# COVENTRY
# UNIVERSITY

***Faculty of Engineering***

***Final Year Project***

# A study of the occupant restraint path in a bespoke special 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 and results that have been obtained from other work are fully referenced. I understand that cheating and plagiarism constitute a breach of University Regulations and will be dealt with accordingly.

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## Abstract

This project was concerned with determining the current level of safety of wheelchair users with special seating systems as an occupied seat when travelling in a motor vehicle. Methods for improving the safety of users during transport was suggested and tested.

Users travelling in custom special seating were identified as being at most risk due to the one-off nature of the design. It was identified that there was a similarity in some custom seat designs concerning the raised sides around the pelvis. The raised sides lift the vehicles occupant restraint system off the pelvis's bony prominences routing it closer to the more vulnerable soft tissue in the abdomen.

During this investigation, two custom seating units were built to accommodate an anthropomorphic test device (crash test dummy). The seats were identical apart from the region around the pelvis. One had no consideration for the occupant restraint while the other had material removed to allow access of the occupant restraint over the bony landmarks of the pelvis. The seats were crash tested according to ISO 16840-4.

The results where compared and it was found that the improved seat that allowed clear path of the occupant restraint, performed much better with a lower risk of injury to the user.

## Acknowledgements

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## Contents

## Glossary

**Anthropomorphic test device (ATD)** – Dummy used to represent user

**Excursion** – Movement of ATD relative to wheelchair **g –**

Acceleration due to gravity, at sea level value approximately 9.8m/s

**Impact simulator** – Dynamic test device used in crash testing

**Impact sled** – Part of impact simulator where wheelchair is mounted

**Interface** – The method or brackets that locate and attach the seat to wheelchair base.

**MSI** – Moulded Seat Insert

**Occupant restraint** – Belts used in transportation vehicles to prevent/reduce movement by exerting restraint forcing on pelvis and torso.

**P point** – A reference point that lies at the cross sectional centre of a 100mm diameter, 200mm long, lightweight (max 0.5Kg) cylinder positioned with the longitudinal axis perpendicular to the wheelchair reference plane such that the curved surface of the cylinder contacts with the backrest and the upper surface of the seat (International standard ISO 71716-19:4)

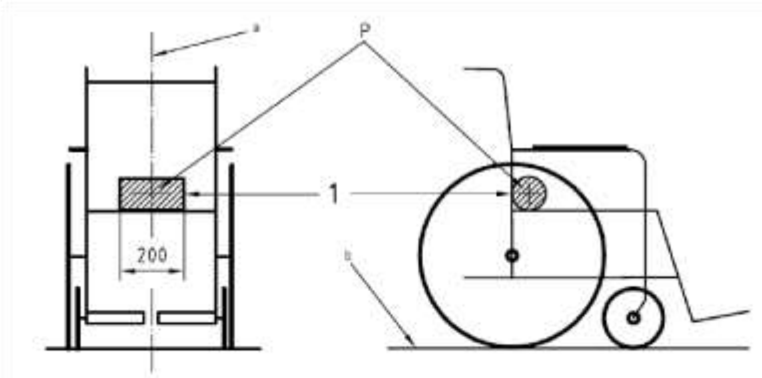


Figure 1.  Diagram to illustrate P- Point (Internal organization for standardization ISO 71716-19:4)

**WTORS** – wheelchair tie-down occupant restraint system

## 2.0 Introduction

Some medical conditions can cause skeletal deformities which can be so severe that the user can not fit in a standard wheelchair. They may not be able to achieve 90 $^{o}$ angle between their torso and legs or thighs there may not have adequate muscle tone or control to keep the torso in an upright position. There are many other reasons why a standard wheelchair is not suitable for all users. For the majority of users, modifying the wheelchair and fitting accessories can adequately meet their needs. For others a functional sitting posture cannot be achieved with the wheelchairs and accessories sold on the market using off the self products.

Special seating can be used to accommodate deformity, exert some corrective forces to the client, improve function and distribute pressure. This can reduce client fatigue and risk of injury from pressure sores [Ham 1998]. An example of a customised seat on a wheelchair base is shown below in Figure 2.1.

Figure 2.1. Custom special seating seat on wheelchair base.

There are many different manufacturers of bespoke seating solutions, using a wide range of materials and manufacturing processes. They can involve taking a cast or digital map of the client. The seats are then produced and interfaced to a wheelchair base. These wheelchair and seating systems are often used as occupied seats in a motor vehicle, as users are often unable to safely transfer to a standard vehicle seat.

The Disability Discrimination Act 1995 was intended to prevent discrimination against disabled people. This has allowed regulations to be passed that will give disabled users equal access to many types of transportation. By giving disabled people equal access to transportation there should be a comparable level of safety (Visvikis 2008). The current level of safety during transportation varies between wheelchair users and the nondisabled population. Some wheelchairs are more compatible with occupant restraint systems than others and therefore can not deliver the same level of safety as other wheelchair users and/or non-disabled people in transportation.

Some manufacturers do not consider the full range of environments that the seats will be used in. It is recommended in the International Standard ISO FDIS 7176-19 Wheeled mobility devices for use in motor vehicles, that the user should transfer into a car seat when possible. In cases when this is not possible, it recommends that the wheelchair and/or seating system should allow the occupant restraint system to maintain good contact with the user.

Due to the design of many bespoke seating systems, the effectiveness of the occupant restraint system may be reduced. The idea of an occupant restraint is to transmit the deceleration force acting on the transporting vehicle to the occupant over a controlled area. The occupant will then match the vehicles deceleration and remain within the vehicle. As the occupant has a separate inertia to that of the vehicle, the equivalent force, with respect to mass, needs to be exerted on the occupant. This is achieved over a predetermined controlled area usually over the pelvis and across the torso. These areas are naturally reinforced with bone and with the load evenly distributed, can withstand a high force better than other areas of the body.

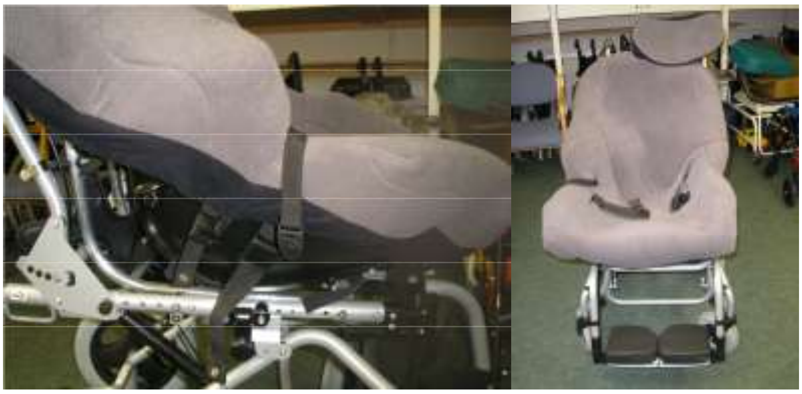

Figure 2.2. Example of custom seating on wheelchair with raised sides to support users pelvis.

Many custom seats have raised sides to stabilise the pelvis and support the user, see Figure 2.2. The high sides prevent the lap belt from touching the sides of the pelvis and if the sides of the seat are very high, the seat can prevent the lap belt from touching the front of the pelvis. The belt can be suspended above the pelvis so in the event of an accident there is no downwards force over the pelvis. The client could slide under the lap belt and out of the chair in the event of an accident or the belt could slide over the pelvis and exert a large force in the soft tissue in the abdominal area causing serious injury.

The NHS provides a wheelchair service to disabled people that live in the UK. There are currently 1.2 million wheelchair users within the UK, 825,000 of which are users of the NHS wheelchair services [Department of Health 4.1.2010]. King's College hospital provide and support a wheelchair service management database to several wheelchair services in South East of England. A query has been run on the database to investigate the percentage of custom seating users within these services (see Table 2.1). The data in Table 2.1 shows that the average percentage of users that have special seating on their wheelchairs is 3.66%. If the figures provided are an accurate approximation of the UK service users, it can be assumed that the potential people in special seating and thus people susceptible to this issue, is in the region of 30,200.

