Transport of wheelchair seated passengers- providing evidence of the limits of tilt and recline in transport

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Abstract

This paper aims to answer the question; at what point should an occupant in a wheelchair travel rear facing due to non-upright posture? The crash testing results produced within with work indicates that only small amount of Tilt can be applied to a chair before a vehicle anchored occupant restraint system starts to dramatically increase the risk of life threatening injury due to improper interaction with the human body. We recorded occupant restraint abdominal intrusion at Tilt angles as little as 10°, meanwhile recline is less impactful to the occupant restraint effectiveness. The results indicate that for optimum crash protection wheelchair users need to be sitting as upright as possible with the seat pan parallel to the ground. If Tilt greater than 10° is required, the possibility of rear facing transportation with suitable support for the backrest of the chair should be explored.

The paper goes on to evaluate the performance of a three point occupant restraint system with a wheelchair anchored lap belt providing enhanced control of lap belt geometry and the subsequent reduction of risk of severe injury due to abdominal intrusion.

Contents

History

During the PMG conference in 2022, Nikki Holbrook, Bob Appleyard and Dave Long presented Supine postures in wheelchair transport - seating orientation (forward-rearward facing) - a case study. During this case study it was determined that the safest way for a particular user with an almost supine posture would be to travel rearward facing. Dynamic tests of a wheelchair and seat/support surface that reproduced those of the actual user compared outcomes of forward and rearward facing vehicle occupancy in foreseeable crash incidents of moderate severity. The outcome achieved by analysis of high speed film of the crash simulations was that for occupants with this particular semi-supine posture, far greater extent of occupant protection can be accessed when adopting a rearward facing orientation.

Post presentation discussions raised new questions, in particular what extent of combined tilt and recline is practical for forward facing vehicle occupancy beyond which rearward facing solutions should be explored for low risk transport?

The highly relevant question inspired continuation of the project to explore extents of open hip angles, seat tilt and back support angles and the effects on vehicle occupant restraint in foreseeable frontal crash events, thus motivating Stage 2 of the work.

This document summarises the outcomes of investigative dynamic tests conducted in 2023 intended to determine limits on the extents of wheelchair seat tilt and backrest recline angles for forward facing wheelchair occupancy. This document also examines the means by which enhanced positioning and control of an occupant restraint system can be achieved, resulting in significant risk reduction of foreseeable occupant injury mechanisms.

Examples of typical seated occupant postures that involve tilt and recline are provided in Annex 1.

1.0 Introduction

Discussions revealed that whilst rear facing orientation during transport can provide low risk transport options for people who need to travel with high extents of tilt and/or recline, or near supine posture, a number of drawbacks or impracticalities may exist, such as,

- Wheelchairs currently have minimum back strength requirements. It is highly unlikely that a wheelchair issued can withstand crash induced forces on the backrest when rear facing. This risk can be reduced by bolstering the chair against a support or chair within the vehicle.
- Some people suffer from motion sickness when travelling rear facing
- Rear facing can reduce carers' ability to monitor the wheelchair user in transport
- Likely to be more practical in an M2 Category minibus rather than in a Wheelchair Accessible Vehicle (WAV) type taxi vehicle.
- Rearward facing can be socially exclusive.

It is again noted that general manufacturer instruction for use in transport provided at mobility device handover will recommend that during occupied transport, the wheelchair should be forward facing, in an upright configuration in order to function as tested. These general 'blanket' recommendations would require a wheelchair seated individual who has a reduced sitting balance or clinical conditions that dictate various extents of tilt and recline to assume an upright seated positioning during transport which is often impossible.

Efforts, therefore, to provide information regarding extents of tilt and recline for forward facing wheelchair seated vehicle occupancy become extremely valuable.

1.1 Project Planning

In order to determine the limitations of tilt and recline for forward facing wheelchair occupancy when travelling in road vehicles, a series of dynamic tests were proposed whereby potential sources of harm would be identified. A typical mobility device capable of a range of settings for tilt and recline would be subjected to a series of tests when occupied by a surrogate human passenger.

1.2 Anticipated Source of Harm

The anticipated primary human injury mechanisms were identified as ejection from the seated position and/or interaction with the wheelchair user occupant restraint system when seatbelt positioning on load bearing regions of an occupant's skeletal structure could not be maintained. It has been very well documented and researched that use of seat belts saves lives. Seat belts work by placing deceleration forces on the user over a small area. Poor location and placement of the seat belt will result in injury to the occupant. Loss of control of restraint to body loads are likely to result in abdominal intrusion of the lap portion of a 3-point occupant restraint system and poor control of the upper torso section of the body.

Symptoms of seat belt abdominal intrusion can range from bruising and pain when breathing or moving arms, to internal organ herniation, damage to the lungs, intestines, liver, kidneys and heart. These injuries can lead to secondary complications such as infection of the damaged organs and even death in some cases [1].

