C O V E N T R Y
U N I V E R S I T Y

Faculty of Engineering

Final Year Project

How Does Number and Location of Attachment Points Affect Performance of Occupant Restraint in Crashworthy Custom Contoured Seating System?

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Declaration

The work described in this report is the result of my own investigations. All sections of the text ands results that have been obtained from other work are fully referenced. I understand that cheating and plagiarism contributes a breach of University Regulations and will be dealt with accordingly.

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1. Executive Summary

Specialist seating systems are designed and built for posture control, often with little consideration of transportation issues, potentially leaving patients dangerously at risk of injury when a vehicle is involved in a crash.

The voluntary ISO (International Organization for Standardization) standards relating to wheelchairs in transportation suggest that all wheelchairs should be designed with integrated occupant restraint systems. However, a review of current practice revealed that floor mounted systems are being used.

Therefore two types of wheelchair occupant restraint systems, used for custom contoured seating, have been compared by means of sled tests. A floor mounted harness system was chosen, this was compared with a system comprising a two point wheelchair integrated restraint and a floor mounted torso restraint.

The results of the test have exposed the floor mounted harness system as being unfit for purpose. The wheelchair integrated solution successfully passed the relevant criteria. Further work is needed to overcome many of the constraints imposed by the consumer groups using these products, to ensure widespread adoption in the industry.

Acknowledgements

Many thanks to Bob Appleyard for giving me so much of his valuable time, sound advice and for offering equipment used in the tests. From Oxford Centre for Enablement, thanks to Rick Houghton for kick starting the project and generously securing the funding. Mark Gascoine was a great help during the manufacturing of the seats, thanks to Andrew Bennett and Damian Green for help during the testing at Millbrook. Thanks to Catherine Scott and Ron Coleman of C & S Seating for spending time with me. Vicky Curling of Kings College Hospital has been inspiring. Thanks to Terry Best from St George's Hospital, London. Finally thanks to Dr Dimitar Stefanov of Coventry University for his supervision.

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2. Aims and Objectives

The attachment points of an occupant restraint system can vary in number and location. The aim of this project is to test how the number and location of these attachment points affects the performance of a crashworthy seating system. To fulfil this aim the following objectives need to be met:

1. Provide evidence that Lynx is a crashworthy seating system.

2. Determine two suitable configurations of occupant restraint, by researching current methods and state of the art solutions.

3. Compare two configurations of occupant restraint systems by sled tests of custom contoured seating systems attached to a surrogate wheelchair.

4. Make recommendations of future direction for development of transportation safety equipment for the specialist seating market.

3. Background

Over the past 30 years the automobile industry has gone to great lengths and expense to improve the safety of automobile occupants, through industry led research and development followed by legislation (Road Safe, 2010). Each year billions of Euros are still being spent by the automobile industry to fund innovations like seat belts, passenger airbags, and advanced breakings systems (Road Safe, 2010). Governments throughout the world have then introduced legislation, for example the UK “Wearing of Seatbelts Regulations 1993” (United Kingdom Parliament, 2012). Unfortunately these improvements have not necessarily been experienced by wheelchair users whilst being transported in vehicles.

To prove this point a “mystery shopper” style survey was carried out with an unnamed transport company. The driver was simply asked to demonstrate how a wheelchair patient would be accommodated in their vehicle. Figure 3.1 shows a “patient” in a custom contoured seating system and standard wheelbase with no added restraints.

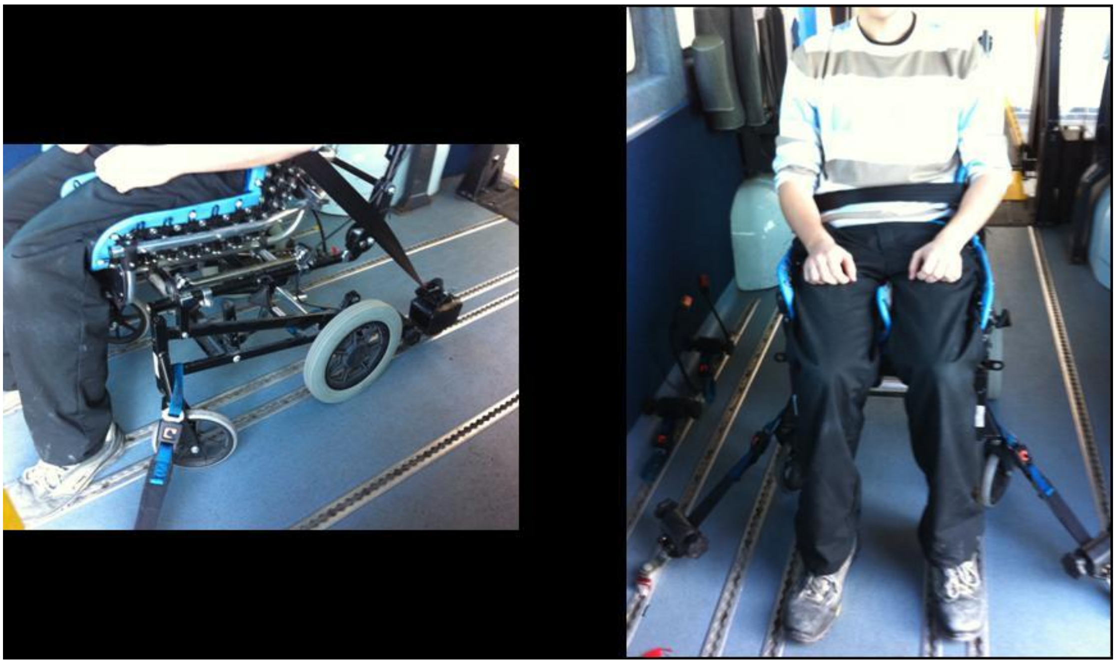

Figure 3.1: Example of current practice within transport service industry

Four tie downs are used to secure the wheelbase to the vehicle and a vehicle mounted pelvic belt with inertial reel is used as an attempt to restrain the patient in the seating. Although the vehicle had shoulder lever mounting points, no torso restraint was being used and the pelvic belt was not secured in an optimal configuration.

This proves that it is up to those professionals issuing wheelchairs to patients to take the initiative in ensuring all the hardware and training is available for their safe transportation.

Although it is true that each patient is unique and especially so in the specialist seating area, there are a number of generalisations that can be made to improve the situation for a wide group of people. Three benchmark configurations have been suggested (Cooper et al, 2006: 200) for which all methods of wheelchair occupant restraint can be compared.

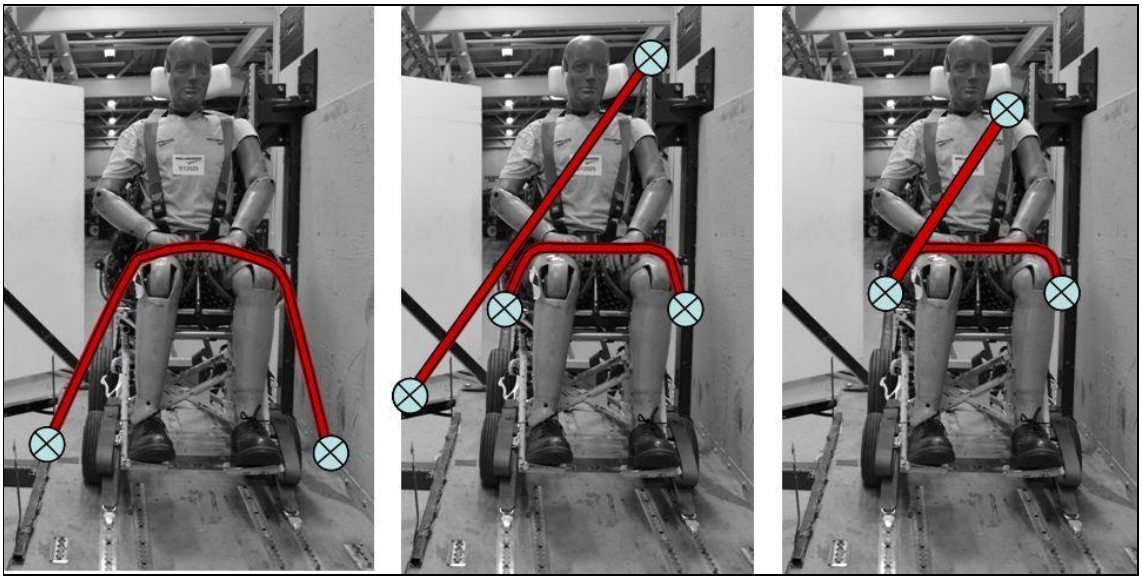

Figure 3.2: Three Benchmark Configurations of Occupant Restraint. From left to right respectively: Type (a) includes a vehicle mounted pelvic restraint. Type (b) has a wheelchair integrated pelvic belt and vehicle mounted torso restraint. Type (c) has a wheelchair integrated pelvic belt and wheelchair integrated torso restraint

With reference to these benchmark configurations, the transport company currently use Type (a) configuration. From the research carried out in this report, the case will be now be made of the importance for all those concerned to move away from this type of configuration as quickly as possible.

3.1 Constraints

It is possible to address the problem of vehicle crash safety of wheelchair users by breaking this complex problem into its component parts and considering these generalised constraints of the wheelchair user. This will allow designs of occupant restraints to be chosen and compared.

3.1.1 Specialist Seating Clinic Patients

The seating that has historically been provided for patients at specialist seating clinics forms part of a 24 hour postural management strategy. Postural abnormalities are accommodated for and any correctable deformities are managed.

By taking a cast of a patient's posture while seated, a custom contoured seat can be manufactured. At the Oxford Centre for Enablement, Lynx is used to achieve the idiosyncratic shape (Figure 3.1.1). Lynx is made from plastic elements connected together using zinc plated mild steel fasteners to create a sheet, which is then moulded to the patient specific postural shape using the cast of the patient. Further details of this process are outlined in section 4.1.

Figure 3.1.1: Example of Custom Contoured Seating made from Lynx at the Oxford Centre for Enablement

Rarely has transportation safety been accommodated for by the clinical team when providing custom contoured seating. Furthermore transport belts have been regarded as a nuisance as they are bigger and bulkier than postural restraints; they are also made from harder materials like stainless steel and high density plastics. If a patient has to sit with these bulky items for long periods there is a danger that they will rub and cause skin problems.

Any solution needs to be as comfortable as possible for the patient. This means the occupant restraint needs to pass over bony prominences and avoid soft tissues. However this is difficult because the seat is shaped to provide support around the pelvis, meaning a belt going over the top of the seating does not come into contact with the bony prominences. A belt threaded through the seat will come into contact with the patient for large amounts of time and therefore the risk of excessive abrasion needs to be mitigated.

3.1.2 International Standards

Currently there is no agreed protocol for allowing patients issued with specialist seating systems to travel as safely as able bodied passengers. A number of groups are actively working towards agreed protocols covering the safe transportation of wheelchairs (Medical Devices Agency, 2001), (Posture & Mobility Group, 2010) and (Manary et al., 2010). The relevant legislation is being used to guide best practice and as the industry is evolving towards comprehensively safer practices so the legislation is evolving too.

The European Council Directive for medical devices is Council Directive 2007/47/EC (European Commission, 2007); this is binding for member states. In the United Kingdom this directive is brought into legislation under The Medical Devices Regulations 2002 (Office of Public Sector Information 2002), being a regulation it is binding in its entirety.

