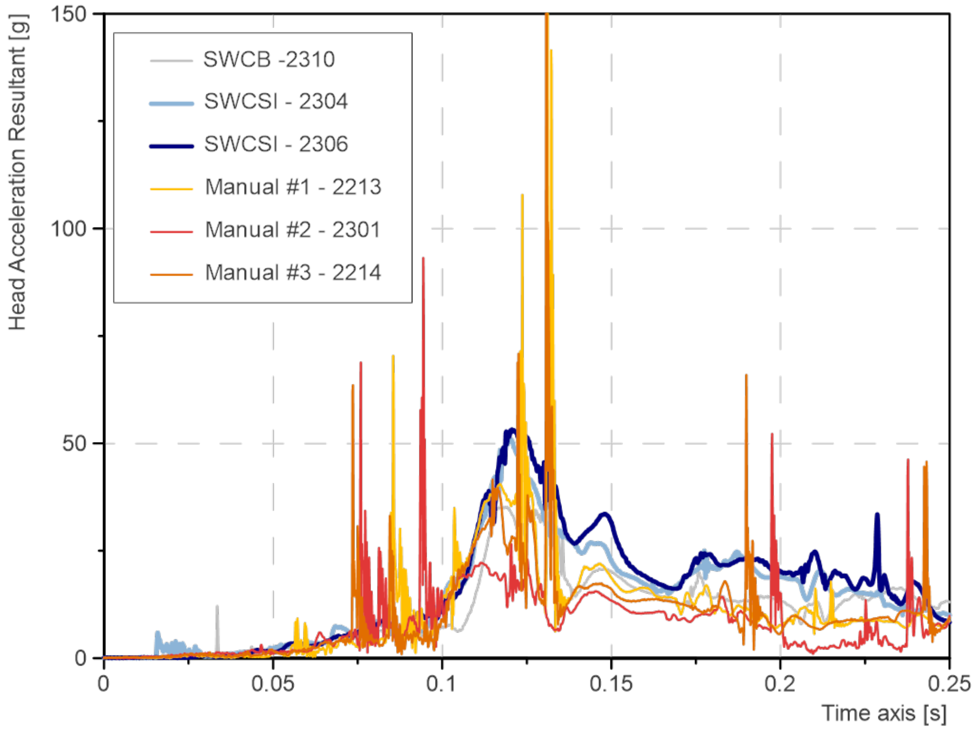


Figure 153. Head resultant accelerations in nearside (center) tests without wall of SWCB, SWCSI, and commercial wheelchair tests secured by SWTORS.

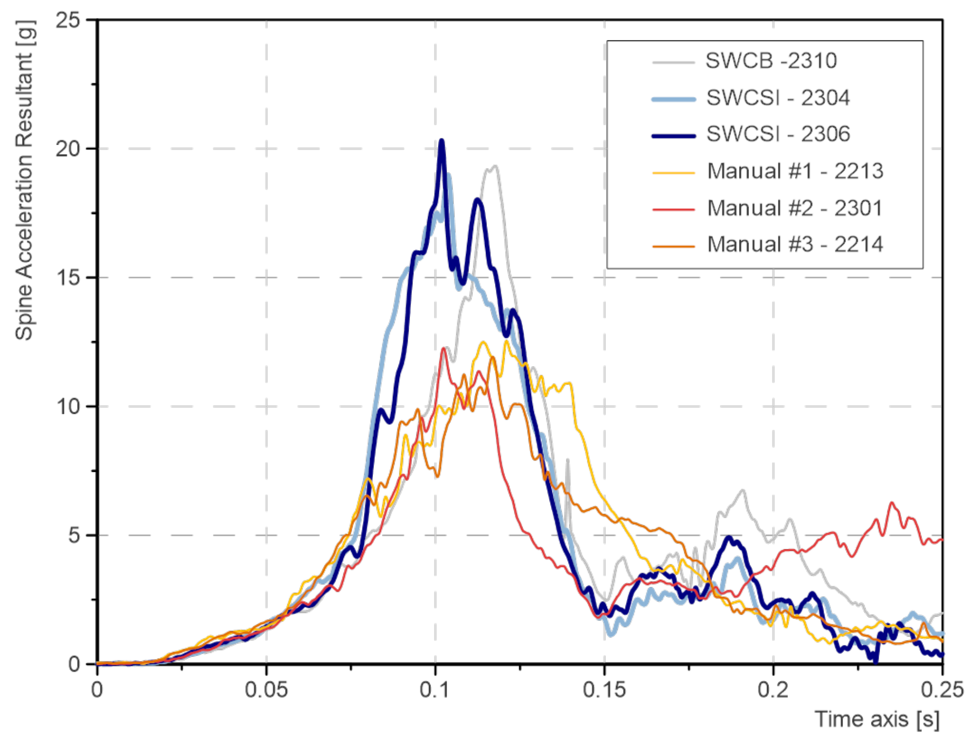
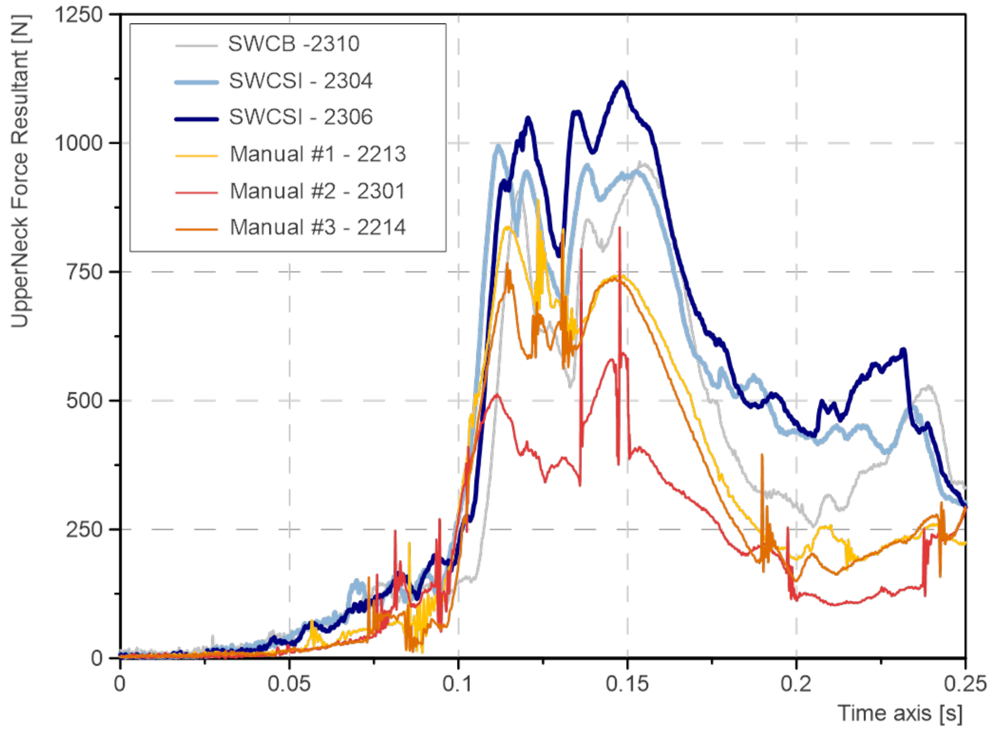


Figure 154. Spine resultant accelerations in nearside (center) tests without wall of SWCB, SWCSI, and commercial wheelchair tests secured by SWTORS.



Upper neck resultant force in nearside (center) tests without wall of SWCB, SWCSI, and commercial wheelchair tests secured by SWTORS.

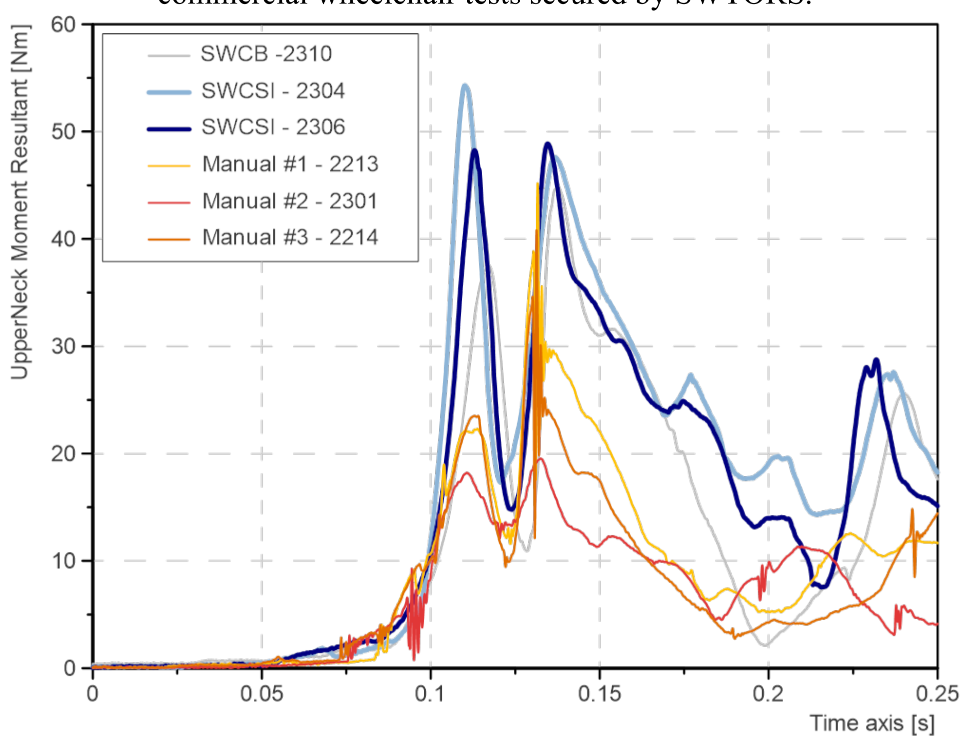


Figure 155. Upper neck resultant moment in nearside (center) tests without wall of SWCB, SWCSI, and commercial wheelchair tests secured by SWTORS.