During this project we will be looking at the belt placement to see if there is any abdominal intrusion of the belt which is a known precursor to the injuries listed above.

2.0 Test Hardware

2.1 Dynamic Sled Test Device

The dynamic test facility and services of Cranfield Impact Centre were again employed in Stage 2 of the test programme. Six dynamic tests were kindly donated by CIC for the purposes of the investigative work to determine limits of tilt and recline to inform the industry and enhance safety for people with reduced mobility.

High speed photography recorded the Anthropomorphic Test Device (ATD) kinematics during each test, with still photography recording the position and set-up of the wheelchair tilt and recline angles.

2.2 Crash Severity

Current (International Standards Organization) ISO standards tests are intended to determine wheelchair failure rather than occupant survival. The focus of Stage 2 work was not the assessment of mobility product integrity during and after a 20g/48kmh crash simulation, but much more focused on user survivability after the incident.

For that reason, a reduced crash severity of 10g/30kmh was chosen, rather than the ISO 7176-19 test requiring 20g/48kmh severity. This selection captures the more probable form of crash event rather than the 'less likely' worst case major frontal impact. At 10g/30kmh a vulnerable occupant with reduced injury tolerance, positioned in a non-upright seated posture is more likely to survive an event of lower severity and therefore improving the foreseeable outcome for this group will have the greatest interest for the project.

This level of crash severity is also appropriate for larger M2 Category vehicles (Minibus) which are frequently used for the carriage of wheelchair seated passengers.

2.3 Surrogate Human Occupant- the ATD (Anthropomorphic Test Device)

A Hybrid III 50th percentile ATD, mid-sized adult male of 77kg was used as a surrogate occupant in each dynamic test. In order to achieve the extents of open hip angle required to represent a human occupant, the Hybrid III 50th percentile was fitted with a standing pelvis, used in the assessment of ambulance stretcher occupant restraint systems where the ATD is supine. The Hybrid III 50th percentile ATD is employed to represent a vehicle seated occupant and has built into its lower spine region a 7° to 9° anterior pelvic tilt, which creates a commonly adopted seated posture for occupants in passenger vehicles, for both passengers and drivers.

When the automotive pelvis is used it is not possible to create the extents of open-hip angle by virtue of rotation of the pelvis around a transverse axis though the femur heads. Instead, a back angle representative of recline is achieved by distortion of the lumber spine.

Hybrid III 50th percentile lumber spine with 7° to 9° anterior tilt


Hybrid III 50th percentile standing pelvis.

2.4 Mobility Device

Three Sunrise Medical Cirrus G5 products were donated to the project by Sunrise Medical. The Cirrus G5 has satisfied the requirements of ISO 7176-19 in an upright mode and is capable of achieving high extents of both tilt and recline in an independent manner. The three wheelchairs were identical and represented a typical host wheelchair for the purposes of the test programme.

The ISO 16840-4 surrogate wheel base used to assess the integrity of seating systems independently from a wheelchair base does not have the ability to provide tilt or recline and could not be used for the purpose of this investigation.

Cirrus G5 at full tilt and recline

2.5 Wheelchair Occupant Restraint

In order to represent the most common form of wheelchair occupant restraint system observed in the UK, a vehicle anchored 3-point lap and diagonal system was employed. Occupant restraint systems of this type will have two floor mounted lap belt anchorages, behind the wheelchair, adjacent to the wheelchair rear securement floor anchorages.

Note: Some commercially available wheelchair tie-downs and occupant restraint system share the anchorage of both lap belt and wheelchair securement.

Upper torso restraint anchorage was provided by a vehicle wall mounting positioned above and behind the occupant shoulder.