A CE mark is required for sale within the European community, which means the manufacturer establishes that the product conforms to the essential requirements of all the relevant directives. This includes a comprehensive documented risk management using BS EN ISO 14971 (International Organization for Standardization, 2007).

Although a custom made device, such as a Lynx seat, does not require CE marking, the Council Directive states that the custom made device must still conform to the essential requirements. This means that any essential requirements that have not been fully met need to be clearly stated. The Directive therefore compels the manufacturers of special seating to examine the risks associated with the product being used as a seat in transportation.

By following the international standards it is possible to prove compliance with all Council Directive essential requirements. ISO 7176-19 (International Organization for Standardization, 2008) sets design and performance requirements as well as test procedures for wheelchairs with seating systems intended to be used as a seat during vehicle transport; whereas ISO 16840-4 (International Organization for Standardization, 2009) is concerned only with the seating system used in transport. Both standards detail the obligation to issue user instructions with the seating system, which for ISO 16840-4 must include “a statement that the seating system meets the requirements of ISO 16840-4” and “a statement describing assembly, use, maintenance and any limitations in using the seating system with a wheelchair base in a motor vehicle”.

The most stringent industry lead voluntary standard is the American standard WC19 (ANSI/RESNA, 2000). To be compliant with this standard, a wheelchair *must* have anchorage points for a pelvic belt (Manary et al., 2010). Manary et al., go further by making three recommendations for the wheelchair anchored pelvic belt that could be included in the standard to make it “a viable option for improving occupant safety” (Manary et al., 2010):

1. Allow attachment of vehicle-anchored shoulder belt to left and right side on inboard side of wheelchair.

2. When not in use, the pelvic belt should not conflict with operation of wheelchair.
3. Should have dual role of crashworthy transport belt and posture belt.

This project is concerned with the seating system, and therefore the crash test will be performed in accordance with ISO 16840-4, which necessitates the use of a surrogate wheelbase. To pass the test the following conditions must be satisfied:

- Anthropometric Test Device (ATD) must remain seated in the test wheelchair.
- Occupant restraint must pass over bony structures and not soft tissues.
- No obvious component failure.
- Wheelchair and ATD excursions (movements relative to initial state) must not exceed specified limits.
- No wheelchair loading of occupant.
- Detachable seat inserts must remain attached.
- No part over 100gm can detach from wheelchair.
- No sharp edges with a radius of less than 2.5mm produced.

3.1.3 Transport Companies and Carers

Carers, parents and those working for the transport companies have limited time to provide correct set up of occupant restraint equipment. Furthermore there is often limited appreciation of the consequences of incorrect use of occupant restraint equipment.

If a protocol is judged to be too complicated or time consuming it simply will not be adhered to in the real world. For that reason the design solution must be simple and not take extra time to use.

3.2 Definition of Need

From consideration of the known constraints the “ideal” occupant restraint solution needs to meet the following criteria:

- Comply with most stringent voluntary standard (WC19 (ANSI/RESNA, 2000))
- Have upper and lower torso restraints.
- Passes over bony structures and not soft tissues
- Anchorages for pelvic belt is integrated with the wheelchair
- Not time consuming to use
- No less comfortable than a postural restraint

3.3 Currently Available Occupant Restraint Systems

There is currently no “ideal” off the shelf solution for wheelchair transport occupant restraints. For the special seating market, bespoke solutions are manufactured into the seats for some clients.

Dan Steedman (Activate For Kids, 2011) has been working with Lindberg to offer a device that can be attached to the back of some wheelchairs, such as the Invacare Action 3 (Invacare, 2011).

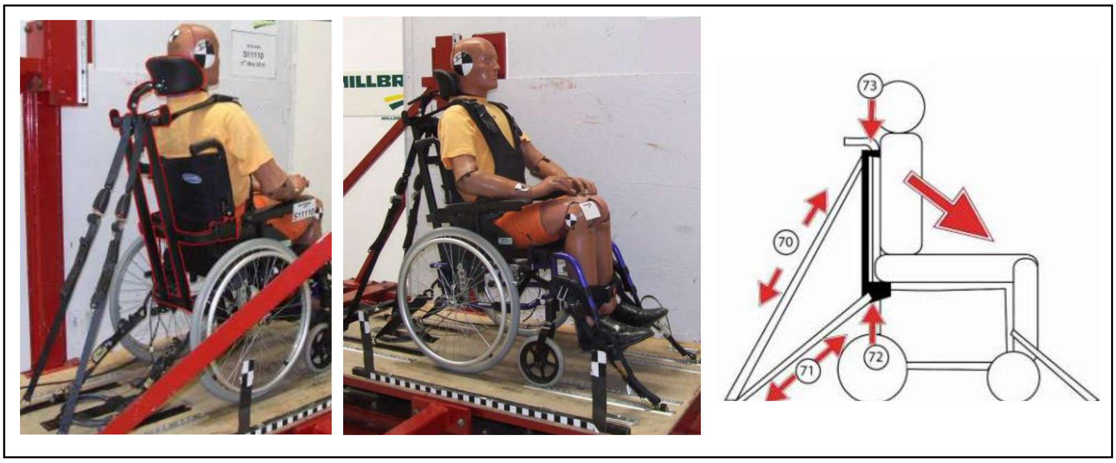

Figure 3.3.1: Lindberg design for fitting to Action 3 (Activate for Kids, 2011)

This seat back design has an integrated harness. It allows for anchorages on the wheelchair. At present it is not suited for use with all types of wheelchair and has not been crash tested with custom contoured seating. Custom Contoured seating often has a large amount of metal work framing to interface the Lynx or Matrix onto the wheelbase. It is unclear how this metal work would interact with this particular solution.

There are a wide range of occupant restraints available within the rollercoaster industry (Figure 3.3.2). This has inspired a range of head rests from Chailey, called the Rollercoaster Head Support (Figure 3.3.2).

Figure 3.3.2: Left: Rollercoaster Occupant Restraint (Chandrigarh Traffic Police, 2011). Right: Chailey Rollercoaster Head Support (Rehabilitation Manufacturing Services Ltd, 2011)

This design idea would solve the problem of finding an anchorage point on the wheelchair base for an upper torso belt. However it is unclear how an occupant restraint attached to this headrest would perform in a crash situation. This solution would only work with patients who have a certain level of postural control ability. With special seating patients a significant portion would not have this required level.

Part of WC19 (ASNI/RESNA, 2000) stipulates that wheelbases have anchorage points for an integrated lap belt. A survey was conducted of the wheelchairs commonly used at the Oxford Centre for Enablement. It was found that the Radcliffe Shadow Wheelbase (Radcliffe Rehab, 2009) and the South West Seating NEO Wheelbase (South West Seating and Rehab Ltd, 2011) do not currently have obvious anchorage points. These are the two most widely used wheelbases for full Lynx systems at the Oxford Centre for Enablement. It was found that options available as anchorage points fell into two categories; simple loops made around existing framework (Figure 3.3.3) and more detailed anchorages involving special hardware (Figure 3.3.4). One important question remains as to which option performs better in a crash test.

Figure 3.3.3: Simple "loop around" anchorages found on CAPS II seats (Active Design, 2011) and the Lomax range (Sunrise Medical UK Ltd, 2011)

Figure 3.3.4: Invacare wheelchairs (Invacare UK Ltd, 2011) meet WC19 expectations with anchorage points. The Rea Azalia has a “loop around” arrangement (bottom right photograph)

A visit was made to C & S Seating in Hastings, formerly of Thornton Heath, Surrey to view the work that was carried out in June 2001 to make the Matrix seats they manufacture crashworthy.

Figure 3.3.5: C & S seating from June 2001 with vehicle mounted pelvic belt and diagonal torso belt with vehicle mounted routing

A handbook has been compiled for users to refer to. This user guide states that the framing of the Matrix has been strengthened for the system known as the “Model-T Matrix” (C & S Seating, 2001). Figure 3.3.5 shows the pelvic belt is threaded through the matrix and can be coupled to the upper torso belt.

The good points about this system are that it has passed the crash test criteria of ISO 7176:19. The pelvic support belt is used for positioning and becomes part of the occupant restraint system when in a vehicle. There is a buckle on the posture belt allowing the upper torso belt to be attached to the pelvic belt.

The drawbacks to the system are that the pelvic belt becomes vehicle mounted when in a vehicle; whereas the load path of a wheelchair integrated system reduces risk of injury (Manary, 2010). Training is required to understand how to set up the system the first time it is used in a vehicle. The extra material used in the framing means it can not be retro-fitted to existing seats. The amount of work gone into the research and development of this product is noteworthy and the result is a satisfying solution for the Matrix system.

3.4 Previous Crash Test Reports

Work was undertaken as part of a previous student research project at Coventry University (Curling, 2009). The study compared the effectiveness of a vehicle mounted occupant restraint that crossed over the high sides of a Matrix seat with an occupant restraint that was able to pass close to the hip bones thanks to cut-outs made in the pelvis region of the Matrix seat.

Figure 3.4.1: "Benchmark seat" (left) and seat with "improved access (right)". From (Curling, 2009) with permission

The results showed reduced (i.e. improved) overall excursions for the wheelbase and ATD knees in the “improved access” seat. The risk of submarining (when the ATD passes under the pelvic belt)was also reduced. However the overall ATD head excursion was not reduced with the improved design.

Curling’s project marked a significant step forward in understanding how crashworthy custom seats can be made.

In discussions with Unwin Safety and the makers of Matrix (South West Seating, 2011) it has been confirmed that more work needs to be done to develop an “ideal” solution.

For a lot of patients, the control of the pelvis provided by the special seating is a key reason for prescribing custom contoured seating. Therefore to simply remove material from this area would not be possible. It is unclear how the structural integrity of the seat has been affected in terms of fatigue loading due to the removal of material from the pelvis.

If this solution was to be rolled out within the special seating industry, all of the old seats would have to be upgraded to the “improved” design. From the results of the Curling study it is unclear if this would be an appropriately justified action. Ideally a solution is needed that allows existing seats to be used in transportation, with as few structural alterations as possible.

The recurring themes from two Transport Research Laboratory reports (Le Claire, 2003) and (Visvikis, 2008) included the non-use and mis-use of occupant restraints. These reports detail nearly 100 crash tests between them, of both paediatric and adult chairs, manual and electric. The reports highlight the dangers of anchoring the upper part of shoulder restraints to the vehicle floor, behind the wheelchair. This is brought to light in two other reports (Posture & Mobility, 2011) and (Medical Devices Agency, 2001); yet such restraints are still on the market.

The danger appears to be due to the way this restraint arrangement loads the spine of the wheelchair user. No previous studies used custom contoured seating with vehicle anchoring of upper part of torso restraint. In fact, apart from Curling and C & S Seating there has been a significant lack of published data about the crash worthiness of custom contoured seating.

3.5 Current Test Protocols

The test sled at Millbrook Proving Ground (Millbrook Proving Ground, 2011) is able to conduct tests at a 30mph and 20g deceleration pulse. This meets the requirements of ISO 7176-19 (International Organization for Standardization, 2008), ISO 16840-4 (International Organization for Standardization, 2009) as well as WC19 (ASNI/RESNA, 2000).

ISO 7176-19 (International Organization for Standardization, 2008) deals with the WTORS (Wheelchair Tie-down Occupant Restraint System), which includes a designated wheelbase.