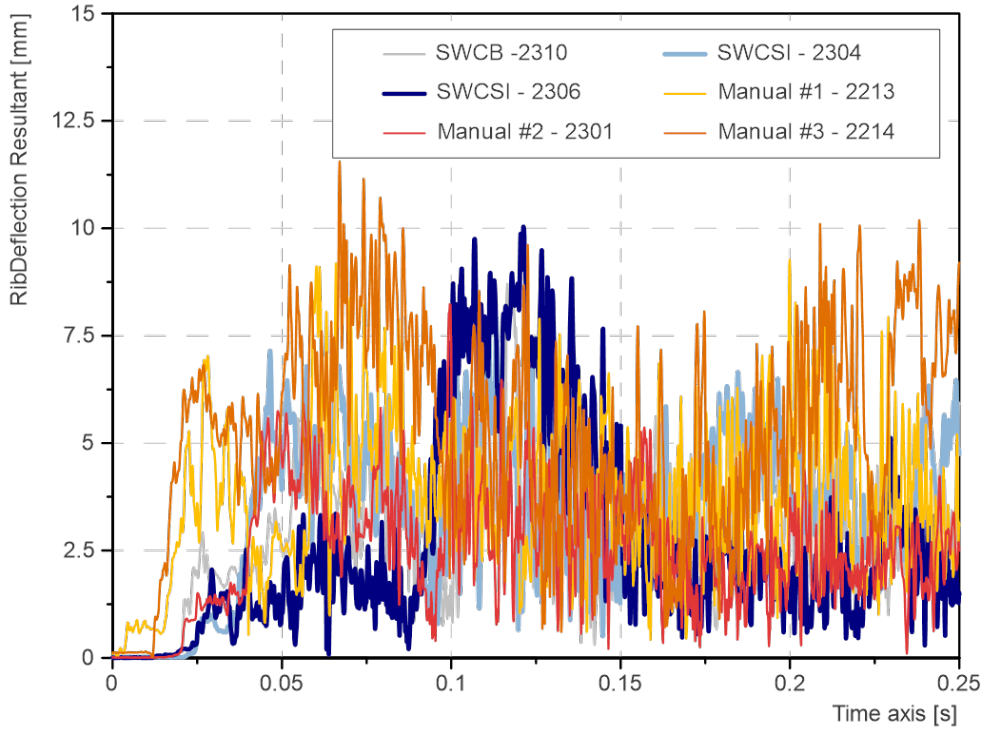


Figure 156. Rib resultant deflection in nearside (center) tests without wall of SWCB, SWCSI, and commercial wheelchair tests secured by SWTORS.

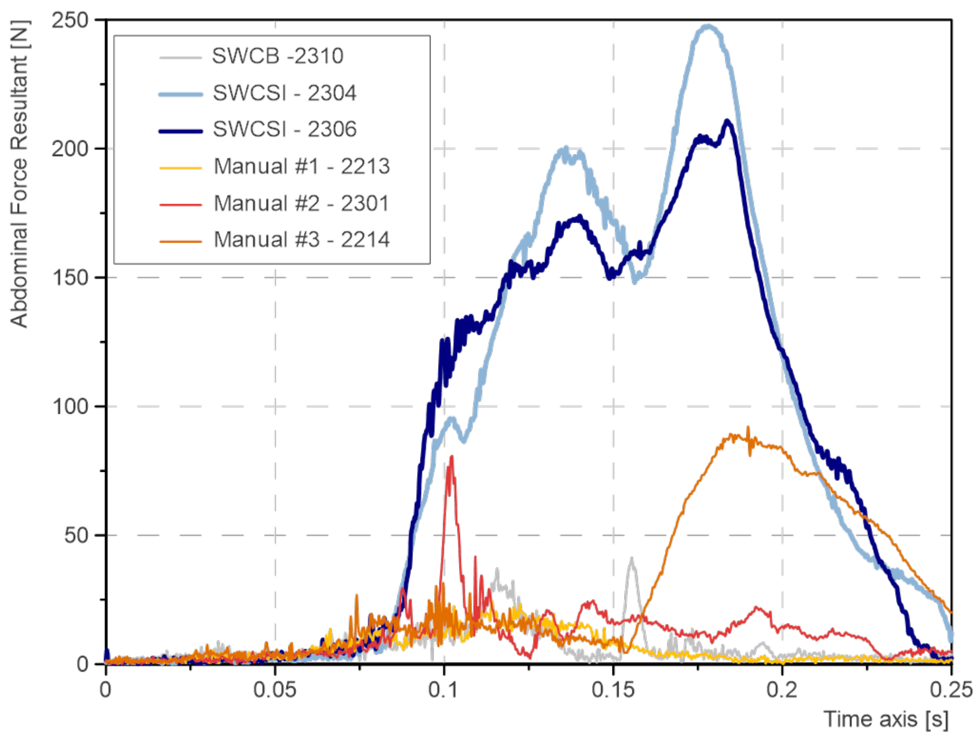


Figure 157. Abdomen resultant force in nearside (center) tests without wall of SWCB, SWCSI, and commercial wheelchair tests secured by SWTORS.

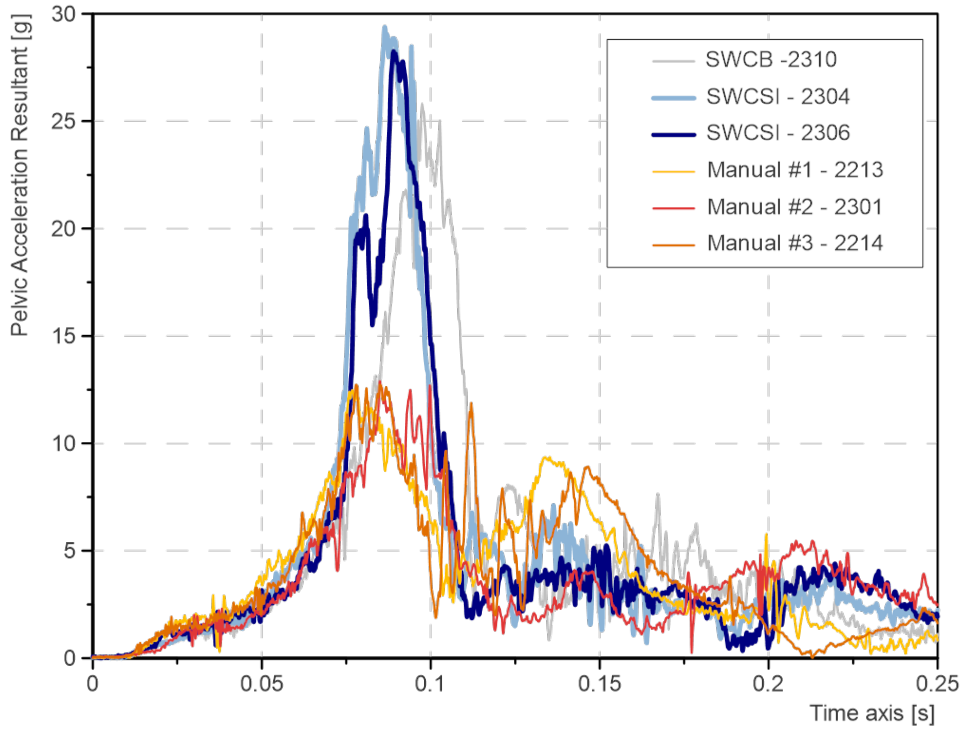


Figure 158. Pelvis resultant acceleration in nearside (center) tests without wall of SWCB, SWCSI, and commercial wheelchair tests secured by SWTORS.