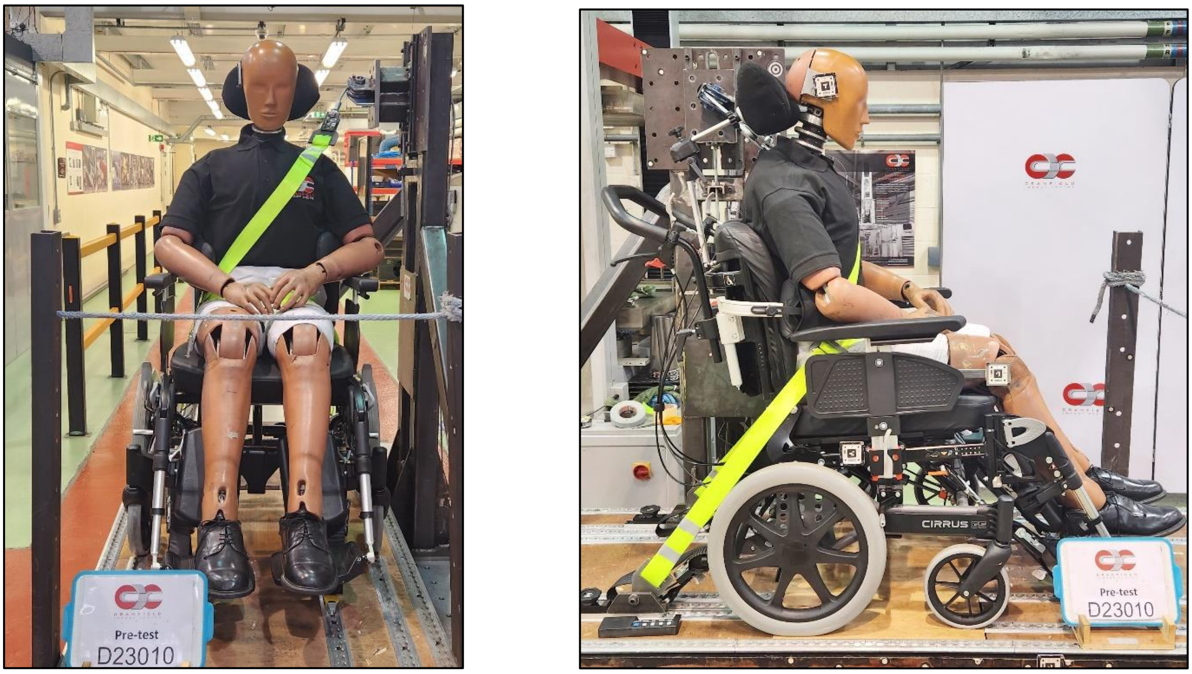
A well proven surrogate occupant restraint was used during all tests to remove the possibility of the restraint failing during the test, potentially rendering the results inconclusive.

The photos below show frontal and side views of the pre-test set-up of sled run D23-010, a baseline test with seat rail at 4° and back support at 8°.

The vehicle anchored surrogate occupant restraint system was set at idealised positions, with a lap belt to horizontal angle of 55°. Steeper angles can be achieved with some wheelchair test set-ups, however lap belt interaction with wheelchair structure frequently prevents angles greater than 55°.

The lap to shoulder belt connection point is located directly over the hip of the ATD occupant.

Upper torso restraint anchorage location is set to achieve shoulder belt application midway on the ATD clavicle, with the belt running over the mid-point of the ATD sternum.



D23-010 Baseline Test, Surrogate Vehicle Anchored Occupant Restraint System Layout

2.6 Wheelchair Securement

In all tests, the Cirrus G5 wheelchairs were secured using a commercially available webbing based four-point tie-down system, with track fittings to secure the wheelchair to the test rig surface via aluminium rail, karabiner end fittings and over-centre webbing tensioners in each of the four straps.

The front tie-downs were attached to the dedicated securement points mounted on the wheelchair seat rails.

Front tie-down arrangement.

Rear tie-down securement arrangement

3.0 The Dynamic Tests

With a limited budget, the importance of test planning in order to reach meaningful conclusions with limited assets is paramount. Baseline tests that provide evidence that the wheelchair tie-downs, surrogate occupant restraint system and ATD, fitted with standing pelvis, perform in accordance with test norms are a necessity to qualify test outcomes.

Based on review of clinical experience of wheelchair seating requirements, a typical, commonly prescribed 'challenging' seating condition was identified where a passenger with an open-hip angle of 20° and wheelchair tilt of 20°, measured at the seat rail, was considered a representative target for the purposes of the investigation.

From dynamic crash test experience and studies of real world crash events, the wheelchair and occupant set-up described above were considered likely to provide an unsatisfactory dynamic test outcome.

3.1 Test 1 – (D23-007) Set-Up and pre-test still photography

The Sunrise Cirrus G5 wheelchair was placed on the test rig, the seat rail angle was set horizontal at 0°.

The adjustable back support of the Cirrus G5 was set at 20° to vertical.

The ATD prepared in accordance with ISO 7176-19:2022 Annex A, with standing pelvis, was positioned centrally in the wheelchair support surfaces with lower extremities positioned by the leg supports provided.

Once the ATD was positioned, the wheelchair tilt mechanism was operated to allow a nominal 20° tilt angle measured at the seat rail.

Seat rail angle set at nominal 20° to horizontal.

Back support angle 40° to vertical (90°-49.4°)

Test 1, D23-007, Side view, pre-test

The wheelchair was positioned on the test platform to provide correct location of the upper torso restraint anchorage surrogate and the surrogate vehicle anchored 3-point occupant restraint system fitted.