It is beyond the scope of this project to consider the compliance of the tie-downs and the designated wheelbase. Therefore, ISO 16840-4 (International Organization for Standardization, 2009) is more relevant and so tests will be carried out on a surrogate wheelbase.

Figure 3.5.1: Seat tested with designated wheelbase (Left) and on surrogate wheelbase (Right)

A cast of the ATD (Anatomical Test Device) was used to shape the seat to the correct shape before it was put on the sled. Each sled test costs £1000 plus VAT meaning that any comparison studies are limited to small runs.

For these financial reasons and in order to save on the considerable set up time of the study, in recent years efforts have been made to utilise the increasing power of computer simulations to enable crash testing to be conducted virtually, at a much reduced cost (Rodgers et al., 2009).

However it has been decided that at present the computer simulations themselves take up too much time to set up. 3D models of the chairs and seating systems are needed and all the variables have to be inputted into the system. Therefore the cost of the sled test is deemed acceptable for this project.

Furthermore, crash sled tests will always be needed to validate the results from the computer simulations.

4. Occupant Restraint Selection

A wheelchair integrated occupant restraint will be tested and compared against a vehicle mounted system.

The main advantage of using a wheelchair integrated occupant restraint is that it can serve the same function as a postural belt. Threading the belt through the Lynx ensures a secure fit over the pelvis when the wheelchair is used as a seat in transport, with no further adjustment necessary.

The problem of how to anchor the pelvic belt to the wheelbase was solved by using a stainless steel locator plate (Figure 4.1).

Figure 4.1: Stainless Steel Locator Plate. 10mm diameter cutout can connect to suitably designed pin

As the surrogate wheelbase does not have a suitable pin connector the author suggested using an M8 x 70 mm stainless steel (A2 -70) bolt with a 10mm outside diameter nylon bearing. This could be secured to the wheelbase using the pre-drilled holes and two M8 nuts (Figure 4.2).

Figure 4.2: M8 stainless steel bolt with nylon bearing

The following calculations prove this is bolt has desired properties:

The maximum force in the anchorage is found from Newton's Second Law (Equation 1).

$$F = ma$$
$$F = 75\ [kg] \times 20g \qquad [1]$$
$$F = 14{,}715\ [N]$$

This is spread over the two sides of the restraint system. Therefore the stress in the bolt is *force / area.* Where the force is:

$$0.5 \times 14{,}715\ [N] = 7{,}400\ [N] \qquad [2]$$

And the area is the surface area of the bolt and connector interface, which is half the circumference of the bolt with nylon *x* thickness of steel:

$$0.5 \times \pi \times 10\ [mm] \times 2\ [mm] = 15.7\ mm^2 \qquad [3]$$

The tensile (normal) stress experienced by the bolt is then:

$$\sigma = F/A$$
$$\sigma = 7{,}400[N]\ /\ 15.7\ [mm^2] \qquad [4]$$
$$\sigma = 470\ [N/mm^2]$$

The material properties of the bolt were found to be (Roy Mech, 2008):

$$\textit{Yield strength} = 450\ [N/mm^2] \quad [5]$$
$$\textit{Tensile strength} = 700\ [N/mm^2]$$

Giving a factor of safety of:

$$\textit{Tensile strength / Expected maximum stress = Factor of Safety} \quad [6]$$
$$700\ [N/mm^2]\ /470\ [N/mm^2] = 1.49$$

Although the bolt will experience a load larger than the yield strength, it will be some way short of the tensile strength of the bolt.

The wheelchair integrated lap belt will require a vehicle mounted upper torso restraint. This will be routed above the shoulder of the ATD through a vehicle mounted routing point (Figure 11). This option will therefore meet the standard of a Type (b) occupant restraint as shown in Figure 3.2 of this report. The complete set up can be seen in figure 4.3.

Figure 4.3: Set up of wheelchair integrated lap-belt with vehicle mounted torso belt and above shoulder vehicle mounted routing

A number of solutions have been suggested for designs to the upper torso belt. For example, the same locator plate and pin arrangement could be used to anchor the upper part of the torso belt to the Lynx seat (arrangement Type (c) in Figure 3.2), creating a 3 or 4-point harness (Appendix A).

Due to the design of the back of the Lynx seat, the upper end of the torso restrain would be located below the shoulder level. The bending moment about the backrest uprights can be calculated using Eq. 1 to get the force due to the acceleration of the 75kg ATD, then simply multiplying the half of this force experienced by each upright by the distance to the pivot point on the backrest:

force x distance = moment [7]

7,400 [N] x 0.8 [m] = 5920 [Nm]

The uprights are made from 19mm aluminium tubing with 16mm x 13mm mild steel tube inserts throughout their length. There is a 90^{o} bend manufactured into these uprights (Figure 12). The mild steel has been pushed into the aluminium and there has been no shrink fitting, therefore we can assume the maximum moment can be found for the system (Benham et al, 1998):

stress = (bending moment x distance from neutral axis) / 2nd moment of area

Using the equation for 2nd moment of area for an annulus: [8]

$$2^{nd} \text{ moment of area} = \pi/64 \times (D^4 \times d^4)$$

Assuming the maximum tensile stress for mild steel is [343 N/m^2] and this maximum “principle” stress is found on the outer surface of the mild steel annulus and further assuming the aluminium does not increase the maximum tensile stress the bending moment is found to be:

[9]

Maximum bending moment = 31.68 [Nm]

This is considerably lower than the 5920 Nm calculated in Eq. 7. However it does not include any of the frame work of the Lynx seating system and the Lynx sheet itself. It is hoped that this structural work will take a considerable amount of the force created by the crash.

Rearranging the formula for bending moment in a solid circular section in terms of diameter, it is possible to calculate the required amount of stainless steel section to cope with the bending moment calculated in Eq. 7.

Taking maximum tensile strength of stainless steel to be 1295 [MN/m^2].

$$2^{nd} \text{ moment of area} = \pi D^4 / 64$$

$$\text{stress} = \text{bending moment} \times \text{distance} / 2^{nd} \text{ moment of area}$$

$$\text{stress} = (\text{bending moment} \times D/2 \times 64) / \pi D^4$$

$$D = \{ 32 \times 5886[Nm] / 1295 \times 10^6 [N/m^2] \times \pi \}^{1/3}$$

$$D = 3.6mm$$

The mass of this much material can be calculated, by knowing the density of stainless steel (7905 [kg/m^3]) to be 9.6 [kg]. This would be for each upright. Therefore the mass of both uprights is 19.2 [kg], which is a considerable addition, severely affecting manoeuvrability of the wheelchair and increasing cost of the seating system.

Another option to strengthen the seating would be to use triangulation. By fixing some material diagonally across the bend the resultant torque at the pivot point is reduced. This might have the result of simply moving the pivot point further up the upright if the load in those structures exceeds the yield strength.

From Newton's Second Law we see that the larger the acceleration, the greater the force, as the mass is a constant. Therefore, we can reduce the torque in the bend by reducing the acceleration of the ATD; this can actually be achieved with a looser restraint, although it will mean an increase in excursions for the ATD which can be extremely dangerous (Le Claire et al, 2003).

If the upper end of the torso restraint continues past the seat back and is anchored to the vehicle, it might be possible to alter the resultant forces such that there is a much reduced torque at the bend of the uprights.

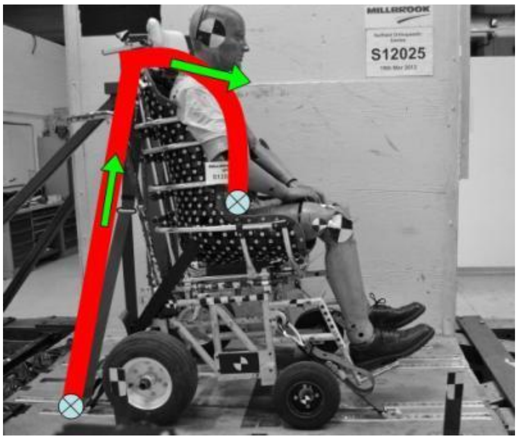

Figure 4.4: Free body diagram showing load pass of torso restraint continuing to floor. It is hoped that interaction of restraint with the seat back will alter resulting forces so the uprights and associated framework can take the force created by accelerating ATD.

A vehicle mounted 4 point harness is available in the Unwin range. It was decided that this product would make a good comparison to the wheelchair integrated solution as the load paths of the restraints are significantly different. If the vehicle mounted system proved successful it would be an off the shelf solution to recommend to clients.

It is an example of Type (a) configuration (Figure 3.2), which as discussed previously is still being used within the industry. There is the potential bonus of having a secure torso restraint (Figure 4.6), reducing excursions of the ATD, not only in frontal impact but also in lateral movements. Should the system fail, it will expose the risk of using untested methods of wheelchair occupant restraint.

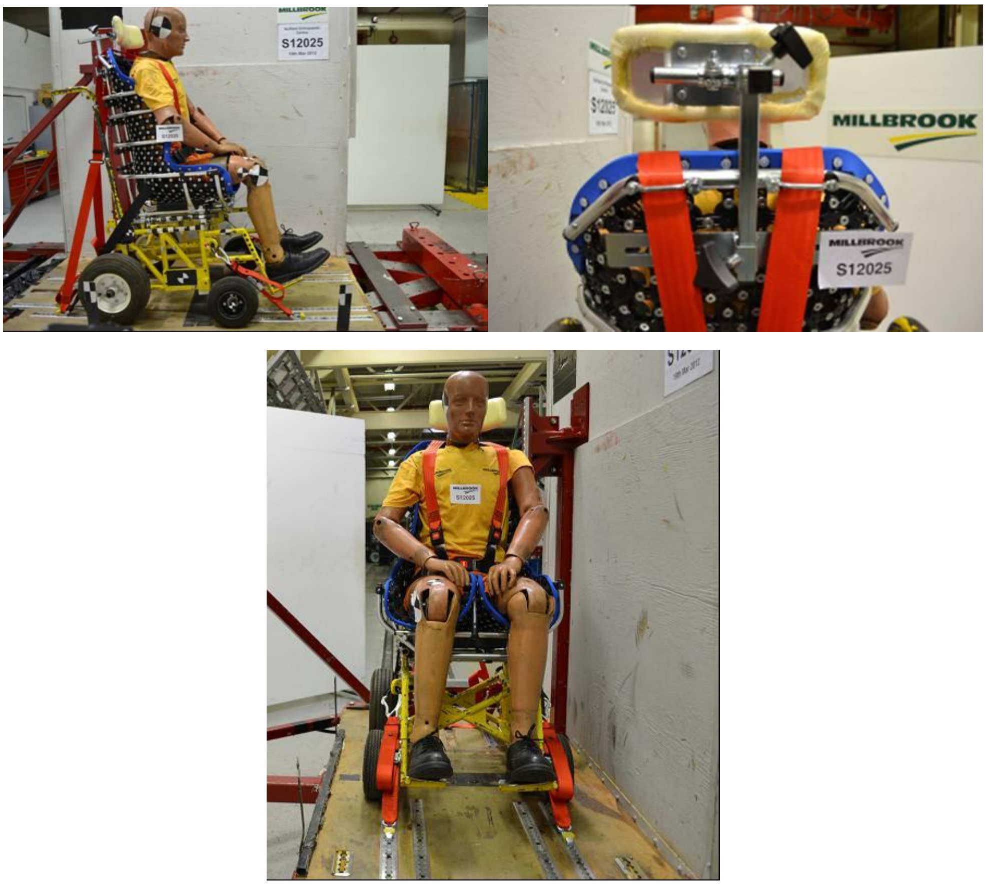

Figure 4.5: Setup of vehicle anchored 4-point harness available from Unwin

5. Manufacture of Seats

Two Lynx seats were manufactured by the author. A plaster cast was taken of the 75kg male ATD, which was used to cold form a sheet of Lynx into the correct shape to accommodate the ATD.