Table 2.1. Percentage of special seating users within wheelchair services.

| Service | Active | Special | % of Special seating users to WC service |
|---|---|---|---|
| Isle of Wight | 2105 | 15 | 0.71 |
| Portsmouth | 12444 | 130 | 1.04 |
| Maidstone | 4592 | 78 | 1.70 |
| Bedfordshire | 5919 | 231 | 3.90 |
| Southwark | 20584 | 153 | 0.74 |
| Barnet | 3643 | 121 | 3.32 |
| Harrow | 3736 | 115 | 3.08 |
| Hillingdon | 3017 | 113 | 3.75 |
| Hounslow | 3000 | 82 | 2.73 |
| Total | 57902 | 1681 | 3.66 |

This research project concentrates on the effects of neglecting the accommodation of the occupant restraint system. The investigation explores the effects of the position of the occupant restraint system and, depending on the results, could possibly help change current practice of these manufacturers to consider the occupant restraint. This project hypothesises that neglecting to consider the occupant restraint within the design of the seat will adversely affect the safety of the user. If the hypothesis is valid, the data from this work may be used to improve custom seat design practice. This project will also aim to produce a solution which allows good occupant restraint.

## 2.1 Special seating

When a user's needs exceed that of what can be offered by standard equipment and accessories, special seating is used. Special seating is made for each client and can be broken down into two categories; custom seating and modular seating.

### 2.1.1 The custom seat

Custom seats are moulded specifically to suit the client's anatomy. A cast of the client's shape is taken and a seat is manufactured based on the shape of the cast. The processes can be seen in Appendix A – Custom seats. There are four common types of custom seating as listed below. Each type is offered by several different manufacturing companies, with some NHS services choosing to manufacture their own seating inhouse.

- Contoured carved foam
- Matrix
- Lynx
- Mould seat insert (MSI)

The seats can be made in two parts (seat and back). Off the self products could also be used along with the custom seating to meet the client's needs. Some of the different types of seat can be seen in Figure 2.3.

Figure 2.3. SOS custom seats offered be Specialised Orthotic Services. From left to right; Moulded Seat Insert (MSI), Matrix and Foam Cast seat.
(Specialised Orthotic Services 2009 custom seating)

Appendix A explains the manufacturing processes for the common four different types of custom seating. The manufacture methods and purpose are very similar to the other seats. The client is sat on a large bean bag while the air is slowly removed from the bag. This gradually makes the bag stiffer while the caster helps the bag form into a shape that will support the user and meet the prescription details that the wheelchair service has issued. Certain design details can be built into the seat at this stage for example increased lumber or lateral support. When the bean bag is solid, Plaster of

Paris or a digital map can be used to copy the shape. The cast or digital map is then used to make the seat.

One advantage to the custom made seat is that the seat is made to match the client's anatomy. This means that the client will have maximum contact with the seat. The client's body weight will be evenly distributed over the seating system, lowering the pressure generated in one area and hence reducing the possibility of a pressure sore developing.

While custom seating reduces pressure and provides a higher level of support they have little scope for modification. As the client changes and the seat becomes unsuitable, they have to be recast which can take a long time. The advantages and disadvantages for each type of seat are listed in Appendix A – Custom seats. Custom seating also tends to be bulky and heavy. This can interfere with wheelchair use. The user may struggle to self propel a chair with custom seating or it may restrict the user's movement. A less restrictive solution is a modular seat.

### 2.1.2 Modular seats

Modular seating systems encourage an orthogonal sitting position. Most systems are adjustable and therefore good for growing children. They are still supportive but not suitable for people with abnormal skeletal anatomy. The image below, Figure 2.4, which shows an example of a modular seat manufactured by Specialised Orthotic Services. There are many other manufacturers all producing modular seats with small variations.

Figure 2.4. SOS Modular seats, a BB seat. (Specialised Orthotic Services 2009 modular seating)

## 2.2 Objectives

This project hypothesises that neglecting to consider occupant restraint path on custom seating will have a detrimental effect of the user safety in the event of an accident. This project hopes to prove this by achieving the following objectives.

1. To produce a seat which replicates the general design of custom seating within the NHS and crash test it according to ISO 16840-4.
2. To produce a seat which improves the design of custom seating with respect to the occupant restraint path and crash test it according to ISO 16840-4.
3. To compare the crash test data to determine if the new design is an acceptable suggestion to improve occupant safety in transport.

## 2.3 Scope

- How manufactures of custom seats approach design to accommodate the path of the occupant restraint.
- Bio-mechanics and the effects on an adult human body in the event of a vehicle accident.
- The Directives and standards that control the design and use of Medical devices.

### 2.3.1 Out of scope

Only adults with normal anatomy will be considered throughout this study. The range of abnormality that custom seating accommodates for and the differences in children's anatomy could be, in the future, subjects of study in the future but are too diverse to be considered in the scope of this project. Equipment misuse is also not in the scope if this project.

## 3.0 Literature Review

The key words used during the general search are listed below in a various combination;

- Custom seat* OR Special seat* OR Bespoke seat*
- AND Transport*
- AND Occupant restraint
- AND wheelchair
- AND crash test

Coventry library, the internet and Kings College resources where all used in the collection of relevant literature. The resources used in the search for journals are listed below;

- Academic Search Complete (EBSCO)
- AMED (EBSCO)
- Compendex
- MEDLINE (EBSCO)
- SAGE Journals Online
- Science Direct
- SCOPUS

The information has been summarised within this chapter.

## 3.1 Relevant legislation

### 3.1.1 Medical Devices Directive 2001/83/EC of the European Parliament

The Medical Device Regulations (2001) in accordance with the Consumer Protection act (1987) requires manufacturers to conduct a full risk analysis to support the CE marking of their products. Part of the risk management is the International standards

ISO 7176/19 and ISO 16840-4 which defines the impact test of a wheelchair. It is given as supporting evidence of wheelchair suitability to travel in a vehicle (Claire, M Le 2003:8). The nature of custom made devices means that they can not be tested individually. To test a "one of a kind" custom device would require its testing to point of failure rendering it unusable. For this reason custom made devices do not require CE marking. The Directive 2001/83/EC of the European Parliament Annex VIII requires a statement on custom made devices including the following:

> *A statement that the device in question conforms to the essential requirements set out in Annex I and, where applicable, indicating which essential requirements have not been fully met, together with the grounds.*

Directive 2001/83/EC has included the essential requirements of medical devices in Annex I and the relevant requirements to this project have been listed below. Annex I, Section 1 of the Directive includes the statement;

> *The devices must be designed and manufactured in such a way that, when used under the conditions and for the purposes intended, they will not compromise the clinical condition or the safety of patients, or the safety and health of users or, where applicable, other persons, provided that any risks which may be associated with their intended use constitute acceptable risks when weighed against the benefits to the patient and are compatible with a high level of protection of health and safety.*

Annex I, Section 2 of the Directive includes;

> *The solutions adopted by the manufacturer for the design and construction of the devices must conform to safety principles, taking account of the generally acknowledged state of the art. In selecting the most appropriate solutions, the manufacturer must apply the following principles in the following order: — eliminate or reduce risks as far as possible (inherently safe design and construction),*
>
> *— where appropriate take adequate protection measures including alarms if necessary, in relation to risks that cannot be eliminated,*

*— inform users of the residual risks due to any shortcomings of the protection measures adopted.*

The Directive forces manufacturers of custom made seating to consider the risks of user injury during transportation.  When the risk can not be eliminated the user must be informed.

A small part of the CE marking process requires the chair to pass the international standard ISO 16840-4 and/or ISO 7176-19 if the manufacturer declares that the seat/chair is suitable for travelling in during transport.  The international standards are used to help manufacturers test their products so that they meet the essential requirements of products included in Council Directives such as the Directive 2001/83/EC.  The nature of custom devices means that they can not all be tested to the International standards without being destroyed.  The standards ISO 7176-19 and ISO16840-4 are used in this industry to prove conformity (Invacare 21.01.2005).

### 3.1.2 ISO 7176-19 Wheeled mobility devices for use in motor vehicles

ISO 7176-19 was designed to test a wheelchair and/or a wheelchair base with seating. Some custom seating manufacturers have produced their own wheelchair base.  In these cases this standard is used to test the whole unit.  In many cases a custom seating system is used with a different manufactures wheelchair base.  The seating can be tested to ISO16840-4 while the wheelchair base is tested to ISO 7176-19 to achieve a CE mark for the whole unit.  By testing the seat separately using ISO 16840-4 and then the wheelchair base, the whole wheelchair unit in theory, should be safe for use. Conversely, if the same seat that passed ISO 16840-4 was then tested on a selected wheelchair base, it should pass the tests in ISO 7176-19.  It follows that both standards are applicable to this investigation.