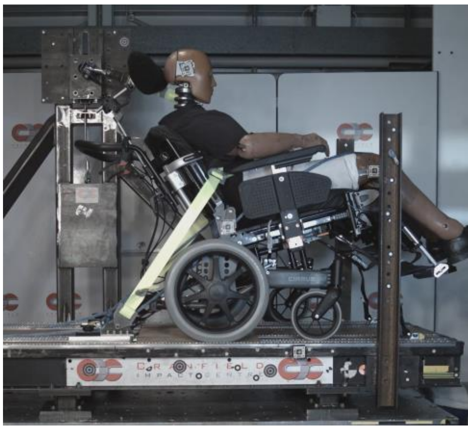
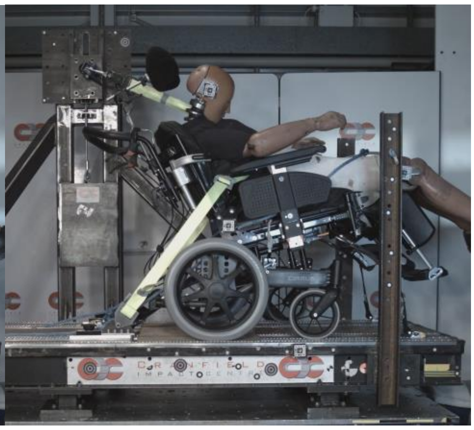
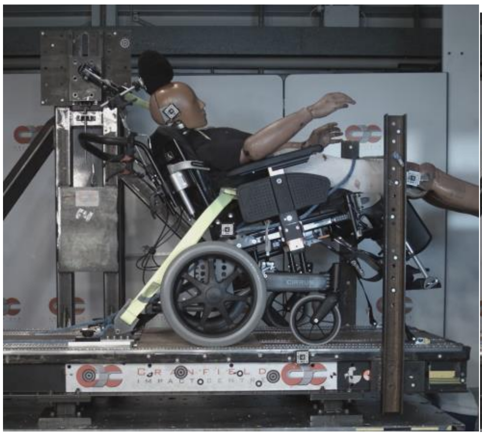
The angle of the lap belt to the horizontal was set at 55°. The junction of the shoulder to lap belt was positioned as close as possible to the H-Point of the ATD, (over the hip).

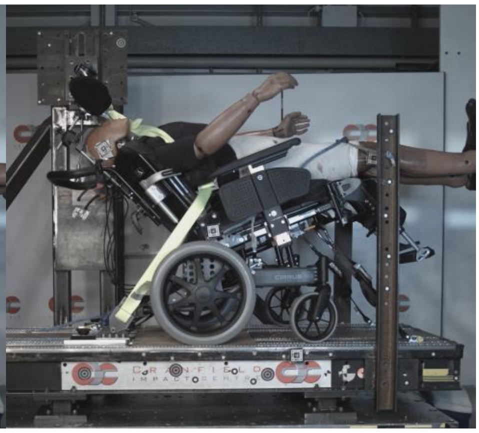
Note: Preferred lap belt angle to horizontal given in ISO 7176-19:2022 is 45° to 75° with a non preferred angle of 30° to 45°.

The wheelchair and ATD were then subjected to the chosen 10g/30kmh acceleration pulse.