Lynx sheets are made up of nylon (grade 66) cross elements connected with mild steel (EN1A grade) zinc-coated M4 connectors (Figure 5.1) made by Active Design (Active Design Ltd, 2010). The nylon is made by Dupont and has been heat stabilised to ensure consistency, the mild steel connectors are zinc plated to an automobile standard (JS500) to ensure consistency. The design means that one thicker element connects immediately to a thinner element allowing the elements to be slid over each other to create shapes from the Lynx sheet (Figure 5.1).

Figure 5.1: Lynx elements are used to create a shape-able Lynx sheet.

It is possible to place the crosses diagonally and even cut the arms if needed. This technique is often used to make cut outs or to go around very tight corners (Figure 5.2).

Figure 5.2: Example of diagonally positioned crosses and a cut down piece.

The Lynx sheet is laid out and the connectors are tightened to around 8 Nm of torque. This makes it easier to handle and shape around a cast (Figure 5.3). When the final shape is made the connectors are tightened to 13Nm of toque using an electric drill.

Figure 5.3: Pre tightened Lynx sheet laid over plaster cast.

Two "uprights" are then bent around the Lynx to start the framework (Figure 5.4). These are made from 19mm diameter 18-gauge aluminium tubing, with 16mm diameter mild steel (EN1A grade) tubing inserted throughout the length. The 90^{o} bend is made with a pipe bender and the uprights are cut down to size.

The mild steel insert increases the moment of inertia of the tubing, which means that larger bending moments are required to plastically deform the tubing.

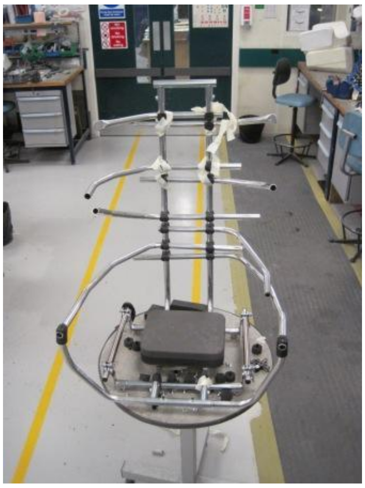

Figure 5.4: Mild steel sleeved uprights with aluminium framework tubing connected by nylon "X Joints". Lynx seat rests on evazote base pad

A South West Seating (South West Seating, 2011) interface kit was used as the interface between the seating and the surrogate wheelchair (Figure 5.5). This includes two 19mm diameter mild steel (EN1A grade) cross members. Mild steel cams were added to the inside of the nylon cams on the interface, this is standard practice to ensure the strength of the connection. The cross members were drilled and a 4mm split pin inserted through each end where they clamp to the longitudinal rail (Figure 5.5). This is not standard practice, however the author thought it would be worthwhile to stop any movement in this part of the interface, otherwise the only securement is from the bolted "hayden" clamp.

Figure 5.5: Interface with split pin (left) and mild steel cams behind nylon cams (right).

The headrest was manufactured in-house to designs drawn up by the Rehabilitation Engineering Department at the Oxford Centre for Enablement. When it was attached and all the framing compete, a blue high density trimming was added to finish off the seat and foam spacers were inserted to replicate the thickness of the covers, which are usually added to a seat but were deemed unnecessary for this destructive crash test (Figure 5.6).

The Lynx method makes adding a pommel relatively easy; therefore it is standard practice to include one where necessary. For this reason a pommel has been included in the seats to be crash tested.

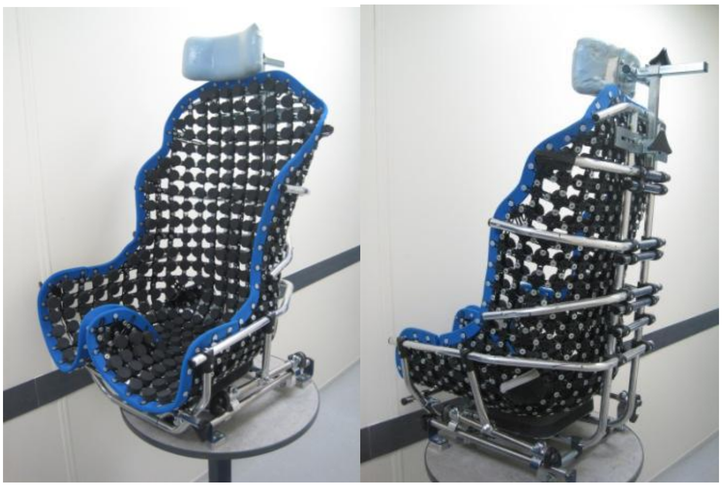

Figure 5.6: Finished Lynx seat.

6. Setup for Crash Test

Both seating systems were setup on the ISO 16840-4 surrogate wheelbase at the Millbrook Proving Ground on Monday 19th March 2012. The 75kg ATD and surrogate wheelbase (63kg) were moved using the crane hoist. Care was taken when lifting the seating system; correct manual handling techniques were used at all times. Safety equipment included steel toe-caps for everyone in the sled test area. When the ram used for the pulse, was being set up and during the pulse firing the sled area was cleared of personnel. The wheelchair system was checked over by the author before each test and a consent form was signed taking responsibility for any damage caused due to incorrect setup of equipment. The Millbrook personnel conducted the setup and firing of the acceleration pulse for safety reasons.

In both systems the surrogate wheelchair was tied down using Quatrro tie-downs wheelchair restraints provided by Unwin.

6.1 Vehicle Mounted Occupant Restraint Harness

Figure 6.1.1: This setup became test number S12025

The black pelvis restraint is mounted on the floor tracking (Figure 6.1.1), is threaded through the Lynx at the pelvis and connected using the tongue and buckle connector on the ATD's pelvis. The red upper torso harness connects to the pelvis restraint with tongue and buckle connectors, the line of action then follows the chest wall over the ATD's shoulders and passes over the top of the Lynx seating system. Two guides were bolted onto the Lynx by the author to prevent the harness slipping off the shoulders in the crash test. The harness is anchored to the vehicle floor (via a loop of webbing (Figure 6.1.2)) at the same location as the pelvis restraint.

The tension in the upper torso harness and pelvic strap was adjusted so it was just slack against the ATD, as required by ISO 16840-4 (Appendix A:5).

Figure 6.1.2: Back view of vehicle mounted harness.

6.2 Wheelchair Integrated Pelvic Belt with Vehicle Mounted Upper Torso Restraint

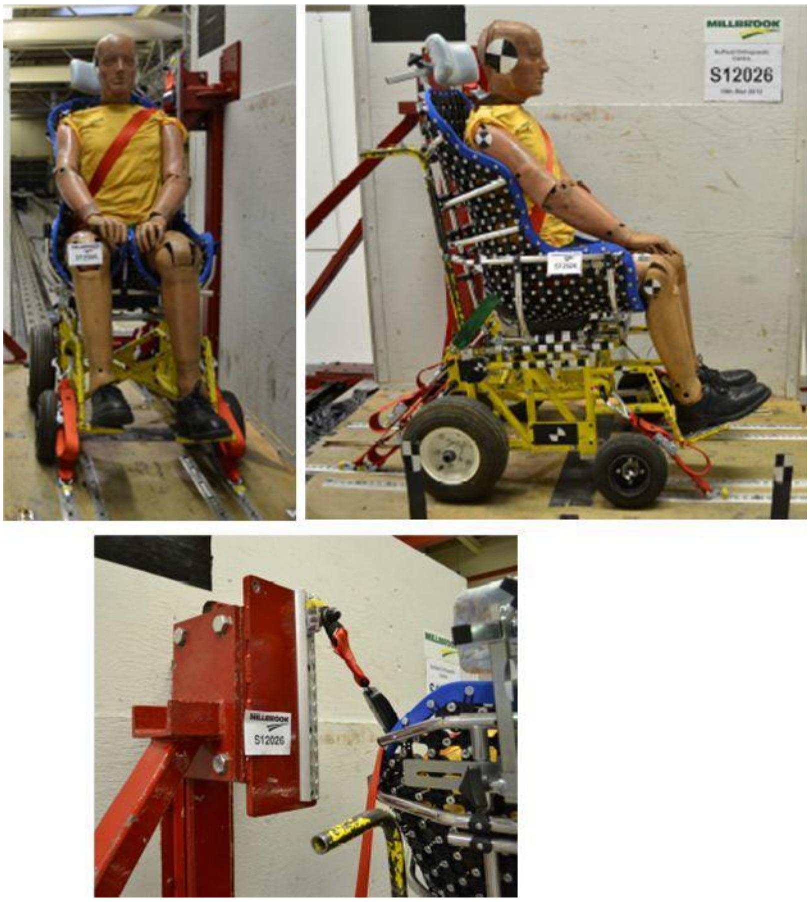

Figure 6.2.1: This setup became test number S12026

The green pelvic belt is anchored to the wheelchair using the stainless steel locator plate and M8 bolt as detailed in section 4. The upper torso restraint is vehicle mounted at the upper end and then passes through a vehicle mounted routing device located above and behind the left shoulder of the ATD. The tension in the upper torso restraint and pelvic strap was adjusted so it was just slack against the ATD, as required by ISO 16840-4 (Appendix A:5).

The angles of the restraint webbing and the tie-downs were recorded (Table 6.2).

Test Number	Front tie-down angle to horizontal	Rear tie-down angle to horizontal	Pelvic belt angle to horizontal	Upper Torso Webbing angle
S12025	37^{o}	45^{o}	53^{o}	78^{o}
S12026	37^{o}	47^{o}	51^{o}	N/A

Table: 6.2 Wheelchair Tie-down and Occupant Restraint Angles at Setup.