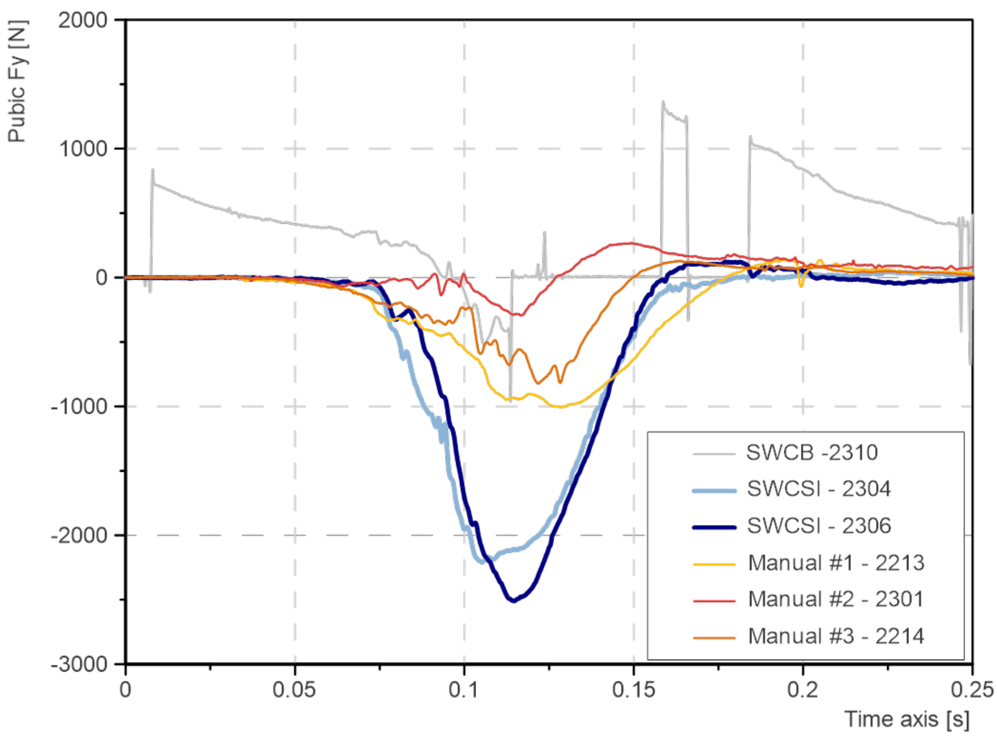


Figure 159. Pubic Y-Force in nearside (center) tests without wall of SWCB, SWCSI, and commercial wheelchair tests secured by SWTORS.

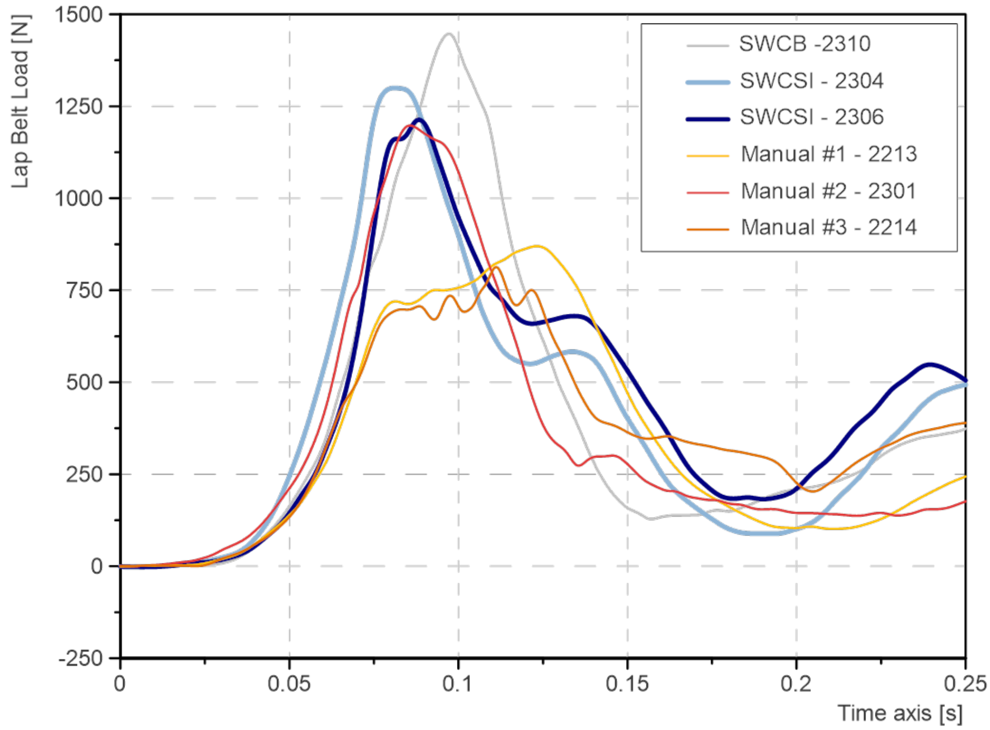


Figure 160. Lap belt load in nearside (center) tests without wall of SWCB, SWCSI, and commercial wheelchair tests secured by SWTORS.

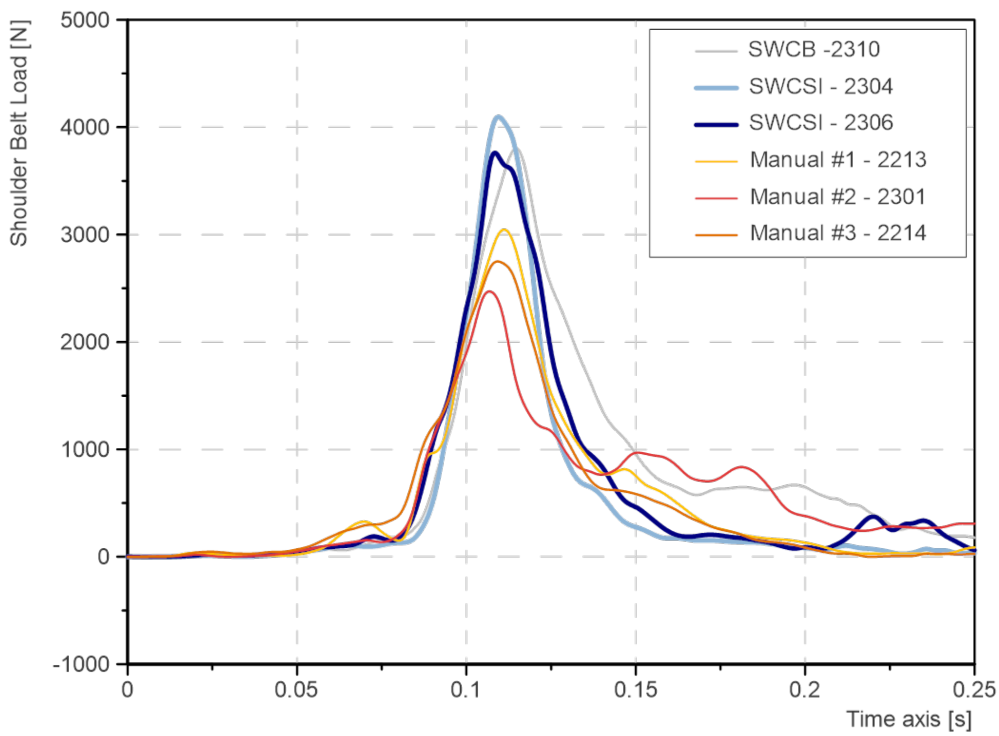


Figure 161. Shoulder belt load in nearside (center) tests without wall of SWCB, SWCSI, and commercial wheelchair tests secured by SWTORS.