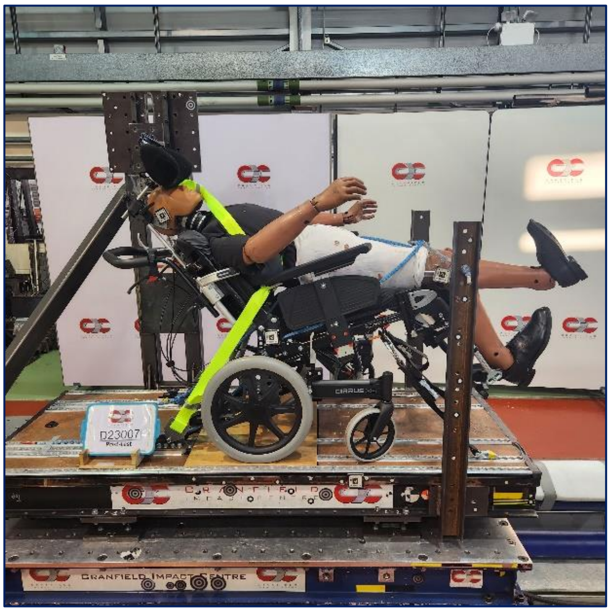
3.2 Test 1, D23-007 ATD Kinematics



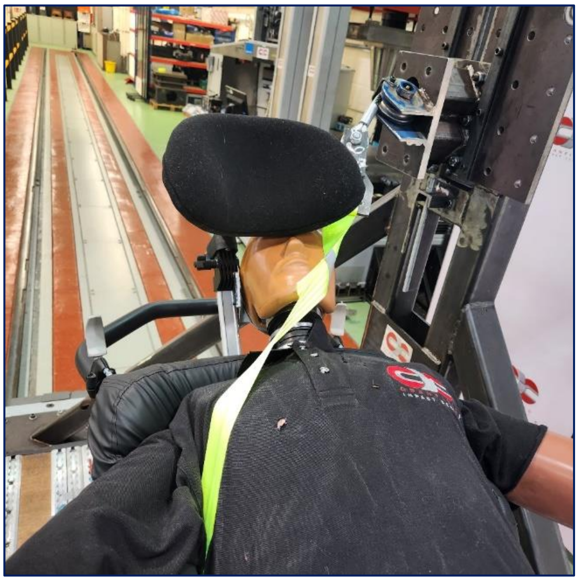



3.4 Test 1 D23-007 Still Photography – Post Test



Test 1, D23-007, Side view, post-test

Test 1, D23-007, Lap belt position, post-test



Test 1, D23-007, Upper torso restraint position, post-test.

3.5 Test 1 Observations

Severe abdominal intrusion occurred during the test, causing life threatening injuries to a human occupant. Poor control of upper torso during the crash simulation.

3.6 Test 2 – D23-008 Set-Up and pre-test still photography

Following examination of high speed footage of Test 1, reduced extents of tilt and open hip angle and subsequent back support angles were applied.

The Sunrise Cirrus G5 wheelchair was placed on the test rig, the seat rail angle was set horizontal at 0°.

The adjustable back support of the Cirrus G5 was set at 15° to the vertical.

The ATD prepared in accordance with ISO 7176-19:2022 Annex A, with standing pelvis, was positioned centrally in the wheelchair support surfaces with lower extremities positioned by the leg supports provided.

Once the ATD was positioned, the wheelchair tilt mechanism was operated to allow a nominal 10° tilt angle measured at the seat rail.

Test 2, D23-008, Seat rail set at 10° to horizontal

Test 2, D23-008, Back support angle set at 25° to vertical axis (90°-65.4°)