The requirement of ISO 16840-4 is that the sled is driven through a change of velocity of 48 km/h (30 mph). At Millbrook Proving Ground, this is achieved by using an acceleration pulse, meaning that the wheelchair is tied down to a sled which is initially at rest. A pneumatic ram then drives the sled forward with a 20g acceleration pulse until the sled is travelling at 48 km/h. The time of this pulse can be calculated:

$$\text{final velocity} - \text{initial velocity} / \text{acceleration} = \text{time} \qquad [7]$$

$$13.3\ [m/s] / 196.2\ [m/s^2] = 0.068 \text{ seconds}$$

7. Results

7.1 Frame Shots from Crash Test High Speed Film

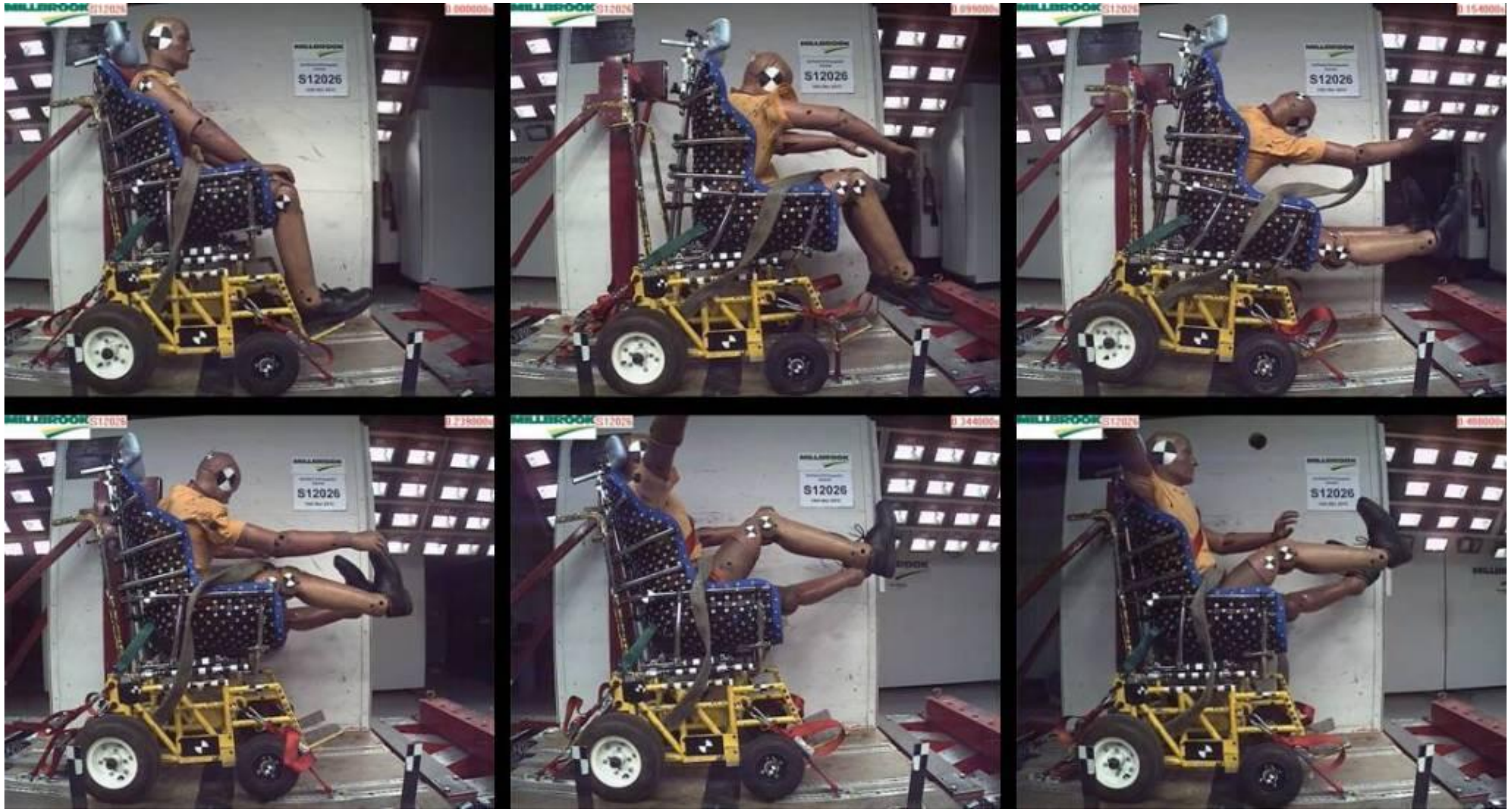

Figure 7.1.1: Frame shots from wheelchair integrated lap belt with above shoulder mounted torso restraint arrangement (S12026). Available at http://www.youtube.com/watch?v=3c_vgPCLFgo

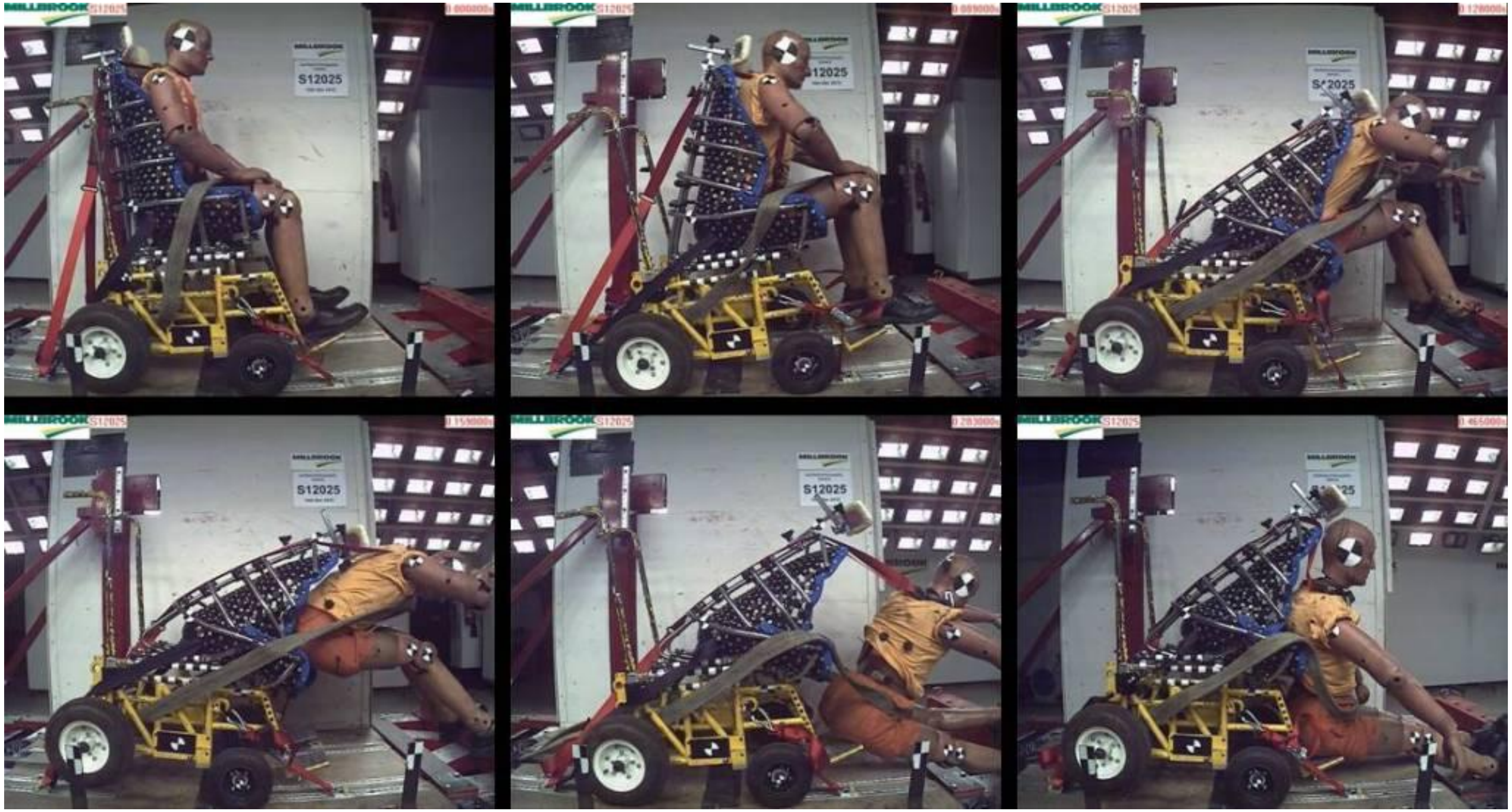

Figure 7.1.2: Frame shots from vehicle mounted harness arrangement (S12025). Available at http://www.youtube.com/watch?v=4uIypKXsxqc

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7.2 Trajectory Data

The requirements of ISO 16840-4 include excursion limits, taken during the test and post test qualification, which are analysed after the test.

The dynamic test of the vehicle mounted harness arrangement resulted in a failure of the post test requirements for ISO 16840-4 on a number of points (Table 7.6.2), including the requirement for the ATD to remain in the seat. Therefore the excursions were not calculated.

For the wheelchair integrated occupant restraint test (S12026) the excursions of the head, knee and wheelchair P-point (a reference point on the wheelchair) were calculated by taking measurements from the high speed film using the targets placed on the ATD, wheelchair and seating.

Head Trajectory

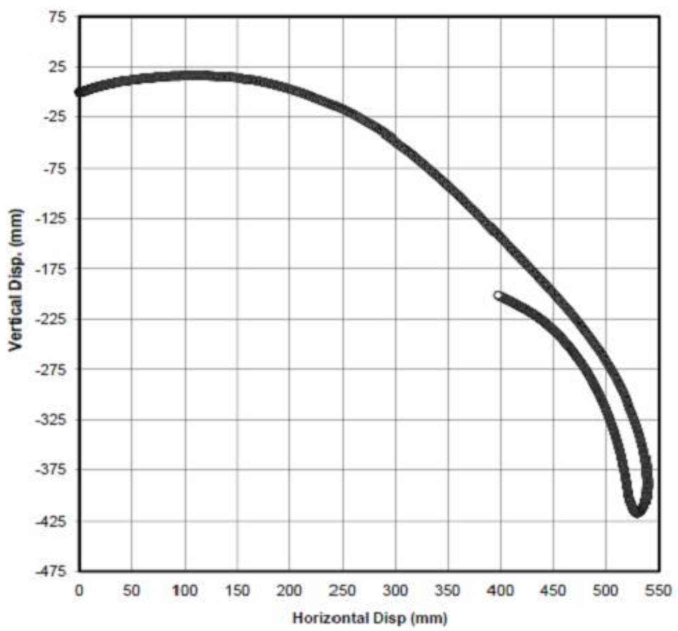

Figure 7.2.1: Head trajectory graph for wheelchair integrated arrangement.