ISO 7176-19 details the requirements for seating and wheelchairs that they must meet, in section 4.2.3 it states:

*Wheelchairs should be designed to enhance the effectiveness of belt-type occupantrestraint systems. If the wheelchair is intended for use with either vehicle or tiedownanchored occupant restraints, it should be designed to allow the unobstructed fitting of the restraint belts to the occupant.*

This means that the seat must be designed in a manor that allows good contact of the user with the occupant restraint system. Any raised sides around the pelvis would restrict the pelvic part of the transport restraint system. The most common occupant restraint system is a 3 point seat belt with double inertia reel, see Figure 3.1.

Figure 3.1. Left: 3 point seat belt with double inertia reel; Right: Static harness (Unwin safety systems 2009 occupant seatbelts)

The diagonal and pelvic parts of the seat belt are on a single strip of webbing which can connect to the double inertia reel. Figure 3.2 shows an Unwin occupant double inertia reel seat belt system. In these photographs the webbing is anchored into the floor which is then suspended on a vertical pole where the inertia reel is secured. The vehicles floor would have to be adapted to have tracks so that the equipment can be securely attached. The webbing is then draped diagonally across the user's torso and clipped into a standard seatbelt receiver. The receiver is anchored into the vehicle floor. The webbing continues horizontally across the pelvis to be anchored in the floor tracking.

Figure 3.2: Left and middle shows Unwin 3 point seatbelt occupant restraint system with Matrix seat and powered wheelchair base on vehicle transport rig. Right shows rig of floor tracking and anchors.

Figure 3.2 also shows the issue with high sided custom seating. The high sides prevent the close access of the occupant restraint path to the pelvis as directed in ISO 7176-19. The standard states in section 4.2.1 that the user instructions should include a statement in the user instructions booklet which specifies the correct position of the occupant restraint. The occupant restraint should be worn low over the pelvis in a preferred zone of 30° to 75° to the horizontal, as shown in Figure 3.3, where a steeper angle is preferable. The standard also mentions that in the user instructions it should also include a comment that the belt restraints should not be held away from the body by wheelchair components or parts, such as the wheelchair armrests or wheels, along with an illustration similar to that of Figure 3.5. The standard also requests that the Figures 3.4 and 3.5 are included in the Instructions For Use (IFU) to demonstrate the incorrect and correct way to fit the occupant restraint.

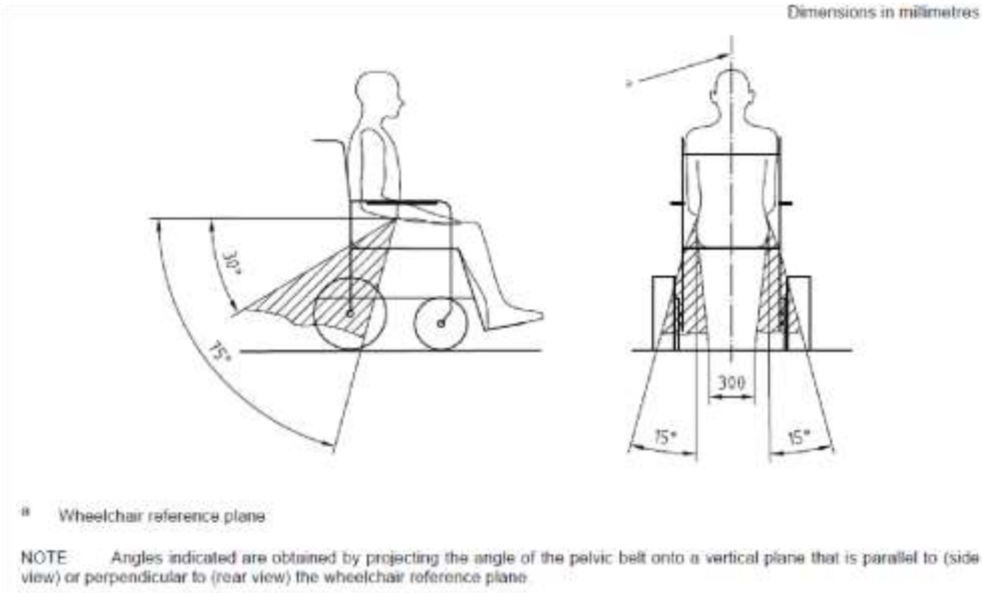


Figure 3.3: ISO 7176-19 suggestion of pelvic belt restraint positioning.

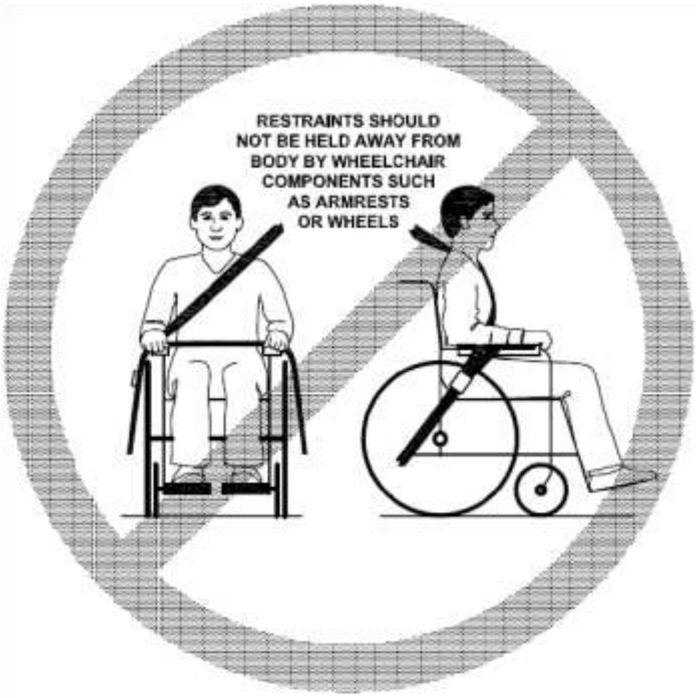


Figure 3.4: ISO 7176-19 Recommended illustration for manufacturers to include in their presale literature for improper occupant restraint fit.

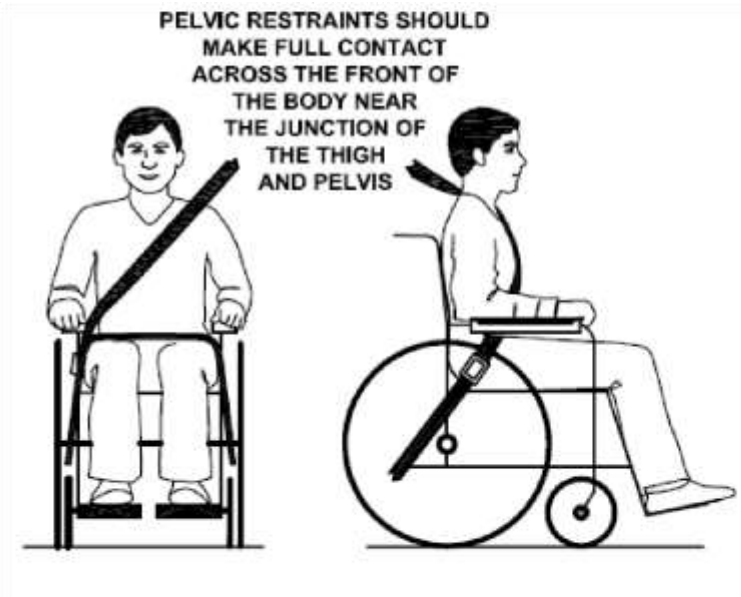


Figure 3.5: ISO 7176-19 Recommended illustration for manufacturers to include in their presale literature for correct occupant restraint fit.

The standard indicates that the belt should have good contact with the client, Figure 3.5 demonstrates this.  Good fit has been defined in Annex D of the standard see Appendix C of this report.  Figure 3.4 shows how the occupant restraint should not be fitted.  The pelvic belt webbing has gone over the parts of the wheelchair and not directly over the user's pelvis.  There is no contact of restraint belt webbing around the sides of the pelvis, only over the top.