Appendix G: WTORS Testing Results

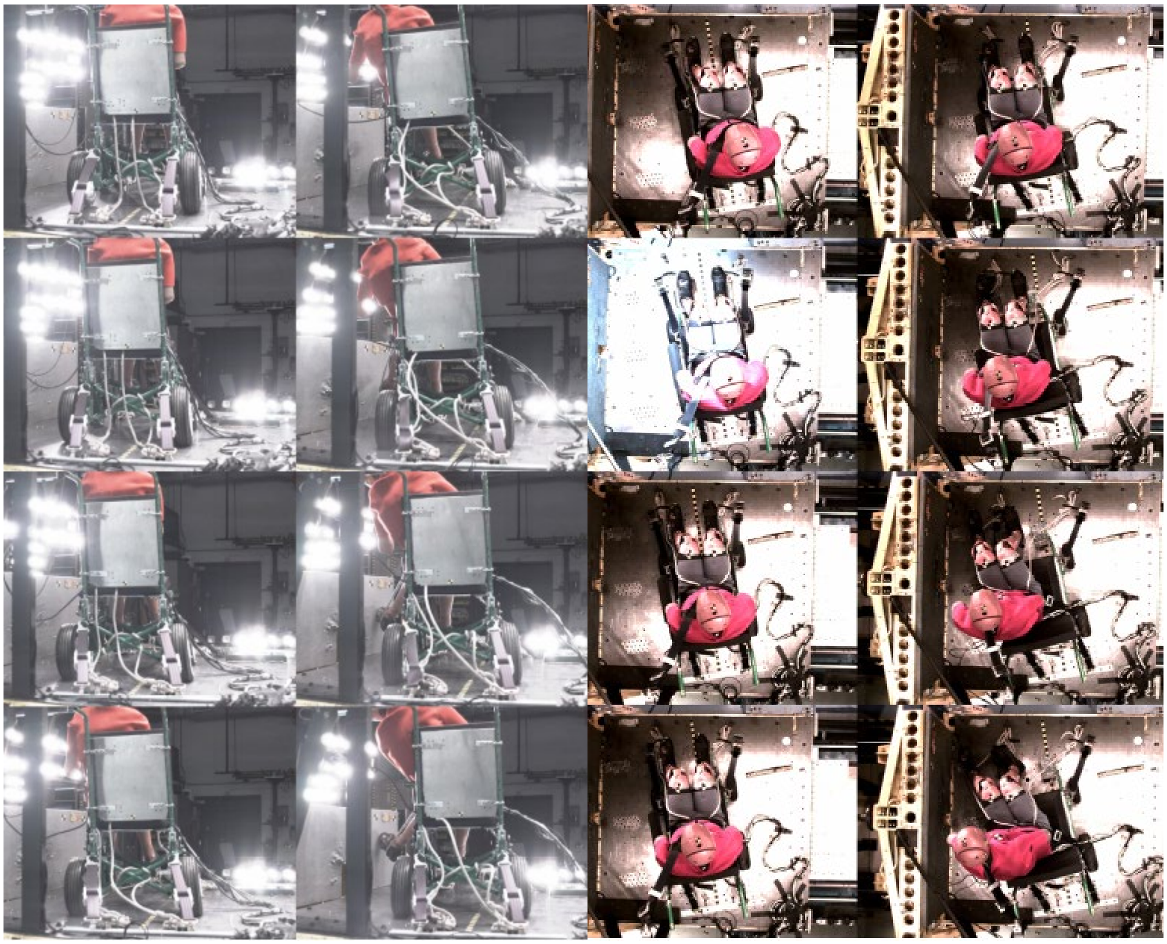


Figure 162. Kinematics for WC2304, SWCSI+SWTORS, from -20 to 120 ms every 20 ms.

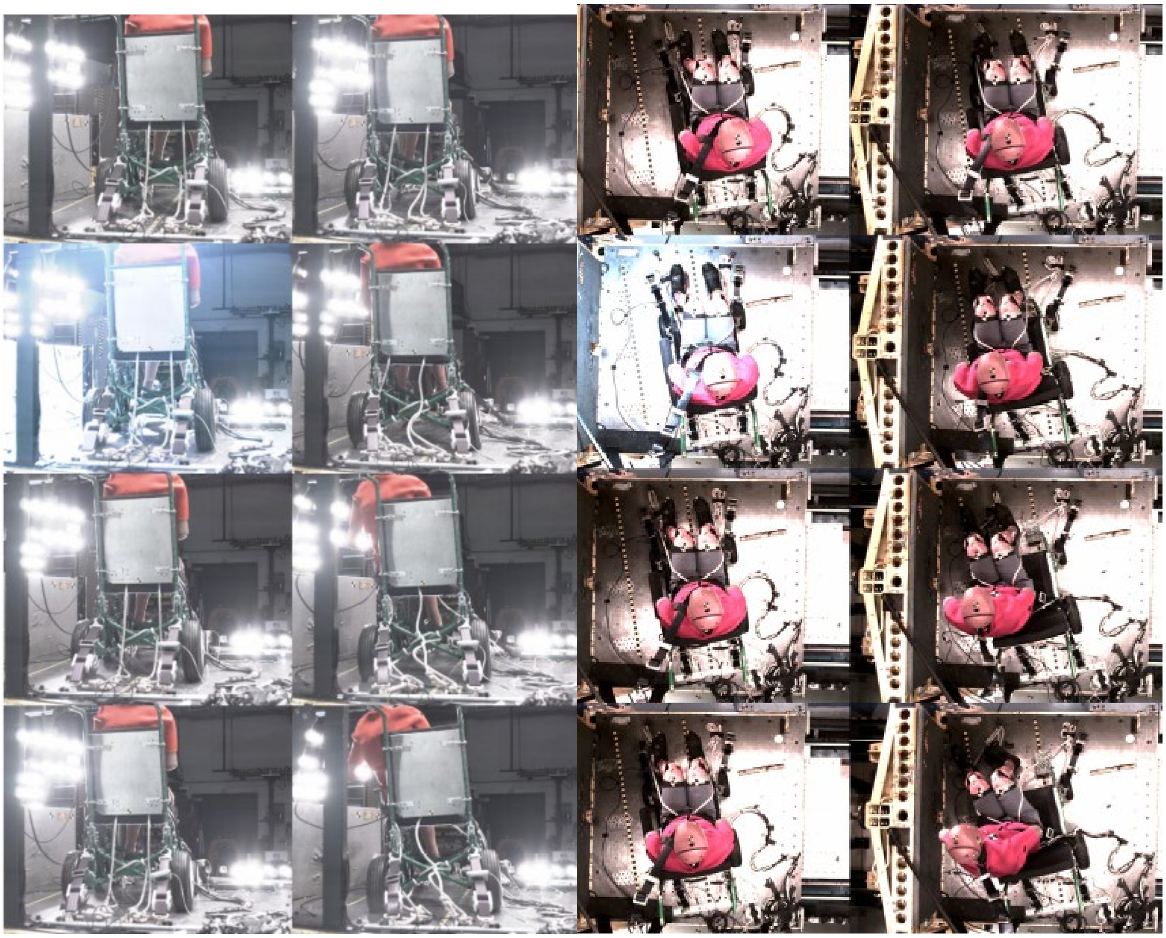


Figure 163. Kinematics for WC2306, SWCSI+SWTORS, -20 to 120 ms every 20 ms.

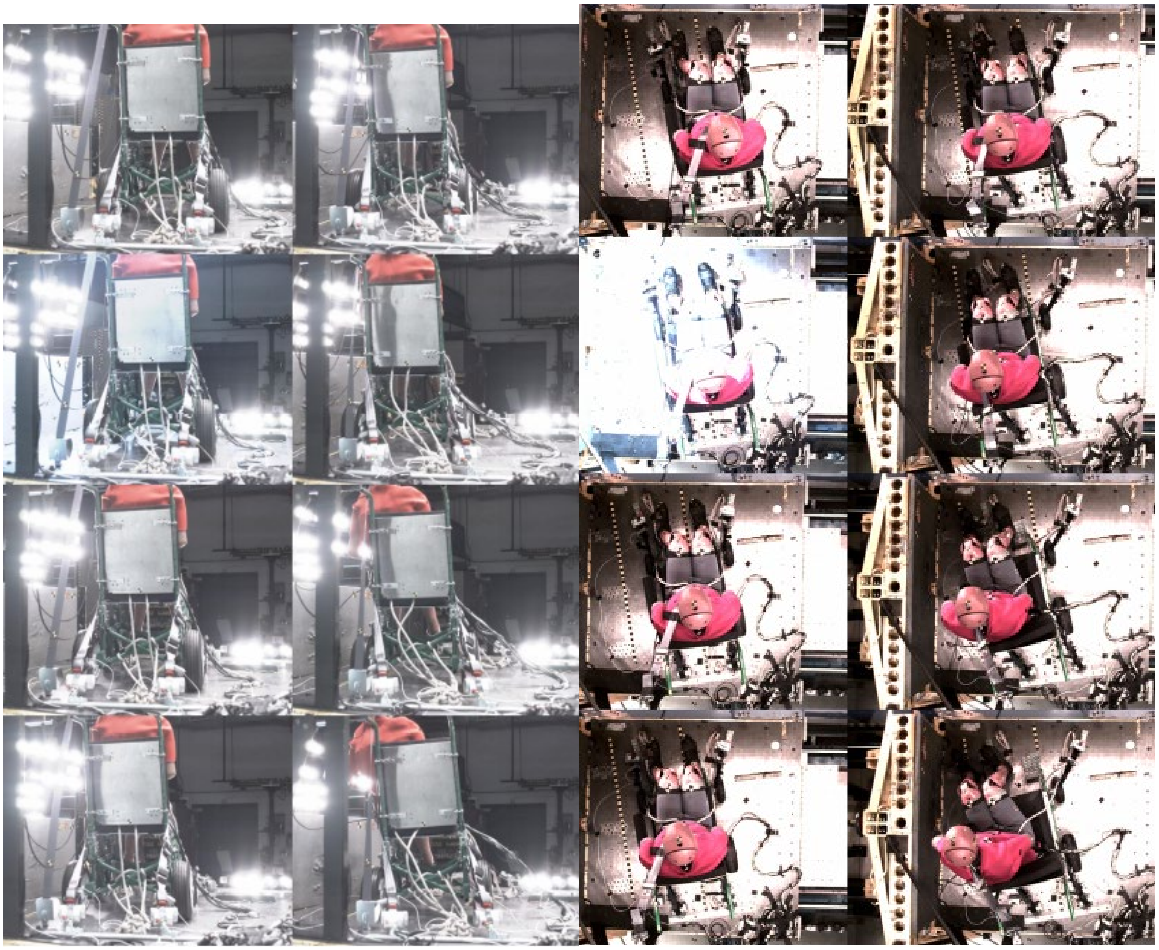


Figure 164. Kinematics for WC2305, SWCSI+4-point #1, -20 to 120 ms every 20 ms.