Knee Trajectory

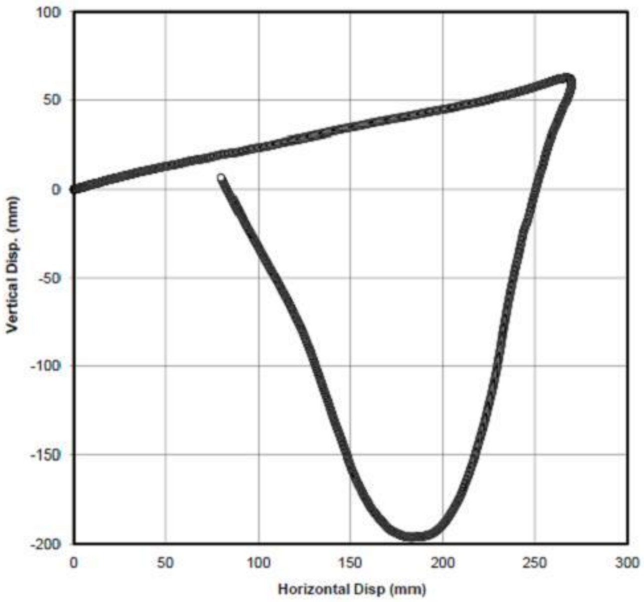

Figure 7.2.2: Knee trajectory graph for wheelchair integrated arrangement

P-Point Trajectory

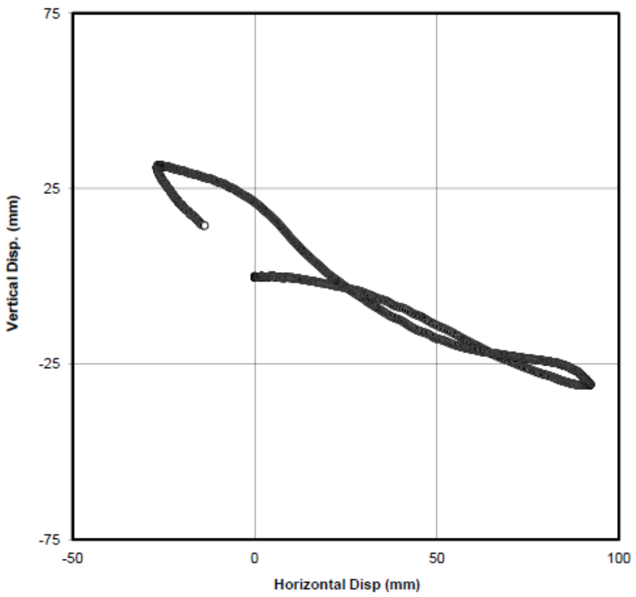

Figure 7.2.3: P-point trajectory for wheelchair integrated arrangement

7.3 Quantitative Analysis

Excursion	Measurement	Value (mm)	ISO 16840-4 Limit	S12026	S12025
Head	Max Horizontal	539	<650	PASS	N/A
	Min Horizontal	0			
	Range	539			
	Max Vertical	17			
	Min Vertical	-417			
	Range	-434			
Knee	Max Horizontal	270	<375	PASS	N/A
	Min Horizontal	0			
	Range	270			
	Max Vertical	63			
	Min Vertical	-196			
	Range	-259			
P-Point	Max Horizontal	92	<200	PASS	N/A
	Min Horizontal	-27			
	Range	119			
	Max Vertical	32			
	Min Vertical	-31			
	Range	63			
Ratio of Knee / P-point		2.93 : 1	> 1.1 : 1	PASS	N/A

Table 7.3: Maximum and minimum excursion data from crash test S12026 taken during the test.

7.4 Post Test Photographs S12025

Photographs were taken of the wheelchair set up post test. These allow the performance of the seating system to be analysed, which is then qualified in Table 3.

Figure 7.4.1: S12025 Post Test.

The pelvic restraint has failed; the ATD has come out of the seat and the upper torso harness has come to rest against the neck of the ATD. These photos also show the plastic deformation of the seating system.

Figure 7.4.2: Details of S12025 Post Test.

Results show plastic deformation of uprights. Interface has ended up disengaging from wheelbase. A nylon T-joint has failed.

Figure 7.4.3: Detail of failure of pelvic belt restraint

The pelvic belt has come apart at two connection points on the left and the right. (Figure 7.4.4) shows the pelvic belt webbing in more detail.

Figure 7.4.4: Post test webbing of pelvic belt (left and centre). Pre-test webbing (right)

The photograph on the left shows how the webbing has been frayed due to contact with the Lynx. The image in the centre shows the post test result of failure of the connection. The image on the right shows a similar pre-test arrangement. The left hand side has been pulled through the loop, the plastic around the edge has come away and the metal bar in the middle has come away from the connection assembly.

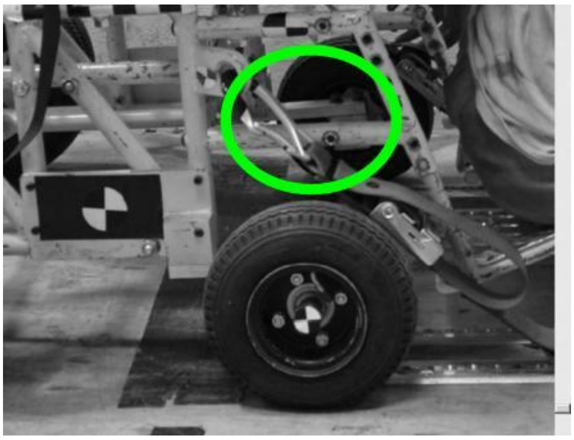

Figure 7.4.5: Front wheels on surrogate chair have deformable mounting castor as specified in ISO 16840-4 Appendix B.

The highlighted section shows the deformable mounting castor has not been deformed. As this was the first test conducted on the day, the castor was left in place. A straight castor is used for each test.

7.5 Post Test Photographs S12026

Figure 7.5.1: S12026 Post Test.

The images show that the ATD remained in the seat. There appeared to be very little plastic deformation and there was no obvious component failure. However figure 7.5.2 shows that the torso belt has unfastened by the end of the test.

Figure 7.5.2: Torso belt found to be unfastened at the end of the test.

Figure 7.5.3: Interface has remained connected

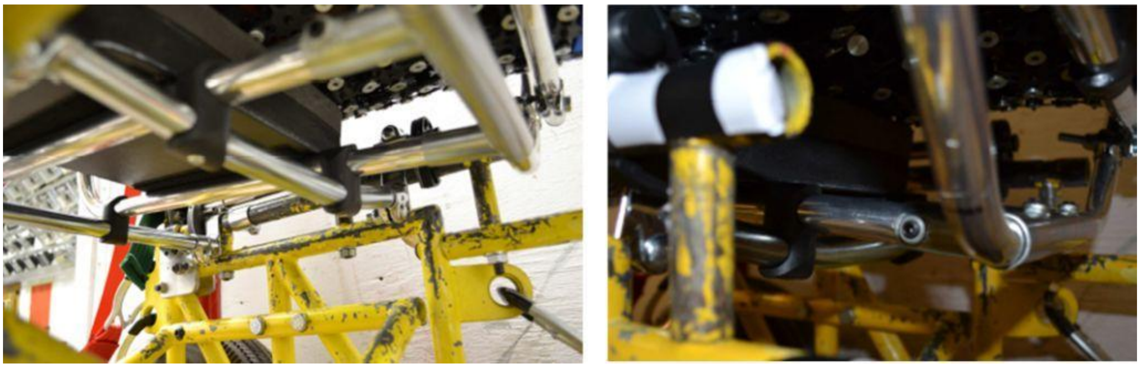

Figure 7.5.4: Some plastic deformation in cross member underneath front of seating system.

The shape of bend suggests downward force caused plastic deformation.

Figure 7.5.5: Deformation in front castor and anchor bolt

Front castors both show significant plastic deformation. The M8 bolt used to anchor the pelvic strap has also plastically deformed.

7.6 Qualitative Analysis

Qualification	S12026	S12025
The seating system shall not break free from the surrogate wheelchair base at any attachment point during the test.	PASS	FAIL

Table 7.6.1: A further requirement of the standard measured during the test.

Qualification	S12026	S12025
The ATD shall be retained in the seating system in a seated posture, with a torso angle of no more than 45^o.	PASS	FAIL
The primary load carrying components of the seating system or attachment hardware shall not show any signs of fracturing or deformation that prevent them from supporting the mass of the ATD.	PASS	FAIL
Components, fragments or accessories of the seating system, with a mass of 100g or more, shall not completely separate from the seating system.	PASS	PASS
Seating system components shall not fragment or separate leaving an occupant contactable edge with a radius less than 2mm.	PASS	PASS
The average post-test H-point height shall not decrease by more than 20% from pre-test	PASS	N/A

Table 7.6.2: Post test analysis of the two seating systems

Qualification	S12026	S12025
The wheelchair satisfied the Dynamic Test requirements of ISO 16840:4	**PASS**	**FAIL**

Table 7.6.3: Final evaluation of the two seating systems

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8. Discussion

The results prove that the Lynx seating system is manufactured in such a way as to pass the requirement for ISO 16840:4 - seating devices for use in motor vehicles. However the choice of occupant restraint significantly influences this results. Furthermore, vehicle anchored occupant restraints, where the upper end of the torso restraint is floor mounted without a routing point above and behind the shoulder have been proven to dangerously load the seating system.

8.1 Vehicle Mounted Harness (S12025)

The seating system failed to pass the requirements for ISO 16840:4 on a number of points. The most crucial failure is the requirement for the ATD to be retained in the seating system.

The ATD was not retained in the seating system because the pelvic belt failed (Figure 7.4.4). It appears that the webbing directly attached to the floor has pulled through the connector; the metal plate within the connector has come out and the plastic has snapped off.

Figure 7.1.2 shows frame shots of the crash test video. By studying these closely a sequence of events can be determined.

From the start until 0.085 seconds the ATD is held in the seat at the pelvis. The shoulder harness allows the torso and head of the ATD to rotate forward. This creates a load on the top of the Lynx seating in the forward direction (the direction the ATD moves in relation to the wheelchair). This load in turn creates a moment in the uprights of the seat back, resulting in elastic deformation.

From 0.085 seconds onwards it appears that the pelvic belt fails, as the restraint appears to go slack. This allows the pelvis of the ATD to travel away from the wheelchair (as the wheelchair and sled accelerate in the opposite direction).

The harness is being pulled with the full force created by the accelerating mass of the dummy. There is no opposing force holding the dummy back in the seat. From around 0.100 seconds it appears that the uprights begin to deform plastically around the bend at the base of the upright, due to the harness applying a load at the top of the seating.

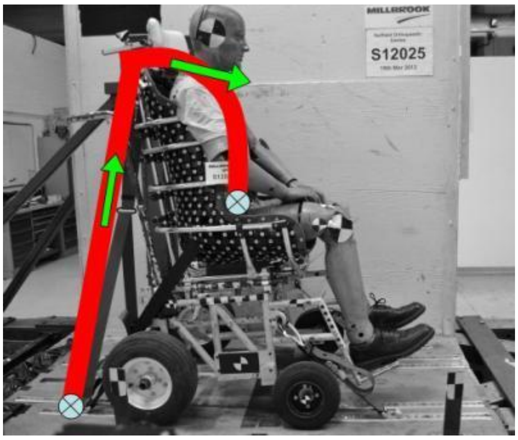

Figure 8.1.1: Freebody diagram showing load path of harness arrangement.

If there was an opposing force trying to keep the dummy in the seat, there would not be as much load on the pelvic belt and it might not have failed. This in turn would reduce the load on the upper part of the seating, which might have lead to reduced plastic deformation of the uprights. This could be achieved by mechanically linking the harness with the top of the seat backrest, and then linking the top of the seat backrest to the vehicle (Figure 8.1.2).

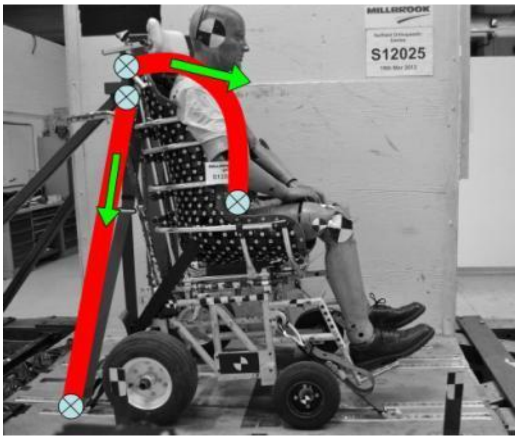

Figure 8.1.2: Creating opposing load paths.