Images have been collected of custom seating systems that do not conform to ISO 717619 (Appendix B – Custom seat examples).  All of these examples are seating systems that have been used on transport with a client in-situ.  The chairs and seats have been used in conjunction with a 3 point seat belt similar to the ones featured in Figures 3.1 and 3.2.  The existence of these custom made seats is evidence that ISO 7176-19 and subsequently the Council Directive 93/42/EEC is not properly being adhered to placing the user and others around, in danger.  The Council Directive does specify the risk must be eliminated or reduced as must as possible and in the event this can not be achieved the user should be informed of the risk.  For these seats it is unknown what attempts where made to reduce/eliminate the risk and whether or not the user was informed of transportation risk.  It is also unknown if the lack of accommodation for the occupant restraint was negated in the interest of their safety or due to rendering the seat ineffective in terms of a medical device.  It is possible to render a seat ineffective by removing material in this area for some individual users with certain medical conditions.

### 3.1.3 ISO 16840-4 Wheelchair seating -- Part 4: Seating systems for use in motor vehicles

ISO 16840-4 used by custom seating manufacturers to partly fulfil the requirements with in the Medical Devices Directive.  The standard is very similar to ISO 7176-19 but requires the test to be completed on a surrogate wheelbase or commercial wheelbase. This test has the same test procedure and suggestions as in ISO 7176-19 but focuses on the seat and seat interface performance.  The manual surrogate wheelchair base is of a generic design as specified in ISO 16840-4 Annex B.

ISO 16840-4 specifies that in the presale literature for the seat, there must be a comment that states that the seat is only to be used with wheelchair bases that comply with the performance requirements in ISO 7176-19.

The ISO 16840-4 also specifies the crash test method for the occupant restraint and the minimum requirements the system has to achieve in order to pass the test which are the same as ISO 7176-19.  The method will be used in the testing section during the crash test.  The criteria to pass the test are also specified.  The seats that will be crash tested will be measured against this standard and passed or failed by its criteria.

## 3.2 Seating Manufacturer's approach to occupant restraint

A selection of the most commonly used manufacturers contracted in the NHS wheelchair service for the production of custom seating has been researched.  A random selection has been featured in the research.  Manufactures contacted have been included below.

- Delicon
- Specialised Orthotic Service
- 886 Contour
- Active design
- RMS
- RJ Mobility Ltd
- Tendercare Ltd
- Otto Bock
- Consolor
- Blatchfords

In all cases the manufacturers did have a solution but it is clear from Appendix B – Custom seat examples, that these procedures are not being put in place.

Appendix B – Seat examples, shows 14 seats manufactured in the South East of England. The images are of seats encountered by seating Engineers during their normal working hours. The seats have been divided into seat type, Moulded seat insert, Matrix and carved foam. The number of examples found in each category can be seen below:

- Matrix 5
- Carved foam 4
- Moulded seat insert 5

Based on the users postural requirements it may not be possible to achieve good contact with the occupant restraint. In some cases to achieve a good posture, the chair will have built up sides to stabilise the body or to ensure a particular position. The images featured in Appendix B show that in some cases postural support will be higher priority than transport safety but also shows that some seats have not had occupant restraint considered when it would have been possible.

In all cases where the manufacturers have specified that the seat can be used during transportation, the user manual did feature the required information as specified by ISO 7176-19 and ISO 16840-4. All the user manuals contain a similar statement to the same effect. One manufacturer has worded their statement for the moulded seat insert as follows:

*The Occupant Restraint should have a clear path from the user to the anchor point and should not be interfered with by any part of the vehicle, wheelchair, seating or accessory.* (Specialised Orthotic Services 2009)

The design of some of the chairs cast and manufactured, means that the statement in their user manual is not achievable. Figure 3.6 shows an image of a MSI seat. The design has raised sides allowing limited or no access of the occupant restraint over the user's pelvis. A strip of black webbing has been placed over the seat to demonstrate the path that the occupant restraint would have to follow. ISO 7176-19 specifically highlights that this is not advisable, see Figure 3.5.

Figure 3.6. Moulded Seat Insert seat and wheelchair base.

Each manufacturer with examples of custom seating that do not follow ISO 7176-19 guidelines for transportation was contacted. In each case the manufactures reply, regardless of seat type, was that they created a slot out of the seat in the pelvic region. For this slot to be included in the chair design, its intended for use on transportation must be declared to the manufacturer. When this information is omitted seats can be created that do not accommodate the occupant restraint system such as the chair in Figure 3.6

This investigation had a limited region of operation when collecting the examples featured in Annex A. The seat images collected do not show a balanced overview of custom seating in the NHS due to the method of collection. The research does indicate that all types of custom seats that have an issue with occupant restraint. The two part nature of carve foam has the potential to easily allow the pelvic restraint to achieve the good occupant contact. The manufacturer and occupant will determine the shape of the custom seat. This results in a large variation of shapes. While there are significant differences in design there is a similarity around the pelvic area. In the images (see Appendix B), the seat has been built up in the pelvic area. The effects of this will be tested in this investigation.

All of the custom seats have examples in current use of designs that the occupant restraint has not been considered. From the seating examples gathered in Appendix B, it appears that there is no seat type that is more or less susceptible to raised sides around the pelvis. It was also not possible in the time and with the allocated resources to collect a wide enough range of samples to accurately identify a seat that has more poor examples than the other three types. The seat that will be crash tested will be the seat where the materials are readily available or have the least cost.

The Rehabilitation Engineering Division at Kings College Hospital does not use Matrix seating regularly but has a stock Matrix sheets. For this reason the seats for the crash test will be constructed out of Matrix.

## 3.3 Bio mechanics

When a wheelchair user remains seating during transportation, they should be forwards or rearwards facing and not side facing (Ham 1998). There is also evidence that you are more susceptible to injury facing rearwards due to the increase of excursion during the rebound phase of impact (Claire, M Le 2003). The occupant restraint has to prevent excursion to remove the possibility of user impact with the vehicle interior or other vehicle users and excessive loading over body parts. The occupant restraint could cause damage to the user through loading on body parts.

Calculating the loading during a crash test is possible using instrumented dummies but it is very difficult to determine if that force would cause injury due to lack of scientific evidence (Visvikis 2008). The ISO 7176-19 and ISO 16840-4 deals with excursion only but is still used as an industry standard.

The 3 point occupant restraint has been developed to distribute the loading from the crash across the strongest parts of the body and limit excursion. The anterior superior iliac spines on the pelvis for the lap belt, the shoulder and sternum to anchor the diagonal belt and distribute the forces, see Figure 3.7 and 3.8 for pelvis landmarks.

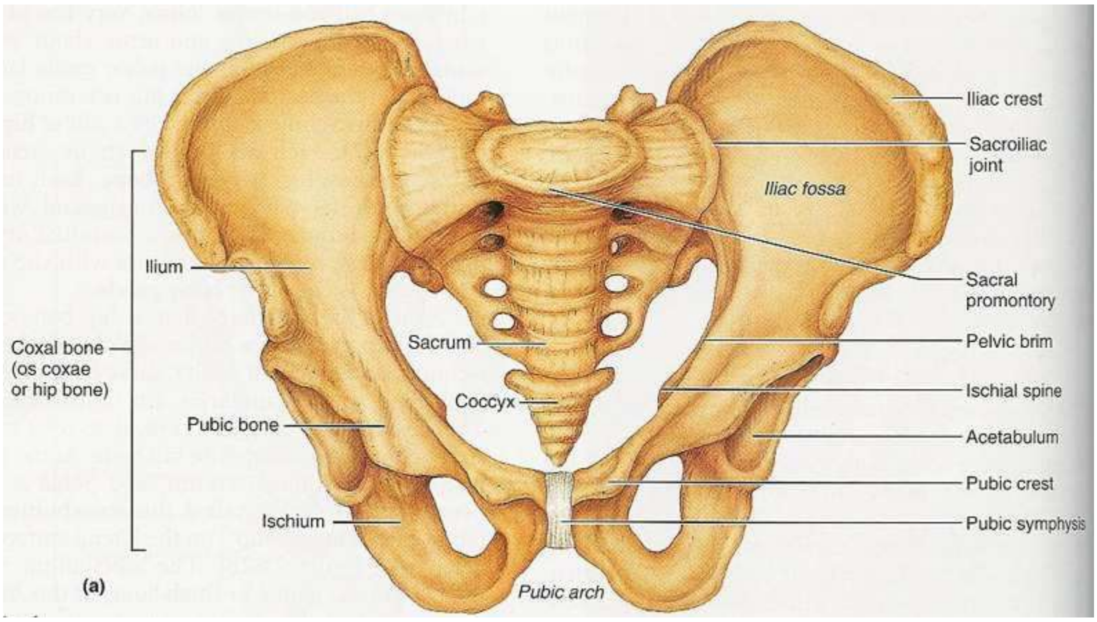


Figure 3.7: Top, Pelvic bones in Coronal plane (front view).