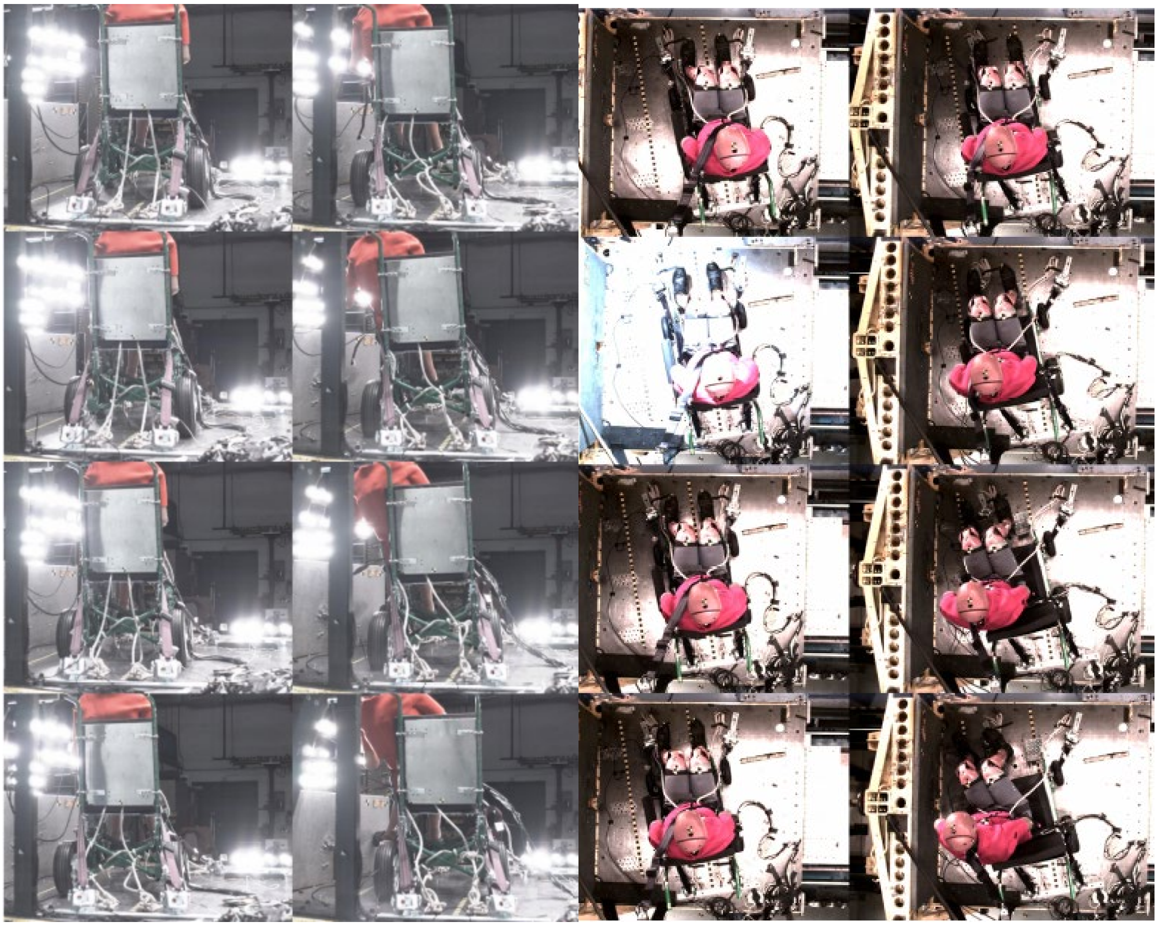


Figure 165. Kinematics for WC2307, SWCSI+4-point #2, -20 to 120 ms every 20 ms.

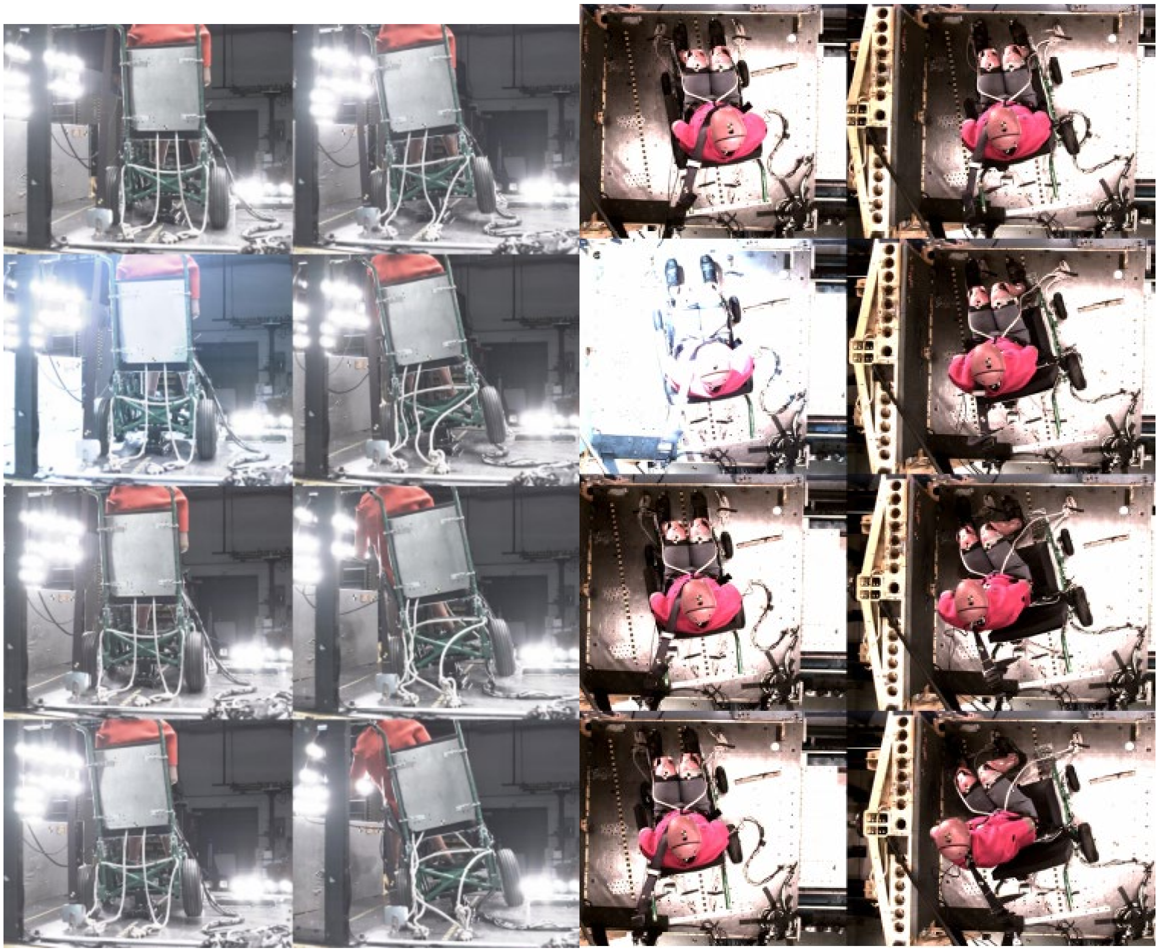


Figure 166. Kinematics for WC2308, SWCSI+Docking #1, -20 to 120 ms every 20 ms.