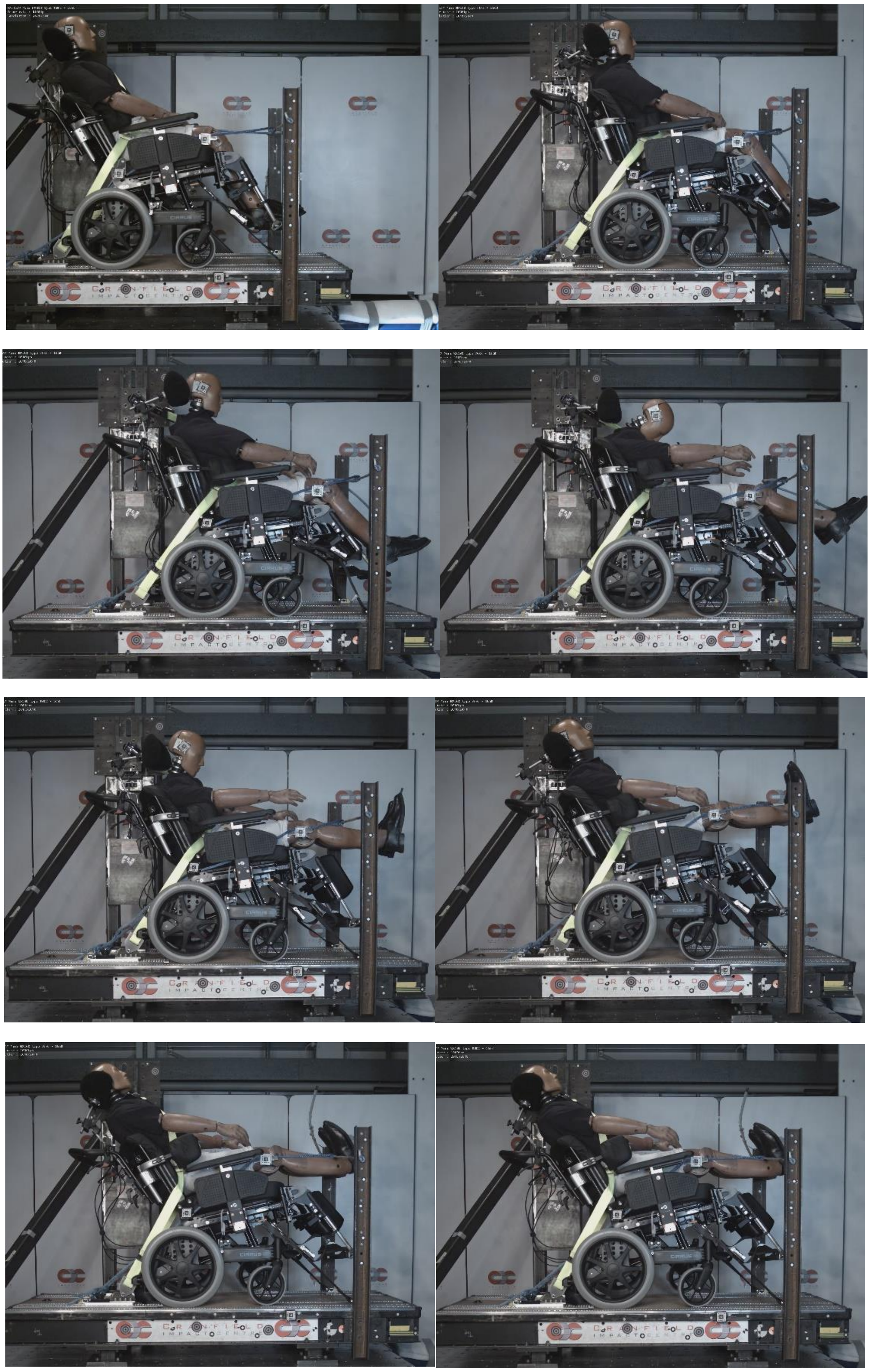
Test 2, D23-008, Side view, pre-test

The wheelchair was positioned on the test platform to provide correct location of the upper torso restraint anchorage surrogate and the surrogate vehicle anchored 3-point occupant restraint system fitted.

The angle of the lap belt to the horizontal was set at 55°. The junction of the shoulder to lap belt was positioned as close as possible to the H-Point of the ATD, (over the hip).

The wheelchair and ATD were then subjected to the chosen 10g/30kmh acceleration pulse.

3.7 Test 2, D23-008 ATD Kinematics



3.8 Test 2, D23-008 Still Photography – Post-Test

Test 2, D23-008, Front view, post-test

Test 2, D23-008, lap belt position, post-test

3.9 Test 2 Observations

Partial abdominal intrusion occurred at right hip region. Still considered an unsatisfactory result.

The outcomes of both Test 1 and Test 2 indicate poor extents of occupant retention due to poor control of the lap belt position on the pelvis of the ATD throughout the tests.

It was summarised that greater control of lap belt position on the ATD pelvis was an essential requirement for any further tests.

3.10 Test 3 – (D23-013) Set-Up and pre-test still photography

Examination of the Cirrus G5 wheelchair noted the presence of an unused 8mm clearance hole on the rear tie-down attachment plate on either side of the wheelchair. It was assumed that the mounting hole was for the placement of a postural support lap belt.

The mounting of two commonly available K12 seatbelt buckle blades on each side of the wheelchair was explored, allowing the creation of a wheelchair anchored lap belt, by means of attachment to the buckle heads by corresponding tongues.

The close proximity of the lap belt mounting location with the rear tie-down attachment point was considered capable of creating an acceptable load path for occupant restraint system loading.

LH Side view of K12 buckle head attached to the rear tie-down securement bracket.

With the seat rail horizontal at 0°, the angle of buckle alignment on the seated occupant was recorded as 63°.

The angle of application on the pelvis of an occupant will clearly remain constant throughout the range of seat rail tilt angles.

Following examination of the potential for improved control of lap belt positioning during dynamic test conditions it was decided to return to the Test 1 set-up of 20° open hip angle and 20° tilt and provide a direct comparison of occupant retention characteristics offered by a vehicle anchored and wheelchair anchored lap belt arrangements.

The Test 1 set up procedure was repeated for Test 3.

The Sunrise Cirrus G5 wheelchair was placed on the test rig, the seat rail angle was set horizontal at 0°.

The adjustable back support of the Cirrus G5 was set at 20° to vertical.