(University of California *n.d*)

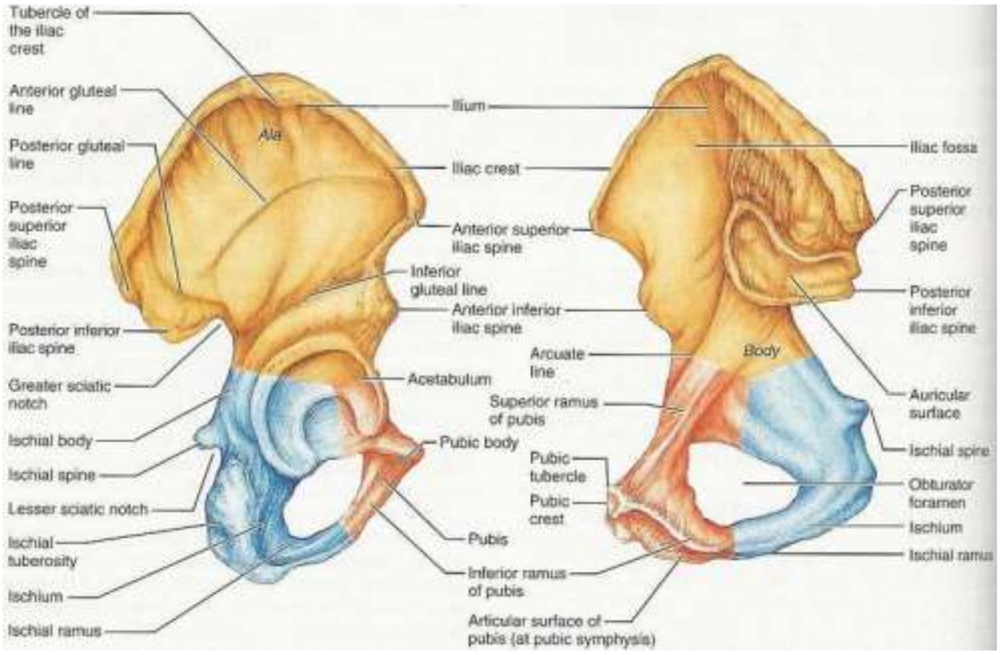


Figure 3.8: Top, Pelvic bones in Coronal plane (front view). Bottom, Pelvic bones in Sagittal plane (side view). (University of California *n.d*)

The lap belt must be as low as possible so that it is nearly over the thighs. The diagonal aspect of the restraint prevents the spine from rapid bending and stretching (Visvikis 2008). While loading is important, excursion also needs to be limited to reduce possibility of injury. The Head Injury Criteria (HIC) is used to estimate the level of damage occurred to the passenger. It can be calculated using the formula below (Interactive maths 12.1.2007):

$$HIC = \max_{t_1, t_2}\left\{(t_2 - t_1)\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5}\right\}$$

A HIC>1000 can indicate a fatal head injury by contact with the interior. The high HIC value can occur even when the torso is properly restrained. The neck can hyper extend and when in rebound the chin hits the chest which can cause a head injury. If the torso is left unrestrained the passenger is at risk of impact with vehicle interior, lumbar fracture from excessive hip flexion and abdominal injuries due to the lap belt being the sole point of distribution of loading (Cooper R 1995).

A German Anatomist/Surgeon Julius Wolff developed a theory that is still accepted today. When loading is placed on bone, it remodels its density and becomes stronger to accommodate the higher loading. To save energy required to maintain bone, if a bone is not experiencing loading it will remodel again to have a lower more appropriate density (Wolff 1986). Wheelchair users do not commonly load through the legs, leading to the assumption based on Wolff's law that their bone density will be lower and thus more susceptible to breakages. In the event of an accident wheelchair users, will therefore be more at risk from broken bones, especially in their lower limbs, than those who can weightbare. This presents two risks placed on user in the event of a collision. One from the excursion causing contact with environment or other users and the other from occupant restraint loading over bones. The occupant restraint loading over the pelvis may produce more breakages in wheelchair users. The legs are mostly effected by Wolff's law since they are weight bearing. Legs experience impact loading during exercise which would also increase bone density. Wheelchair users will still weight bare through their torso due to the effect of gravity but their lower limbs may be weaker than non wheelchair users increasing their risk of injury. This increases the importance of allowing adequate space around wheelchairs in transport.

There are also concerns that if an occupant restraint is fitted over a postural belt buckle, during a vehicle impact, the buckle may cause additional loading on the user (Visvikis 2008:80).

Many chairs have adjustable tilt and recline for user comfort and postural requirements. The tilt and recline changes the users position in relation of the WTORS (wheelchair tie-down occupant restraint system). By reclining the user back in the chair the pelvis is tilted rearwards increasing the chance of the occupant restraint slipping over the pelvis and into the soft tissue within the abdomen . It is called submarining when the user slides under the pelvic belt. The influencing factors for submarining are extensive. Work has been completed indicating that not only the position of the belt over the pelvis but the angle of the pelvis and even the stiffness of the wheelchair seating can also be factors (Bertocci, G. 2003). By maintaining a $90^o$

angle between seat and back rest the occupant restraint can engage on the pelvis effectively.

When anchoring the pelvis, the head excursion increases which makes the requirement for increased space in front of the user greater (Visvikis 2008). Sufficient space around the wheelchair should be allowed to accommodate this excursion during an impact. The wheelchair should have 400 mm behind and 650mm for 3 point systems or 950mm for 2 point systems in front wheelchair. From the front of the head there should be 650mm for a 3 point restraint system and 950 for a 2 point system. There should also be 200 mm of clear space either side of the wheelchair centre line (British standard 10542-1:2001; 11).

## 3.3.1 Biomechanics during the crash

During studies using Hybrid III dummies and an impact simulator with a 10g and 20g over 100ms deceleration pulse, four phases of movement has been identified (Adams TC 1992).

1. 80 – 100ms after impact dummy moves forwards. All joint angles remain constant

2. The forward rotation phase. The hip motion is reversed and the truck, head, shins and thighs rotate forwards. During this phase the maximum forward displacement of head, torso and legs are observed. A suitable diagonal belt across the torso will limit this movement at this time. This is also the phase where injury to the neck and head injuries are most likely to occur.

3. The rebound phase. The dummy moves back to the initial position impacting on the backrest.

4. The extended rotation phase. The dummy continues to move backwards hyper extending the neck if no head restraint is present

## 3.4 Previous crash tests

TRL (Transport Research Laboratory) sponsored the report “The safety of wheelchair occupants in road passenger vehicles”. A manual wheelchair, power chair, heavy power chair and surrogate chairs where tested using computer simulation and dynamic crash testing. A surrogate chair is a reusable device, the design of which has been specified in ISO 16840-4:2004 Annex B. The surrogate chair simulates wheelchair for the purpose of testing WTORS.

The investigation was to determine the main risks to safety during transportation in a wheelchair and then to compare the data with the level of safety of other passengers in the vehicle seating. The research was based on the best use of occupant restraint with no influencing factors. The report identified that there should be a minimal distance between the head and back rests. Raising the back up to meet the head rest could produce issues in achieving good contact of the occupant restraint over the shoulder.

The TRL report “ The safety of child wheelchair occupants in road passenger vehicles” studied the level of current safety. Different vehicle types where investigated with different wheelchair types. In all the tests the occupant restraint was fitted in the best possible way. The report did highlight that in reality, the WTORS would not be installed in a manor that would provide the best restraint for each use. Misuse of WTORS was not within the scope of the project. Custom seating was also not in scope of the report as the medical conditions are too varied. The report did repetitively stress the one of the most influencing factors for safe transportation was ensuring that any recline of the back rest should be removed to prevent submarining (Visvikis 2008).