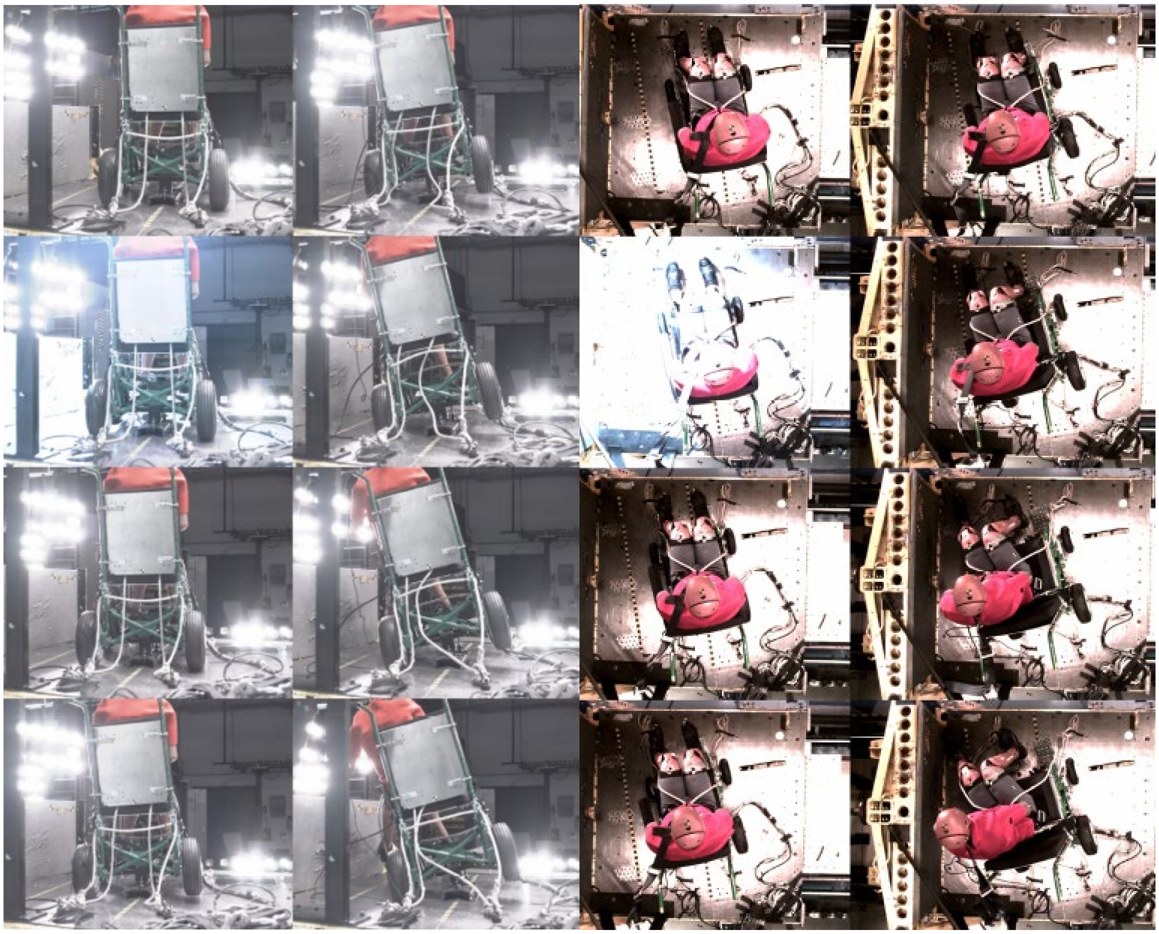
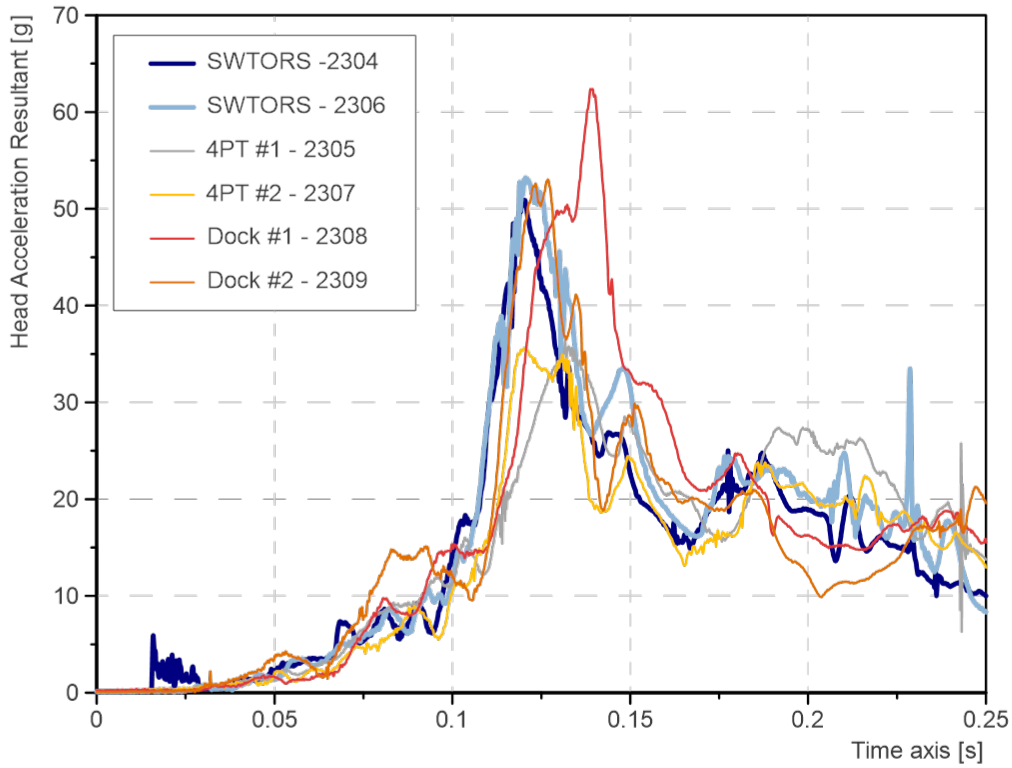


Figure 167. Kinematics for WC2309, SWCSI+Docking #2, -20 to 120 ms every 20 ms.



Overlay plots of head resultant accelerations for four commercial products and SWTORS, evaluated with SWCSI.

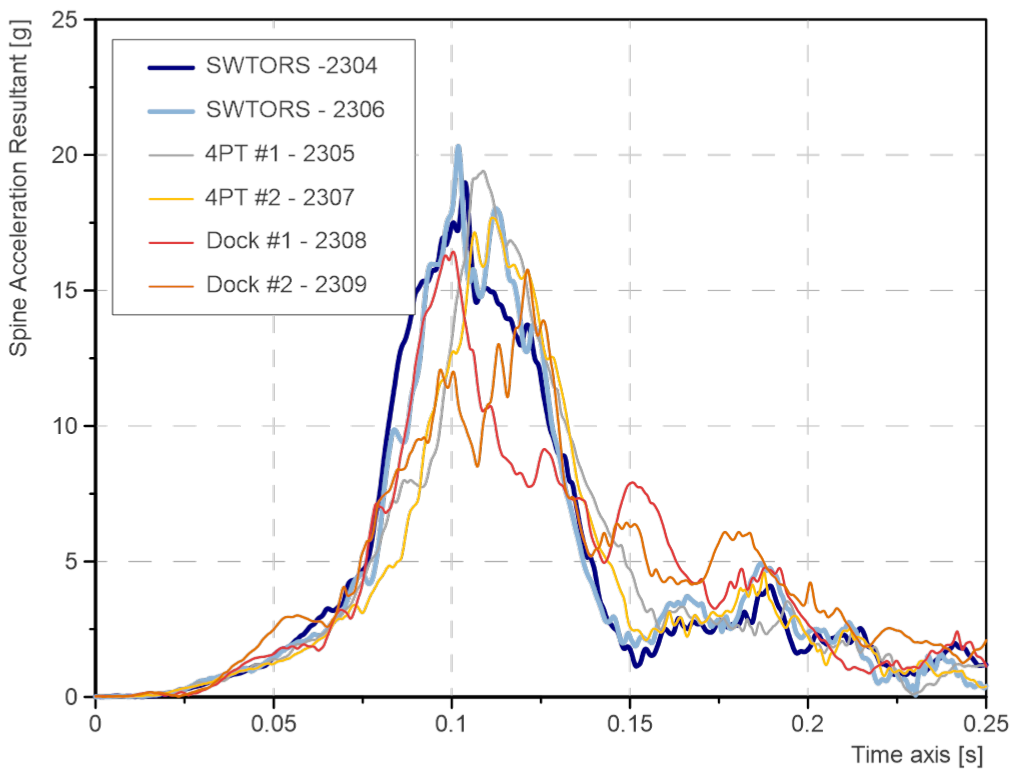


Figure 168. Overlay plots of spine resultant accelerations for four commercial products and SWTORS, evaluated with SWCSI.