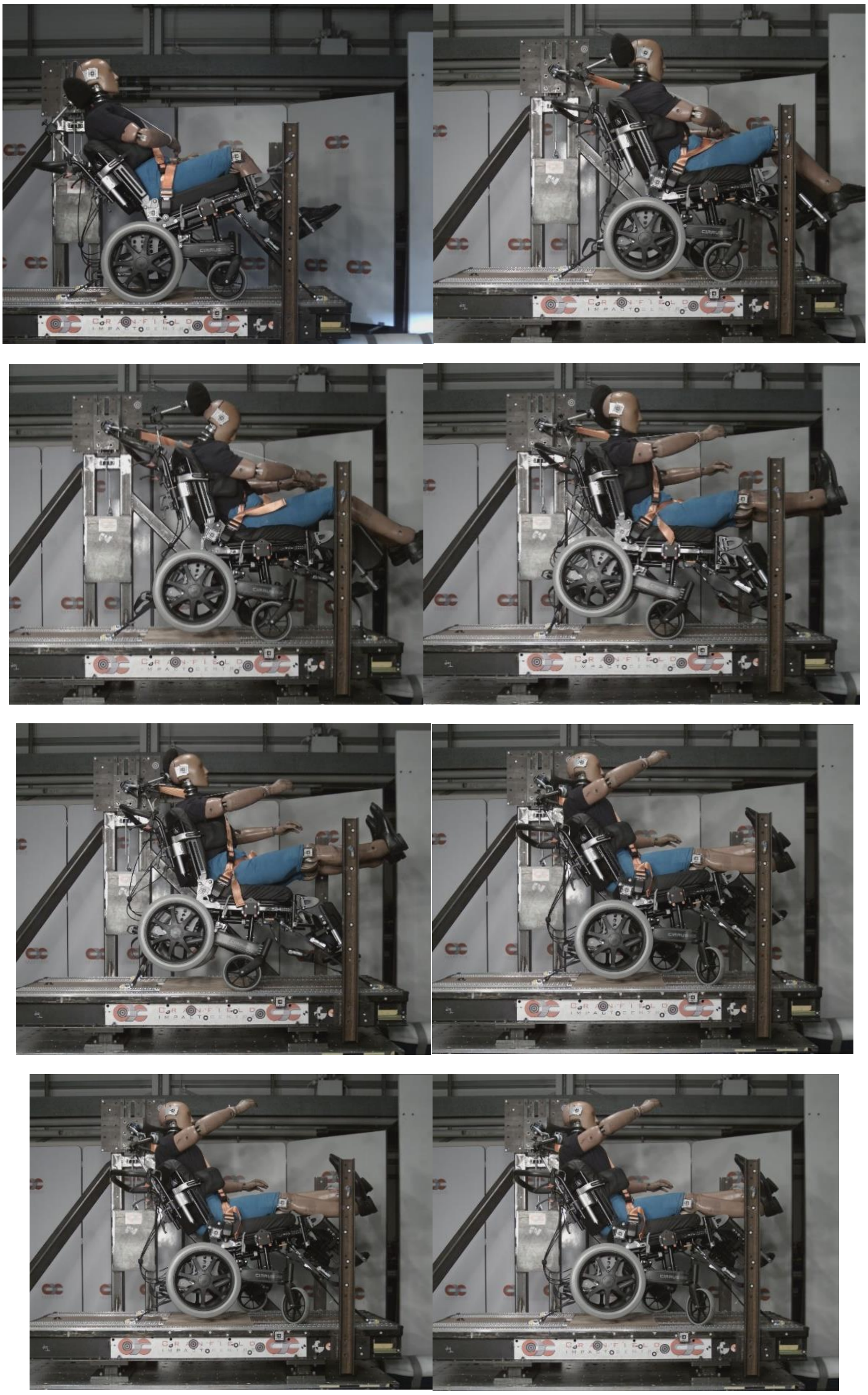
The ATD prepared in accordance with ISO 7176-19:2022 Annex A, with standing pelvis, was positioned centrally in the wheelchair support surfaces with lower extremities positioned by the leg supports provided.

Once the ATD was positioned, the wheelchair tilt mechanism was operated to allow a nominal 20° tilt angle measured at the seat rail.

Test 3, D23-013, RH tongue and buckle arrangement, pre-test

Test 3, D23-013, LH tongue and buckle arrangement, pre-test

3.11 Test 3, D23-013 ATD Kinematics



3.12 Test 3, D23-013 Still Photography – Post-Test

Test 3, D23-013, Front view of occupant restraint system position, post-test

Test 3, D23-013, Front ¾ view of lap belt position on the pelvis of the ATD, post-test.

4.0 Conclusions

1. Form of occupant restraint system has profound effect on outcomes for forward facing vehicle passengers. Vehicle anchored wheelchair occupant restraint systems are prevalent in UK.
2. A well fitted vehicle anchored occupant restraint may be capable of maintaining occupant position with 10° tilt on rail and 15° open hip resulting in a 25° back support angle, with respect to vertical.
3. A wheelchair anchored lap belt provides far greater extent of control of pelvis during a crash event.
4. For a mobility device equipped with a wheelchair anchored lap belt, limits for tilt and recline could be beyond 20° on seat rail and 20° open hip angle, being 40° back support angle, with respect to vertical.
5. As a risk control measure, a wheelchair anchored lap belt restraint has the capability of providing significant improvements to occupant safety when upright or positioned with tilt and recline.

5.0 Discussion

Correct placement and control of positioning of the pelvic part of the occupant restraint is critical to ensure the safety of the occupant in the wheelchair. Incorporating a wheelchair anchored lap belt within the occupant restraint system improves the effective control of the pelvis during a crash event.

The recline angle has less impact on the injury outcome of the user. However, when the back support angles approach 40° from the vertical, achieving ideal location of the upper torso restraint anchorage of the occupant restraint system will become challenging.

Back support angles greater than 40°to vertical are likely to introduce reduced extents of upper torso restraint during a crash event.