Occupant restraint has been extensively tested when used in the optimum configuration but no previous work could be found investigating the negatively influencing factors that are so common in everyday use. Computer simulations and impact testing have been completed to demonstrate the variation of effect when using a tie-down system to secure the chair (Bertocci ,GE 2000) but similar investigations have not been completed with the 3 point occupant restraint. Effects of into submarining on the human body has also had research completed. Abdominal injuries due to submarining could cause serious internal injuries to organs, internal bleeding and even death (Leung Y 1982). The missing area of research that this investigation will start to address is within the area of occupant restraint incompatibility. While the restraint is being used correctly, the wheelchair interferes with its use.

## 3.5 Action plan

Two seats will now be produced. One will be reflective of the seat design currently adopted within the images in Appendix B. The second seat will be of an improved design which will be determined in the next section. Both seats will then be crash tested and the data compared with particular focus on ATD (Anthropomorphic Test Device) excursion.

## 4.0 Design development

The simplest resolution to the problem would be to develop a solution that can be achieved without adding anything to the custom seating while maintaining the current designs of occupant restraint. The most obvious solution would be to remove material from the seats until the occupant restraint makes a good contact with the user. During the initial client assessment at which point a custom seat is prescribed, it should be determined if the seat would ever be used on transport. If the chair is to be used on transport, during the casting, the design of the chair can be modified by allowing for one of the solutions offered within this project. Table 4.1 below demonstrates the advantages and disadvantages of this solution.

Table 4.1 – Solution 1 advantages and disadvantages

| Solution 1 – Careful removal of material from custom seat in pelvic area | |
|---|---|
| Advantages | Disadvantages |
| • No additional material/bracket/device needs to be added to the seats. This will make it easy to implement.<br>• Current designs of occupant restraint can continue to be used<br>• Can have good user-occupant restraint contact if seat designed correctly<br>• Could include inertia reel so user is comfortable in transit. | • Removal of material **may** weaken seat – re-enforcement of area may be required<br>• User-occupant restraint contact will depend on design of chair and thus the skill of the caster/manufacturer. |

Another solution would be to develop an integrated pelvic belt that acted as a restraint. The belt would be attached to the chair permanently and used instead of a vehicle anchored occupant restraint. This would make the chair easier to prepare for transportation. There is a large range of pelvic supports all designed for a range of different needs. For the postural support to be replaced by an occupant restraint, the same range of design needs to be supplied. The occupant restraint could be added as well as the postural support but this would raise the cost of the seat. Since postural items are fitted for different reasons in different places to achieve certain results, a postural belt and occupant restraint may be required in some cases. Both belts might need to be fitted on the chair in the roughly the same location. A special bracket would need to be designed and tested to allow the installation of both belts. The belt would also have to be designed and tested. The disadvantages and advantages can be found in Table 4.2 below.

Table 4.2 – Solution 2 advantages and disadvantages

| Solution 2 – Wheelchair integrated pelvic restraint | |
|---|---|
| Advantages | Disadvantages |
| • Good user to occupant restraint contact<br><br>• Would not weaken seat | • Would need two belts, one for support and one for restraint. Range of pelvic support design is extensive and the range restraint belts would have to be as large to allow just one belt to be fitted<br><br>• The two belts would be located over pelvis in similar or same area. They may interfere with each other and cause high loading on user in the event of an accident.<br><br>• Pelvic belt may get confused with restraint belt<br><br>• Both belts would have to be anchored on the chair in a similar place. New bracket design needed to accommodate all designs of pelvic belts and restraint belt in same location<br><br>• No inertia reel so user has limited movement in transit. |

The third solution would be to cut/create slots in the seat either side of the pelvis and thread the occupant restraint through the slots. The occupant restraint would be anchored into the vehicle floors tracking. The slots will have to be big enough to allow the webbing buckle to be threaded through. This could be difficult and the wheelchair will get in the way. If the client is in a power chair this may make it even harder as the motors, electronics and batteries are stored under the chair making access difficult. Advantages and disadvantages can be found in Table 4.3 below.

| Solution 3 – Different type of occupant restraint which is feed through holes in the custom seat one either side of the pelvis and is anchored to the vehicle floor | |
|---|---|
| Advantages | Disadvantages |
| • Good user-occupant restraint contact<br>• Inertia reel included so user is comfortable in transit<br>• Will not weaken seat as much as solution 1 | • New design of occupant restraint required<br>• Each time it is used on transport, it would be difficult to fit and time consuming. Transport companies might not use the slots and revert back to passing the occupant restraint over the sides of the chair. |

Table 4.3 – Solution 3 advantages and disadvantages

## 4.1 Solution selection

To help select the most appropriate solution a weighted Evaluation Matrix was used. The solution with the highest rank will be progressed to manufacture and testing. Solutions 1 to 3 have been explained and have been identified in Tables 4.1 to 4.3 respectively in section 4.0. They have been weighted against the following six questions:

- Will the seat loose strength? In the event of a collision the seat will need to be as strong and rigid as possible. The removal of material may weaken the seat. The more removal of material a solution has the lower it will be rated.

- Will new design of restraint be required? This is undesirable as the user will have to buy a new restraint. If a new restraint is required the solution will rank low.

- Will the restraint have an inertia reel for user comfort? An inertia reel allows for slack in the restraint adding comfort for long journeys. No inertia reel will lower the ranking.

- Ease of restraint use? The restraint must be quick and easy to use otherwise carers and users will not use them to save time. The easier the restraint is to use the higher it will rank.

- Will the chair need a new device to fit the restraint/postural belt? Thousands of seats are already being used on a daily basis. The simpler it is to improve these seats the more likely occupant restraint will be correctly applied. Also if no additional equipment is needed to improve the seats the more likely wheelchair services will implement the changes. If no new device is required the solution will rank high.

- Good user-occupant restraint contact for each seat made? The user–occupant restraint contact must be good for each chair. The more certain that each seat will have a good contact the higher the ranking.

| Evaluation Questions | Solutions (see tables 1 -3) | | |
|---|---|---|---|
| | Solution 1 | Solution 2 | Solution 3 |
| a. Will the seat loose strength (3 being most strength lost – 1 being the least) | 3 | 1 | 2 |
| b. Will new design of restraint be required? (1 for yes, 2 possible, 3 no) | 3 | 1 | 3 |
| c. Will the restraint have an inertia reel for user comfort? (1 for unlikely, 2 for possible, 3 for yes) | 3 | 1 | 2 |
| d. Ease of restraint use? (1 Hard, 2 fiddly, 3 easy) | 2 | 2 | 1 |
| e. Will the chair need a new device to fit the restraint/postural belt (1 Yes, 2 possible, 3 No) | 2 | 1 | 2 |
| f. Good user-occupant restraint contact for each seat made? (1 no, 2 possible, 3 yes ) | 2 | 3 | 2 |
| Total | 15 | 9 | 12 |

Table 4. Solution Evaluation Matrix. Each solution has been ranked 1-3 compared with each other based on the question asked. The solution with the highest ranking will be the solution that is progressed manufacture and testing.

The selection matrix was completed by three Rehabilitation engineers form Kings College Hospital. Each weighting was agreed upon after discussion. Solution 1 – The careful removal of material shall be selected for manufacture and testing. If the removal of material is kept to a minimum then the chair should not be weakened too much.

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# 5.0 Manufacturing the crash test seats

## 5.1 Seat design

Two seats will be produced for testing. One will act as a benchmark. The other will be the improved design. The seats will be constructed of Matrix. The custom seat will be made to fit a Hybrid III dummy as the standard ISO 16840-4 dictates. The standard has detailed information for the test procedure of crash testing a wheelchair and will be used for this projects' crash test.

Within the standard ISO7176-19:2001 Annex D shows a numerical system for the scoring and rating accommodation of vehicle-anchored belt restraints, see Appendix C of this report. Based on the research and images collected which can be found in Appendix B, the pelvic belt restraint is commonly obstructed by the seat design. The design of the "improved seat" will be focusing on improving the contact of the user with the pelvic restraint. The pelvic region has proven to be an issue with restraint positioning in custom seating so the shoulder restraint will remain at a constant rating for each of the test seats.

Both seats shall be designed so that the shoulder restraint will achieve "excellent contact" and "excellent location" when rating using tables D.3 and D.5 from ISO717619:2001 Annex D. The location of the pelvic belt will be scored following manufacture of the seats, aiming to achieve "excellent" with the improved design.