The effectiveness of this arrangement would depend on the location of the vehicle anchor. It is the horizontal component of the load in the link that needs to match the acceleration of the ATD mass. Otherwise it is the stiffness of the uprights that still need to counter the torque created at the bend. Increasing the stiffness of the bend would require triangulation and/or a stronger material than the current design of structural mild steel and aluminium tubing. The amount of extra material needed might make this impractical. Further design calculations to work out the moments and resolved forces in the structures concerned would confirm this.

From 0.100 seconds the ATD begins to leave the seating system as there are no forces acting to keep it in place. This only changes when the broken part of the restrain comes into contact with the neck of the ATD (Figure 7.4.3). The ATD is then dragged back to the ground and lands on the footplates.

Although considerable care was taken to pad the Lynx where the pelvic restraint was routed through the seating system, the webbing has still been frayed as a result of the large forces experienced during the crash test (Figure 7.4.4).

The deformable castors on the front wheels of the surrogate wheelbase are used to replicate energy absorbing crumpling effects of a real wheelbase. However it was found that after test S12025 the castors were not deformed (Figure 7.4.5). Therefore all the energy from the crash had been taken up by deforming the seating system. Figure 7.4.2 shows the plastic deformation that occurred to bend the uprights, the cross bars, to break a T-joint and to disengage the interface.

This catastrophic failure of the restraint and thus the seating system is a direct result of the load path of the harness (Figure 8.1.1).

8.2 Wheelchair Integrated Restraint (S12026)

With the integrated restraint and above shoulder routed upper torso restraint, the Lynx seat passed all the requirements of ISO 16840:4. Analysis of the high speed film footage allows a sequence of events to be determined (Figure 7.1.1).

From the start of the test until 0.085 seconds the ATD is securely held at the pelvis. Forward rotation of the ATD results in the head and upper torso reaching limits of their excursions at around 0.140 seconds. However the upper torso restraint is effective in pulling the ATD back into the seating system. The head of the ATD comes into contact with the headrest at 0.300 seconds. From then on the seating system rotates backwards and actually comes into contact with the push handles of the surrogate wheelchair.

It might be that further deformation was prevented by these push handles. However the push handles are connected to the wheelchair with deformable aluminium struts to replicate a real wheelbase, these did not deform; suggesting the forces were not too high.

The quantitative analysis of the high speed film (Table 7.3) shows that the head excursions were within acceptable limits. A tighter torso belt would have reduced the head excursion, however as mentioned previously a balance between forces, accelerations and excursions is required to reduce injury.

Figure 7.5.2 shows that the torso belt was found to be unconnected at the end of the test. It is thought that one of the foam spacers used to represent the thickness of the covers has pushed the release mechanism. However the buckle is designed to stay in place while there is force through it even if the release mechanism has been pressed.

The interface remained connected to the wheelbase. Hayden clamps were fitted onto the wheelbase, as is standard practice when interfacing a Lynx seating system and it appears these clamps prevented further movement of the interface.

There was evidence of plastic deformation of the front cross member. This can be seen from the high speed film to have occurred in the first 0.150 seconds of the crash, when the ATD is at its maximum forward and downward excursion. It is not possible to say whether the split pins through the clamps have prevented failure of the cross members, however the cross member has not been pulled out of the clamps even though it bent. Therefore it will now be standard practice to insert split pins through the clamps (Figure 5.5).

The M8 bolt used to anchor the pelvic belt suffered some plastic deformation, which means it passed its yield point, however this was predicted in the design calculations.

The deformable front castor has obviously taken considerable load as it has bent. This shows that the energy of the crash was taken up in the elastic deformation of the system and the plastic deformation of those castors. The elastic deformation of the seating system has directly contributed to the success of passing the requirements for ISO 16840:4. Apart from the small deformation in the front cross member, the structural integrity of the seating system appeared to be as good post-test as pre-test.

9. Conclusions and Recommendations

The aim of this research project was to test how the number and location of occupant restraint attachment points affects the performance of a crashworthy seating system. To complete this aim the following objectives have been met:

1. To prove Lynx is a crashworthy seating system.

2. To determine two suitable configurations of occupant restraint, by researching current methods and state of the art solutions.

3. To compare two configurations of occupant restraint systems by sled tests of custom contoured seating systems attached to a surrogate wheelchair.

4. To make recommendations of future direction for development of transportation safety equipment for the specialist seating market

This research has proven that a Lynx seat is suitable as a seating device for use in a motor vehicle. However the wrong choice of occupant restraint system will result in extremely dangerous consequences in a crash situation. Therefore it is vitally important that the initiative is taken to ensure checks are being made to all special seating that is issued to patients.

Results from this study suggest that anchoring the upper end of a torso belt to the vehicle, behind the wheelchair user without using an above shoulder routing device creates a load path that puts undue stress on a wheelchair system. Combining this result with known information about undue loading of a wheelchair user's spine (Le Claire et al, 2003) the case has been made to finally stop using this method of restraint.

It is the author's belief that Rehabilitation Engineers are uniquely skilled to work in an interdisciplinary manner to lead the dialogue between transport companies, patients, carers and clinicians. This dialogue should involve an element of training, through written guides, lectures, presentations and online videos (YouTube, 2012).

An important development has been the validation of the locator plate and M8 bolt method of anchoring the wheelchair integrated pelvic belt. From a manufacturing point of view, it would save considerable time and effort to have a specially designed piece of Lynx that will allow an occupant restraint to be threaded through, without the need to cut down the nylon cross pieces and pad them to prevent damage to the webbing. This could be easily retro-fitted to existing chairs. Combing with a wheelchair integrated occupant restraint (including locator plate anchorage arrangement) would bring them up to the required standard; saving the need to make major structural adjustments, as would be the case with the slot method proposed by Curling (Curling, 2009).

It waits to be seen whether patients will be comfortable using the integrated pelvic belt as a positioning belt. It is obviously not ideal to have large cumbersome buckles next to a patient's body for long periods of time. The current choice of transport rated products in the market is limited; this is an example of where dialogue is needed to develop a range of transport rated products to meet the complex needs of special seating patients.

The voluntary standards ISO 16840:4 and ISO 7176:19 require the use of ATD's that represent the anatomy of able bodied people. They are required to experience 20g accelerations that represent a sudden frontal impact at 30 mph. The users of custom seating have complex anatomical complications. The 20g crash is not necessarily a fair representation of the many thousands of road traffic incidents (including harsh braking and severe manoeuvres) that happen on the UK's roads every day.

The automobile industry has pressed for change in the legislation that governs motor vehicle passenger safety over the past 30 years. This has lead to an ever evolving set of laws that are designed to make sure manufacturers and road users are doing everything to improve safety.

Rehabilitation Engineers need to be pressing for changes to the medical device legislation to ensure the safety of disabled people is given the same attention as able bodied passengers in motor vehicles.

9.1 Future Work

Wheelchair users who cannot transfer out of their seating when using transportation are at risk of not travelling as safely as people who can sit in vehicle seating. An ideal solution needs to be developed that can meet all of the constraints put forward in this research project. Specifically there are two areas that should be considered:

1. A wheelchair integrated occupant restraint, which has anchor points on the wheelchair for both the pelvic and upper torso belts, would meet most of the constraints laid out in this project. The seating system would need to be designed to withstand the loads from the crash so that no structural deformation of the seating occurred.

2. *No less comfortable than a postural restraint*. Vehicle seat belts have the attachment buckles down the side of the seat, away from the occupant. At present all the wheelchair restraints have buckles lying on the occupant's body. Padding would be a step towards increasing comfort. But the answer may lie in using connectors different than the current tongue and buckle arrangement. For example greater use of removable connectors, like karabiners.

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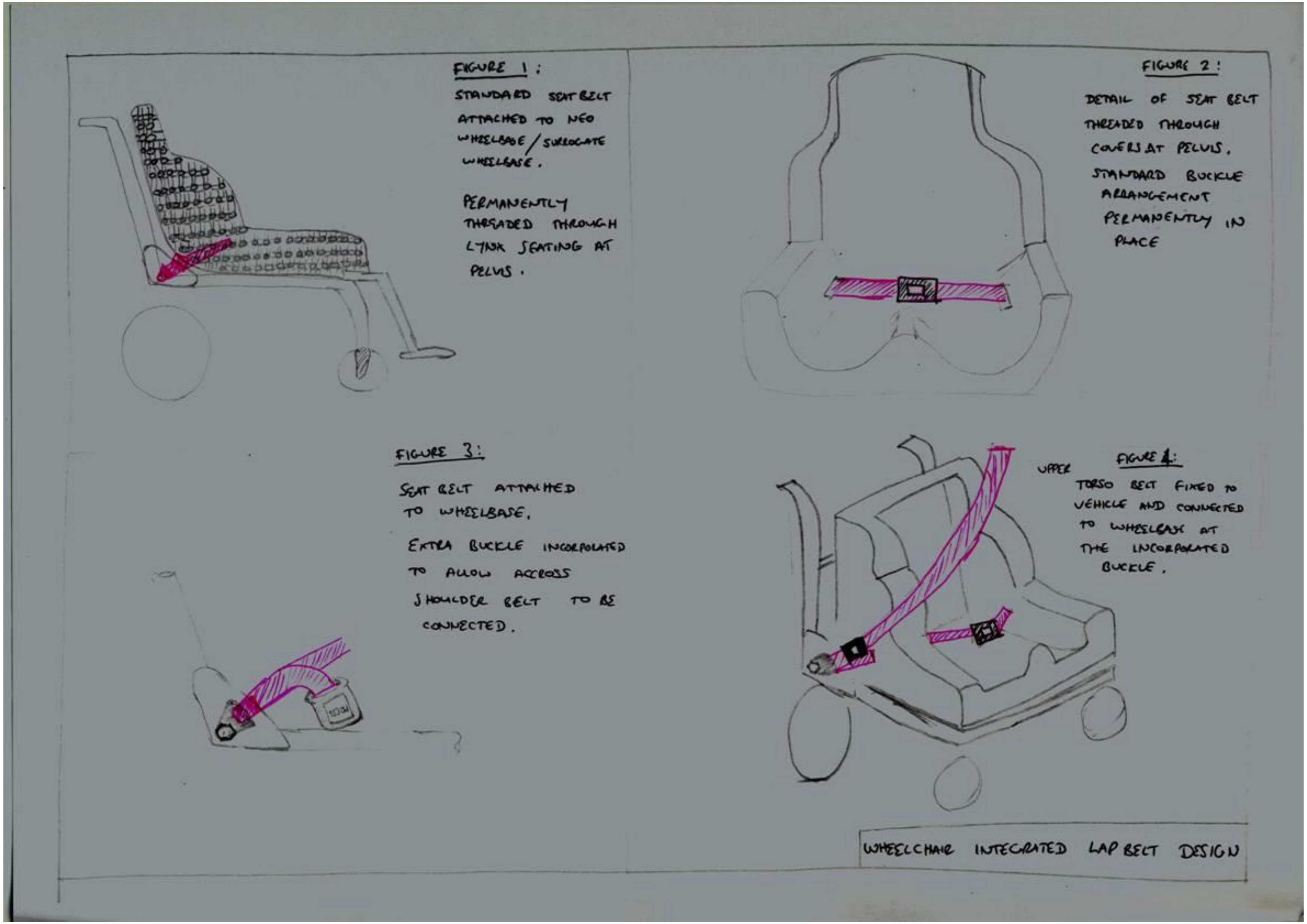
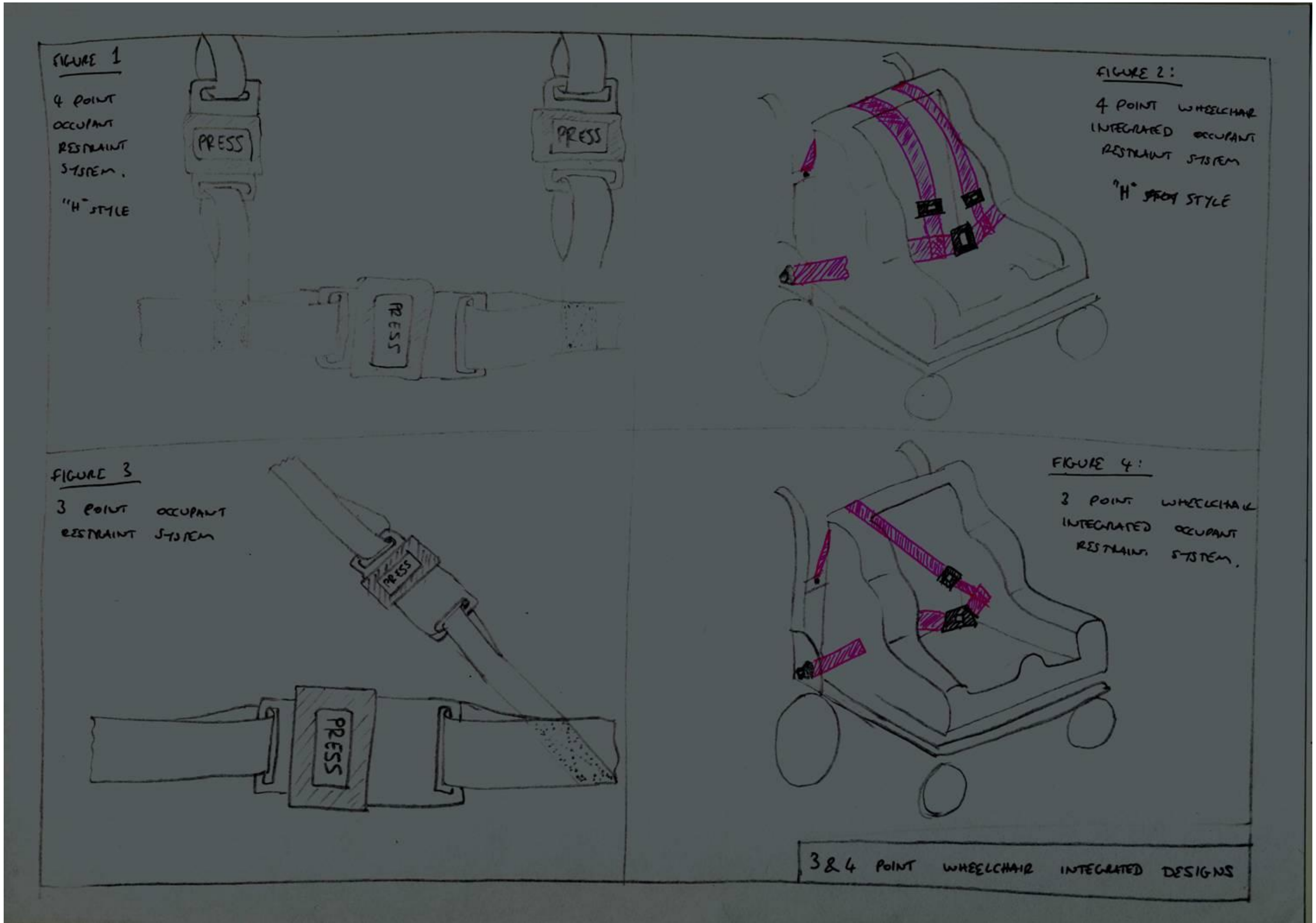
Appendix A. Design Solutions