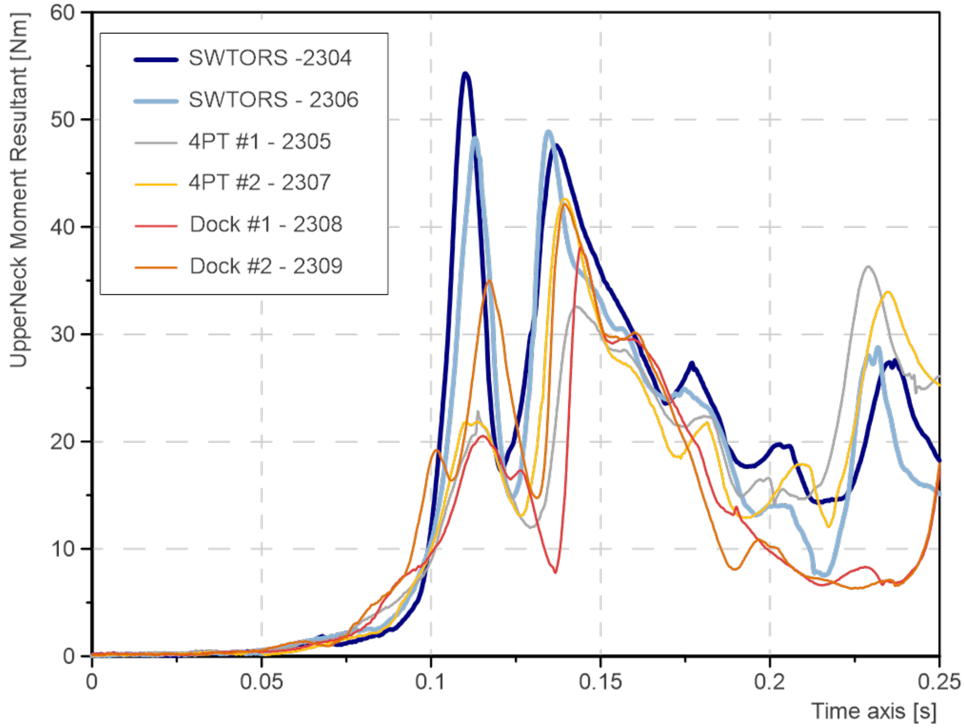


Figure 169. Overlay plots of upper neck resultant moment for four commercial products and SWTORS, evaluated with SWCSI.

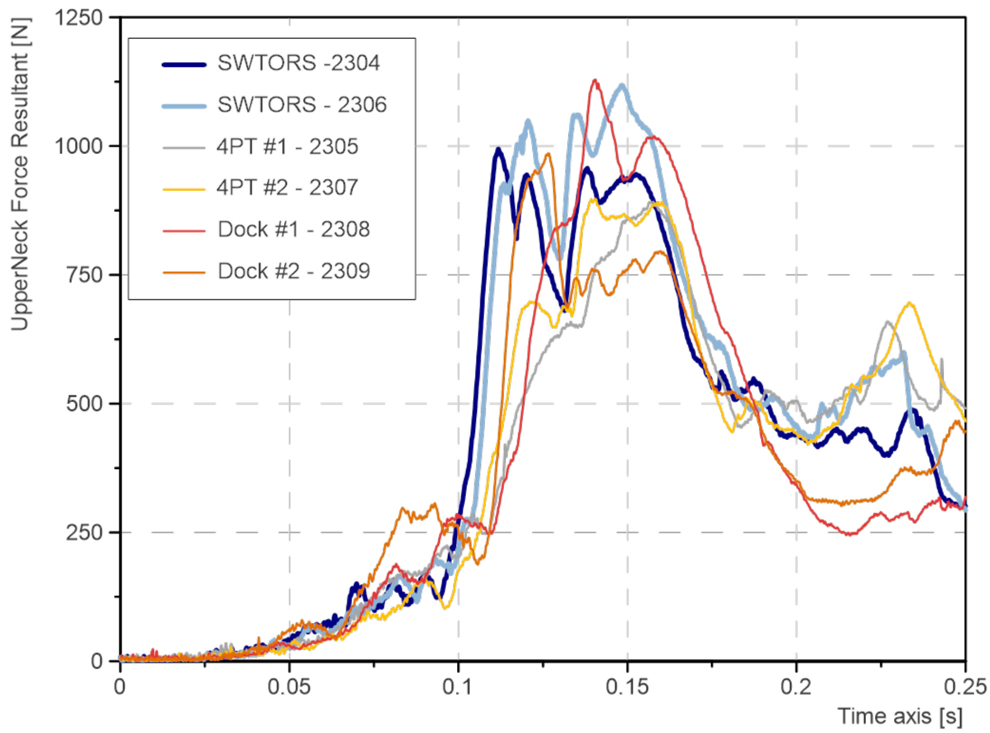


Figure 170. Overlay plots of upper neck resultant force for four commercial products and SWTORS, evaluated with SWCSI

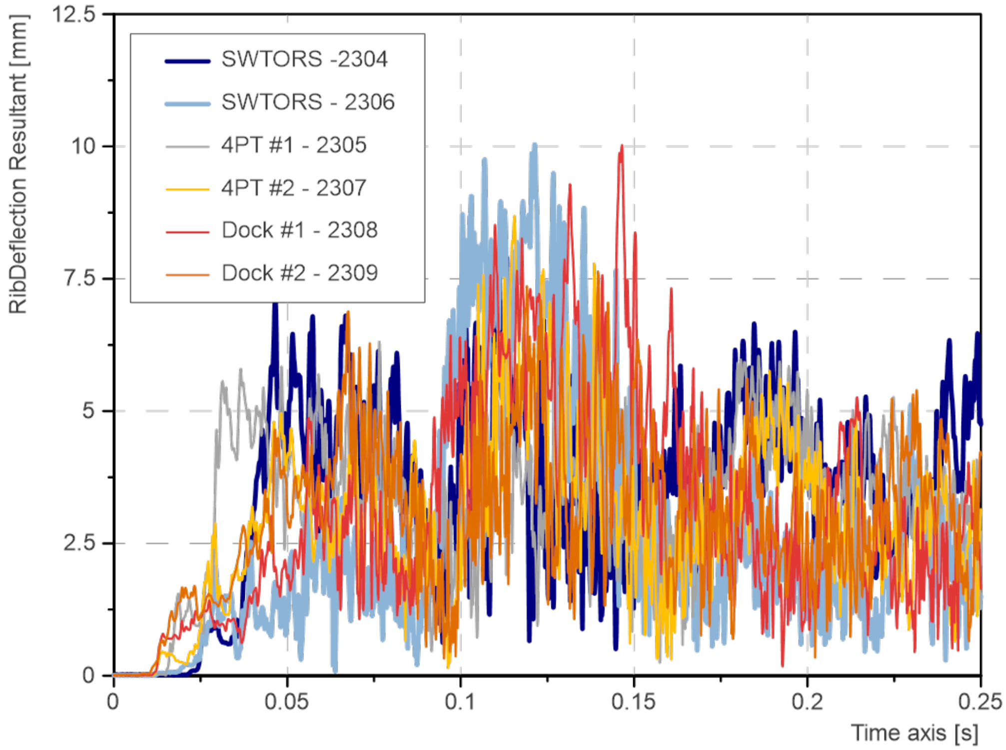


Figure 171. Overlay plots of rib deflection resultant for four commercial products and SWTORS, evaluated with SWCSI.

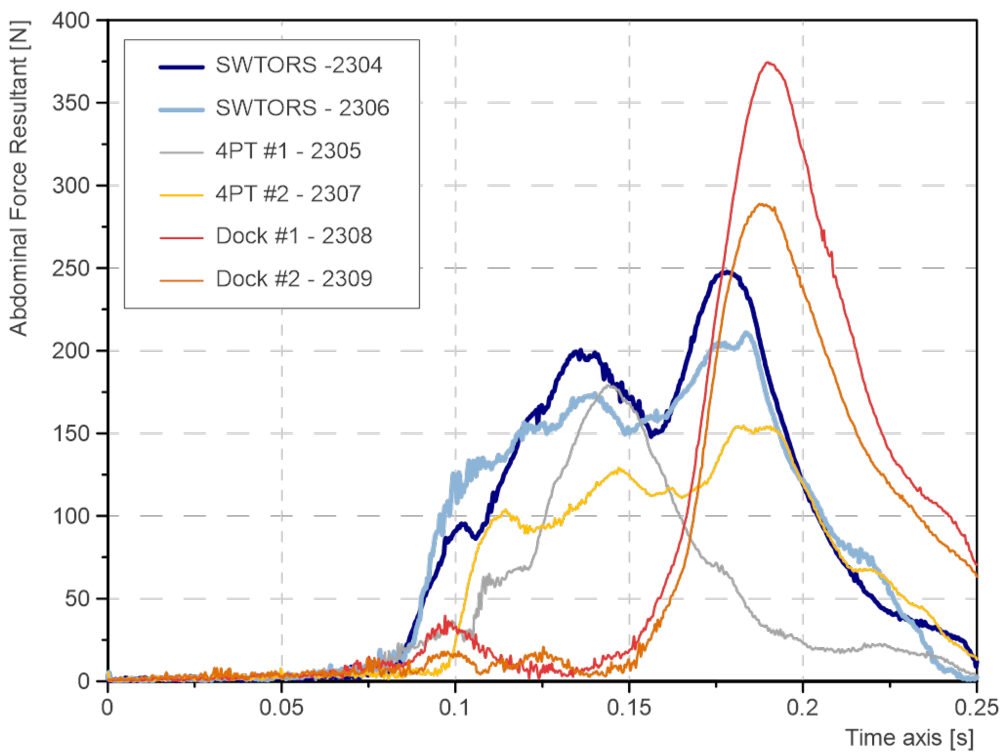


Figure 172. Overlay plots of abdomen force resultant for four commercial products and SWTORS, evaluated with SWCSI.