Most wheelchairs have a pelvic or safety belts already fitted. As a standard procedure the wheelchair services provide a 2 point pelvic belt with every custom seat. There are very few seats issued without a pelvic belt so one will be installed for the crash test. Where as the restraint is designed to prevent the user from being ejected from the chair or making contact with the vehicles interior in the event of an accident, the 2 point pelvic belt is present for postural or safety requirements. Postural supports can come in a verity of harnesses and belts and are only designed to help the user maintain a good posture when using the chair in the normal manor.

A pelvic belt is included with each seat but depending on the requirements of the user a harness or foot restraint may not be provided. For this reason only a postural pelvic belt will be used during the crash test. Regularly, seats are issued with no other postural support other than a pelvic belt.

## 5.2 Seat manufacture

The Matrix used for the crash test seats was developed by South West Seating (SWS). I made both seats under the direct supervision of a qualified engineer who has had the manufacturers training directly from SWS and reviewed all work undertaken in the construction of the seats.

SWS matrix consists of interlocking modules which are used to create a cold formed plastic shape. The modules are made from plastic, aircraft aluminium and stainless steel (South West Seating n.d.). The modules are connected together using plastic links see Figure 5.1 and 5.2 below.

Figure 5.1 SWS Matrix components

Figure 5.2 Small SWS Matrix sheet

(South West Seating n.d.)

A hybrid III dummy was once cast by King College Hospital. They had a plaster cast copy of the impression that the dummy made during the casting process. This plaster cast was used to create both seats, see Figure 5.3 below.

Figure 5.3. To the left Hybrid dummy cast. Middle and to the right Matrix sheet laid over Hybrid III dummy casting for construction of benchmark seat.

The Matrix is delivered in a flat sheet which is laid over the outside of a cast, see Figure 5.3. Modules and links are loosened and removed until the Matrix conforms to the cast shape. An aluminum frame is then cut and bent around the Matrix for enforcement (see Figure 5.4).

Figure 5.4 Matrix and frame for benchmark seat

The two vertical framework sections are constructed from two tubes, one inside the other, diameters of 5/8" and ¾" (18 gauge). All the tubing underneath which makes up the base is also double tubing. This is to reinforce the components that will experience the highest loading during vehicle impact. A wheelchair interface system is fitted to the base and frame is secured on to the frame by inserting screws through the holes in the interlocking components, through the metal tubing and into the black plastic cross junctions.

The seats where reinforced with extra modules around the edges and where the occupant restraint will touch the seating.

Figure 5.5. Both crash test seats with covers, pelvic belts and head support fitted.

Figure 5.6. To the left, benchmark seat side view.  To the right, crash test seat with improved access to occupant restraint design.

Figures 5.5 and 5.6 show the crash test seats with completed frame work, red security straps, Body point 2 point pelvic belts with plastic buckles and Otto Bock head supports.

## 6.0 Testing

The seats for testing where set up on the surrogate wheelchair base.   The surrogate base was fixed down on the test sled using Uwin's safety systems Quattro (a four point Karabiner wheelchair restraint and 3 point occupant restraint with inertia reel) the occupant restraint was fitted in it's most effective configuration as per ISO 16840-4 guidelines.  The staff at Millbrook's conducted the crash test for safety reasons.

The was conducted in accordance with ISO 16840-4 Annex A Test method for frontal impact.

## 6.1 Equipment

- One benchmark Matrix seat with raised sides around pelvis with postural pelvic belt and Otto Bock head rest
- One improved design Matrix seat with cut away sides around pelvis with postural pelvic belt and Otto Bock head rest
- Surrogate chair meeting ISO 16840-4 Annex B Surrogate wheelchair specifications
- Crash test sled which create the deceleration pulse as defined in 16840-4 Annex A, see Figure 6.1 of this report.
- Digital camera
- Four point tie down system supplied by Unwin safety systems
- Three point occupant restraint supplied by Unwin safety systems
- Side view high speed camera minimum of 500 frame rates per second
- 1 ATD 5$^{th}$ percentile, with static resistance of 1g at each joint and close fitting clothing.

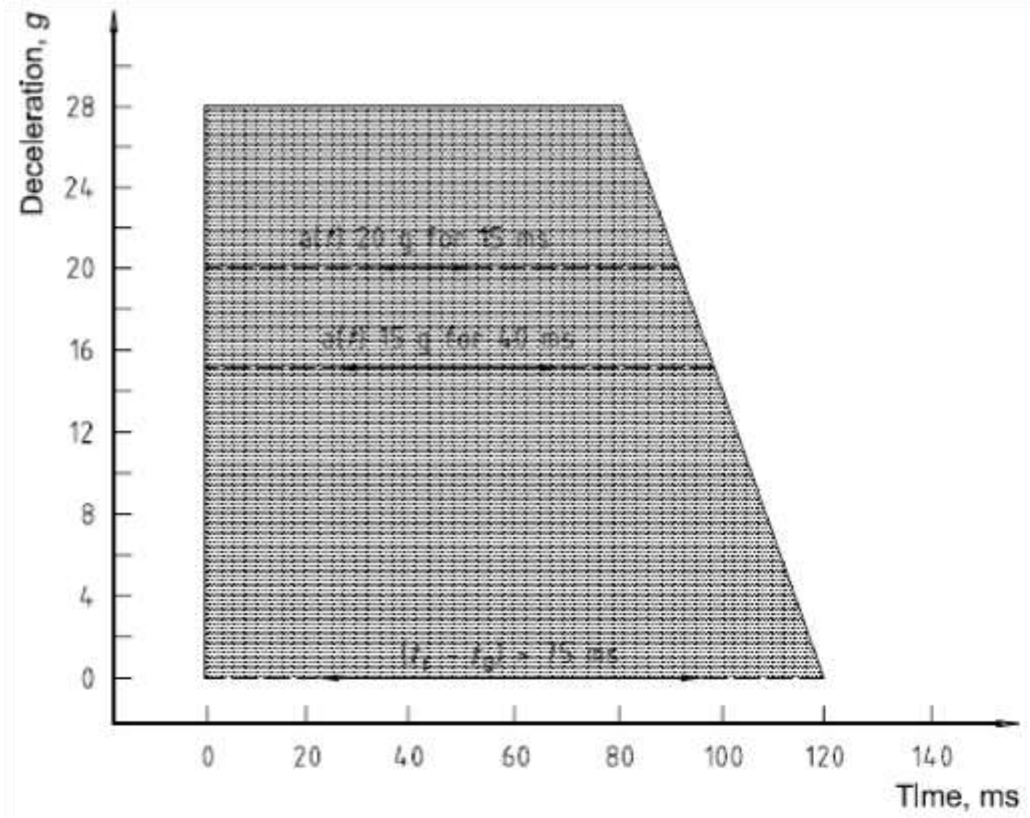



Figure 6.1. Deceleration Vs. time graph showing region that crash test deceleration pulse as found in ISO 16840-4.  Pulse shall remain in shaded region exceeding the values for a 20g pulse depicted by a broken line.

## 6.2 Crash test procedure

1. Seat interfaced on surrogate wheelchair base
2. ATD positioned on seat and pelvic belt adjusted for close fit
3. ATD, seat and surrogate wheelchair base hoisted onto impact simulator sled
4. WTORS fitted in most effective configuration as per ISO 16840-4 and manufactures guidelines.
5. Measure and record the angle of the WTORS
6. Grade the occupant restraint system using ISO 7176 Annex D as featured in Appendix C of this report.

7. Take pre test images of the test set-up after assigning individual test number (see Appendix D of this report).

8. Fire impact simulator to match deceleration pulse as featured in Figure 6.1. and run high speed film

9. Take post test images of ATD and chair with particular focus on damaged areas of seating and ATD final position.

10. Repeat test for second seat.

## 7.0 Results

The benchmark seat with limited consideration for occupant restraint was tested first and given the unique test number of S11012. The improved seat was tested second and given the unique test number of S11013. The seats will be referred in this report by these numbers from this point.

Figure 7.1. Seat S11012

Figure 7.2 Seat S11013

Both seats where scored in using the tables featured in Appendix C – ISO 7176-19 Annex D scoring tables. The results can be seen below in Tables 7.1 and 7.2. The Tables show that the S11012 test seat has an overall scoring of Poor. According to the ISO 7176-19 Annex D, one score of 0 gives an automatic Poor score. The S11013 test gives an overall rating of 12 which equates to an “Excellent” rating.

The ratings/scores where assigned to each chair based on 4 engineers consensus using the descriptions in ISO 7176-19 Annex D scoring tables.