Seat base angle is more relevant to effective occupant restraint and should not exceed 10° to horizontal with a vehicle mounted occupant restraint system (ORS). The test D23-008 completed at 10° tilt was deemed only just acceptable/survivable with partial abdominal intrusion observed.

Considerations from a transport risk management perspective, when the clinical needs of a wheelchair seated passenger dictate that tilt and recline angles are applied, a vehicle anchored lap belt will provide a lower level of occupant restraint with a higher probability of occupant injury due to interaction with the restraint system, especially at the abdomen. The high probability of abdominal intrusion combined with established internal injury mechanisms create a high risk of severe harm with possible loss of life.

Photographic comparison of occupant restraint positions on the body of a wheelchair seated vehicle passenger for vehicle and wheelchair anchored lap belt restraints are provided in Annex 2.

The use of the commonly available, well proven K12 tongue and buckle connection for lap belt anchorage to a host wheelchair provides greater extent of occupant protection by design. In transport operations, drivers and passenger assistants would be able to easily identify lap belt attachments points as they are of common design to those used in vehicle seats.

Additionally, providing clearly identified lap belt anchorages on a host wheelchair removes the potential for incorrect routing of lap belt webbing through the wheelchair structure or creation of lap belt geometry likely to cause ineffective occupant restraint.

The concept of such a wheelchair anchored lap belt is of particular relevance to devices with tilt and recline facilities. Not all mobility devices lend themselves to integrated occupant restraint and considerations for their adoption on powered wheelchairs would need to include the total combined mass of wheelchair and occupant and the need for high capacity wheelchair rear tie-downs.

Integrated occupant restraint requires additional forces to be transmitted through the wheelchair chassis. Ideally the pelvic belt angle would be in a similar location plane/angle to the tie down location which would allow for load path management to pass into the tie downs and into the floor of the vehicle.

Greater extents of occupant protection can be achieved by rear facing travel, requiring additional or supplementary back support of the wheelchair to be provided.

6.0 Further work

- Consideration of including a design requirement for the inclusion of appropriate attachment points for wheelchair anchored lap belts for mobility devices with tilt and recline facilities.
- Inclusion of a common design requirement for the attachment points for wheelchair anchored lap belts.
- Consideration of the development of a back support strength test for inclusion into existing wheelchair standards
- Exploration of a method of providing wheelchair securement and supplementary back support for rearward facing transport.

7.0 References

[1] Rutledge R, Thomason M, Oller D, Meredith W, Moylan J, Clancy T, Cunningham P, Baker C "The spectrum of abdominal injuries associated with the use of seat belts." The Journal of Trauma 01 Jun 1991, 31(6):820-5; discussion 825-6

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Annex 1
User Presentations

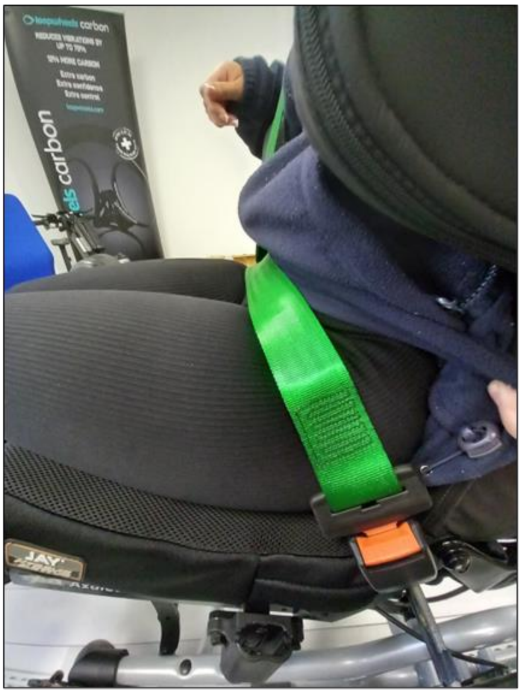
Annex 2
The Hertford Seating Trials

Wheelchair #1 – Vehicle anchored occupant restraint system

Position of the junction of lap and diagonal sections of the occupant restraint creates poor position of upper torso belt. Shallow angle of lap belt section creates a high position close to abdomen.

In tilt position the lap belt becomes located directly over the abdomen. Vicky's forefingers are placed on ASISs.

Wheelchair #1 – Simulated wheelchair anchored lap belt with continuous 3-point restraint system



Belt positions when upright.

Belt positions when in tilt

Wheelchair #3 – Vehicle anchored occupant restraint system

Note high position of upper torso restraint and lap belt over abdomen when in tilt.

Lap belt over abdomen.

Wheelchair #2 – Simulated wheelchair anchored lap belt with continuous 3-point restraint system

Wheelchair anchored lap belt provide excellent position over pelvis when upright.

General position of occupant restraint system maintained as tilt applied.