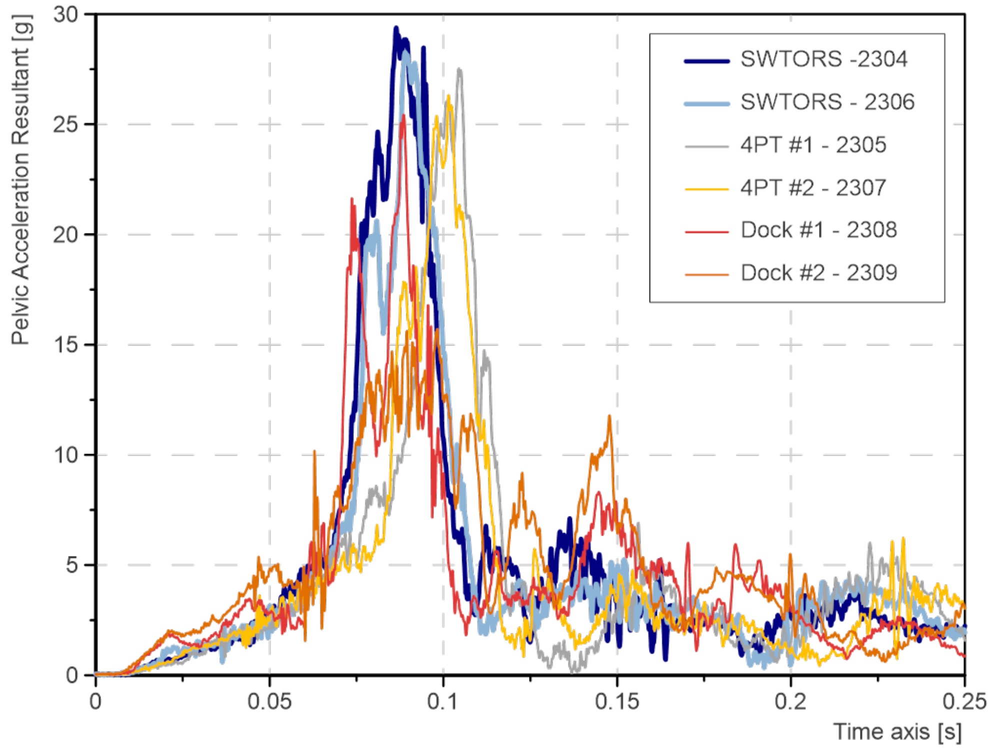


Figure 173. Overlay plots of pelvis acceleration resultant for four commercial products and SWTORS, evaluated with SWCSI.

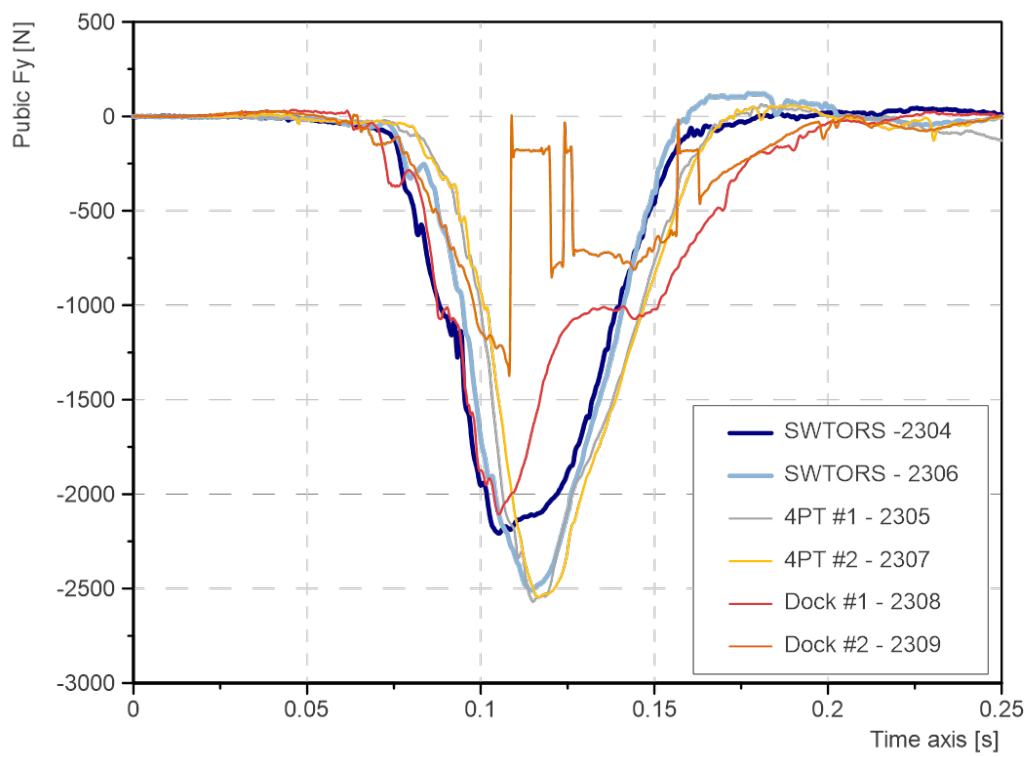


Figure 174. Overlay plots of pubic Y-force for four commercial products and SWTORS, evaluated with SWCSI.

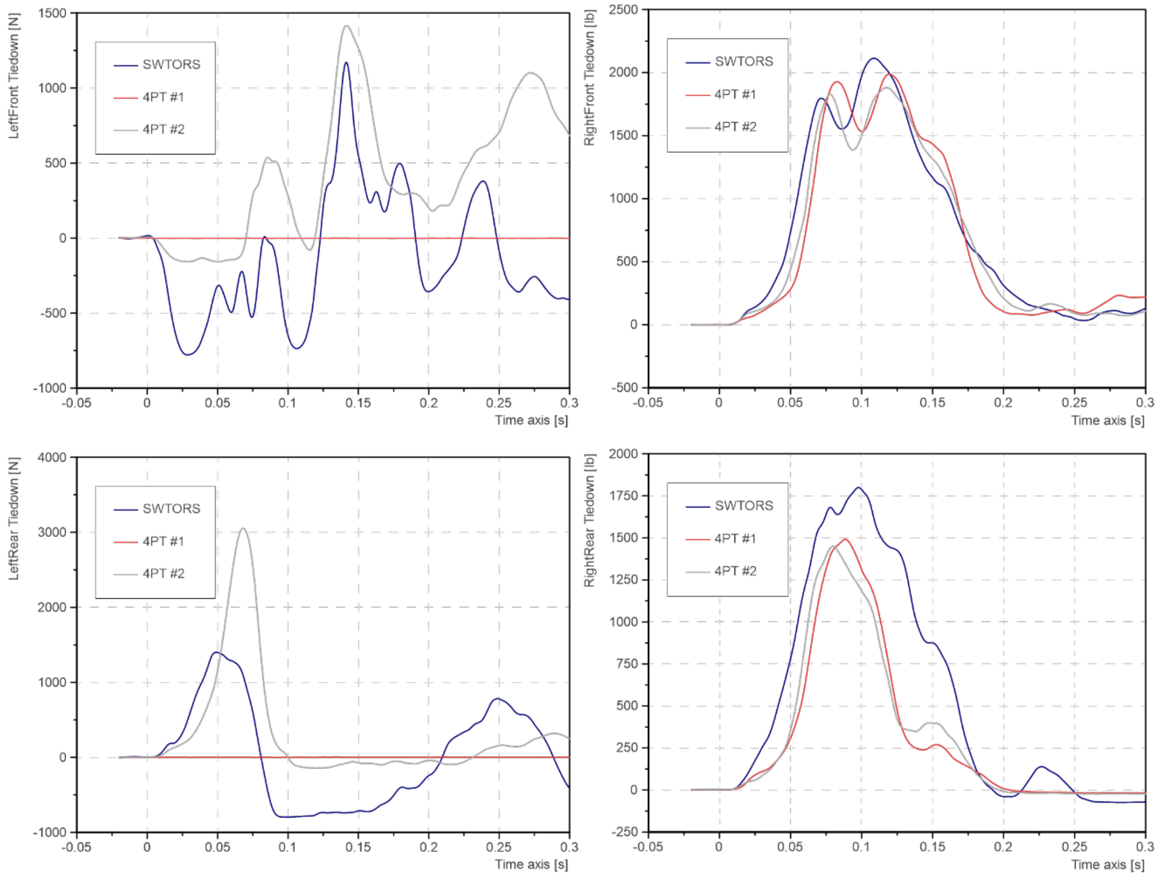


Figure 175. Overlay plots of available tiedown forces for two commercial products and SWTORS, evaluated with SWCSI.