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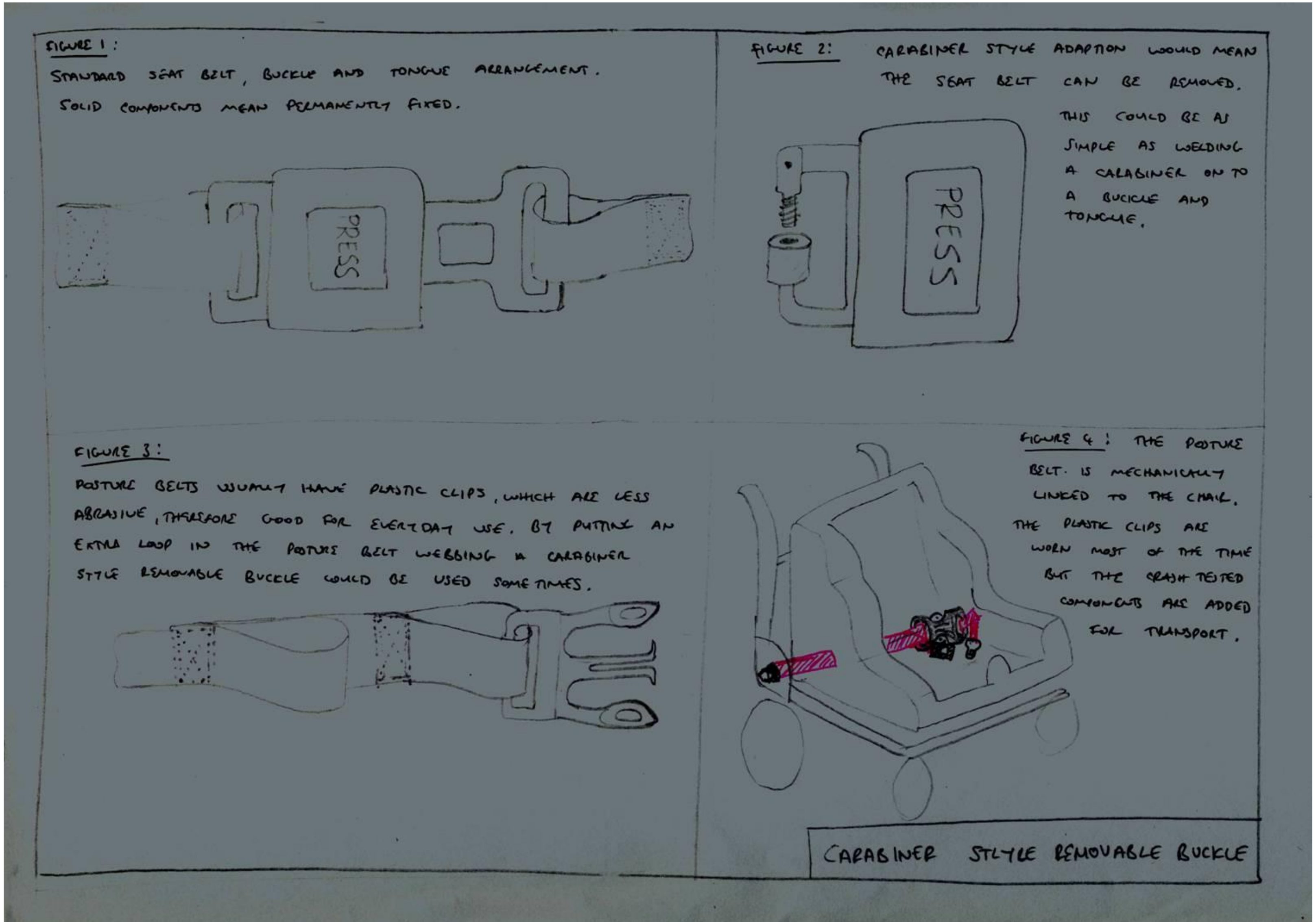
FIGURE 1:
STANDARD SEAT BELT, BUCKLE AND TONGUE ARRANGEMENT.
SOLID COMPONENTS MEAN PERMANENTLY FIXED.
PRESS
FIGURE 2:
CARABINER STYLE ADAPTION WOULD MEAN THE SEAT BELT CAN BE REMOVED.
THIS COULD BE AS SIMPLE AS WELDING A CARABINER ON TO A BUCKLE AND TONGUE.
PRESS
FIGURE 3:
POSTURE BELTS USUALLY HAVE PLASTIC CLIPS, WHICH ARE LESS ABRASIVE, THEREFORE GOOD FOR EVERYDAY USE. BY PUTTING AN EXTRA LOOP IN THE POSTURE BELT WEBBING A CARABINER STYLE REMOVABLE BUCKLE COULD BE USED SOMETIMES.
FIGURE 4: THE POSTURE BELT IS MECHANICALLY LINKED TO THE CHAIR. THE PLASTIC CLIPS ARE WORN MOST OF THE TIME BUT THE CRASH TESTED COMPONENTS ARE ADDED FOR TRANSPORT.
CARABINER STYLE REMOVABLE BUCKLE

		Design Solution			
		Wheelchair Integrated Lapbelt	3 Point W/C Integrated	4 Point W/C Integrated	Carabiner Style Removable Buckle
Feature	Comfort	3	2	1	5
	Expected Safety Performance	3	4	5	2
	Ease of Use	4	3	2	5
	Pass Over Bony Points	4	4	4	4
	Avoid Soft Tissues	3	3	3	3
	Avoid Submarining	4	3	3	4
	Novel Solution	3	4	4	5
	TOTAL	24	23	24	31

Table A.1: Matrix of scores by analysing design solutions

Student ID	3542587

For **comfort**, the karabiner style removable buckle scores highest as it can be removed thus does not rub against the wheelchair user's skin. The 4 point solution scores lowest as there are 3 buckles all positioned over the patient.

Expected safety performance rates how the solution is expected to perform. This is the reason for doing the sled test, to make sure the expected safety performance is accurate. There is a chance the karabiner could fail; therefore it scores lowest on this measure. The 4 point "H-Style" solution looks the more secure than the 3-point solution, certainly in terms of lateral movements. The wheelchair integrated lap-belt with vehicle mounted across shoulder belt looks good, but because it relies on a vehicle mounted component it loses points.

The karabiner option has been designed to be very **easy to use**. There is a chance that the other two designs could be removed if the patient is not going into a vehicle for a while. Therefore the lap-belt would be easiest to remove followed by the 3 point and 4 point options respectively.

All the options are designed to pass over the **bony points**: however there is a chance of slippage, especially on the upper torso. This means none gets top marks.

Again slippage might be a problem for **soft tissue contact**. Therefore none gets top marks and although the way the belt runs through the seating means it should sit low on the hips there is a reasonable chance of soft tissue contact, such as abdominal intrusion during a crash situation.

Submarining occurs when an occupant slips under the restraint. The lap-belt should sit low on the hips therefore should not allow any submarining. However the load path of the straps on the 3 and 4 point solutions is unclear, so they score fewer points.

The carabiner is the most **novel** solution as all occupant restraints rely on a solid, permanent buckle and tongue arrangement. This allows for an interchangeable arrangement. The lap belt with vehicle mounted upper torso restraint is something desirable, but the "ideal" solution is for a fully wheelchair integrated occupant restraint system. Therefore the lapbelt option scores fewer points here.

The totals show that the 4 point and the lap-belt solutions should be compared in a sled test. It would also be very interesting to crash test a karabiner style removable buckle. However because of the cost of running the sled it might be wise to limit the variables between the two comparisons.