Table 7.1. The scoring of the occupant restraint in test S11012 using ISO 7176-19 Annex D scoring tables.

| Occupant restraint characteristics | Rating | Description | Score |
|---|---|---|---|
| Overall ease of belt positioning | Excellent | Optimal placement of both pelvic and shoulder belts on the ATD can be easily achieved without inserting webbing and hardware through openings or between components | 2 |
| Pelvic belt contact area | Poor | Belt webbing is held completely away from ATD pelvis because of wheelchair components | 0 |
| Shoulder belt contact area | Good | Belt webbing makes some contact with the front of the ATD chest | 1 |
| Pelvic belt contact location | Poor | Belt contacts the ATD above the pelvis and on the abdomen | 0 |
| Shoulder belt contact location | Good | Belt webbing contacts the ATD's neck | 1 |
| Pelvic belt angle | Good | Projected side view angle is between 30 and 45 degrees to the horizontal | 1 |
| Pelvic belt clear paths to anchor points | Poor | Belt webbing makes contact with wheelchair components resulting in a change in belt angle greater than 30 degrees | 0 |
| Belt proximity to sharp edges | Good | Belt webbing does not contact but comes within 25mm of sharp edges of the wheelchair | 1 |

Table 7.2. The scoring of the occupant restraint in test S11013 using ISO 7176-19 Annex D scoring tables.

| Occupant restraint characteristics | Rating | Description | Score |
|---|---|---|---|
| Overall ease of belt positioning | Excellent | Optimal placement of both pelvic and shoulder belts on the ATD can be easily achieved without inserting webbing and hardware through openings or between components | 2 |

| | | | |
|---|---|---|---|
| Pelvic belt contact area | Excellent | Belt webbing makes good contact across the full breath of the ATD | 2 |
| Shoulder belt contact area | Excellent | Belt makes good contact with both chest and shoulder of the ATD | 2 |
| Pelvic belt contact location | Excellent | Belt contacts the ATD low on the pelvis near or at the thigh-abdominal junction | 2 |
| Shoulder belt contact location | Good | Belt webbing contacts the ATD's neck | 1 |
| Pelvic belt angle | Good | Projected side view angle is between 30 and 45 degrees to the horizontal | 1 |
| Pelvic belt clear paths to anchor points | Good | Belt webbing makes contact with wheelchair components resulting in a change in belt angle less than 30 degrees | 1 |
| Belt proximity to sharp edges | Good | Belt webbing does not contact but comes within 25mm of sharp edges of the wheelchair | 1 |

Test seat S11013 had a higher scoring than test seat S11012 on the pelvic belt contact area and pelvic belt contact location. This subsequently affected the shoulder belt contact area. Due to the improved pelvic contact location on seat S11013 the “pelvic belt clear paths to anchor points” score was also improved.

The angles of the WTORS where measured with respect to the horizontal. The values can be found in Table 7.3.

Table 7.3 shows the angles that the WTORS was set to for both tests in degrees

| Test sample | Rear wheelchair tiedown angle to the horizontal | Front wheelchair tiedown angle to the horizontal | Occupant restraint angle from receiver buckle to floor securement point |
|---|---|---|---|
| S11012 | 44 | 42.5 | 46 |
| S11013 | 48 | 42.5 | 54.7 |

After the crash test, images where taken of the seats to demonstrate the effects of the tests. Seat S11012 suffered frame failure at the front of the seat which can be seen in Figure 7.3. The images show bending and shearing in the reinforced, double tubing. The broken tubing was in the region where a screw had been inserted to fix it in place. The black plastic cross joints also have failed around the points where screws where inserted to fix them in place.

Figure 7.3. Test seat S11012 frame failure images

Figure 7.4 shows the test seat S11013 after the crash test. The seat did not fail in the same manor as seat S11012. There was a small amount of bending in the front of the frame which can be seen in Figure 7.4 in the region on the black plastic cross junction. This tube was also reinforced with double tubing.

Figure 7.4 Seat S11013 tube bending after test

Figures 7.5 and 7.6 show the horizontal and vertical displacements of the ATD head in both tests. The high speed film was used to measure the movement which has then been plotted on graphs and included in these figures. The head in test S11013 shows a much larger displacement horizontally and vertically than in test S11012.

Figures 7.7 and 7.8 show the horizontal and vertical displacement of the P-Point in both tests. The P-Point refers to the wheelchairs movement and shows that in both tests the movement was similar in direction and magnitude. Data was created using the same method as the head trajectory.

Figures 7.9 and 7.10 show the knee trajectory of the ATD in both tests. They show that in test S11012 the knees moved forwards more than in test S11013.

Table 7.4 has been included below to compare the maximum and minimum movements of the head, P-pint and knees measures during both tests. The higher values for range of horizontal displacement have been highlighted. The numerical data shows that the head did move further in test S11013 but the knees moved by approximately 30% less than the ATD in test S11012.

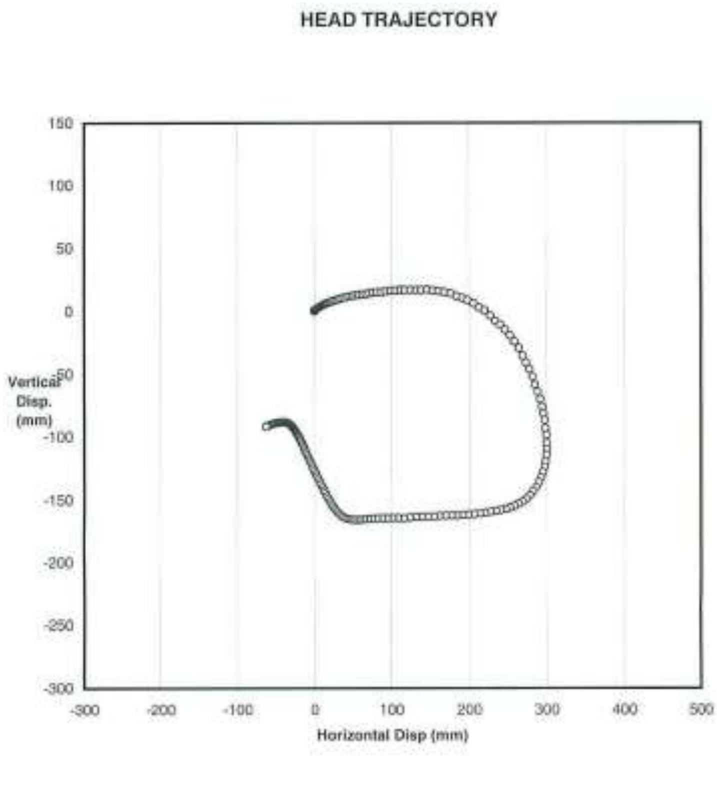



Figure 7.5. S11012 head trajectory

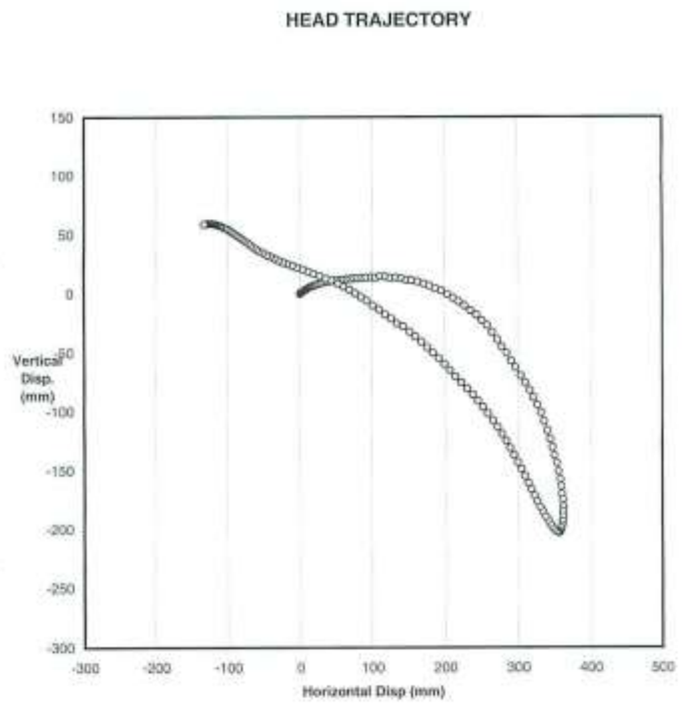



Figure 7.6 S11013 Head trajectory

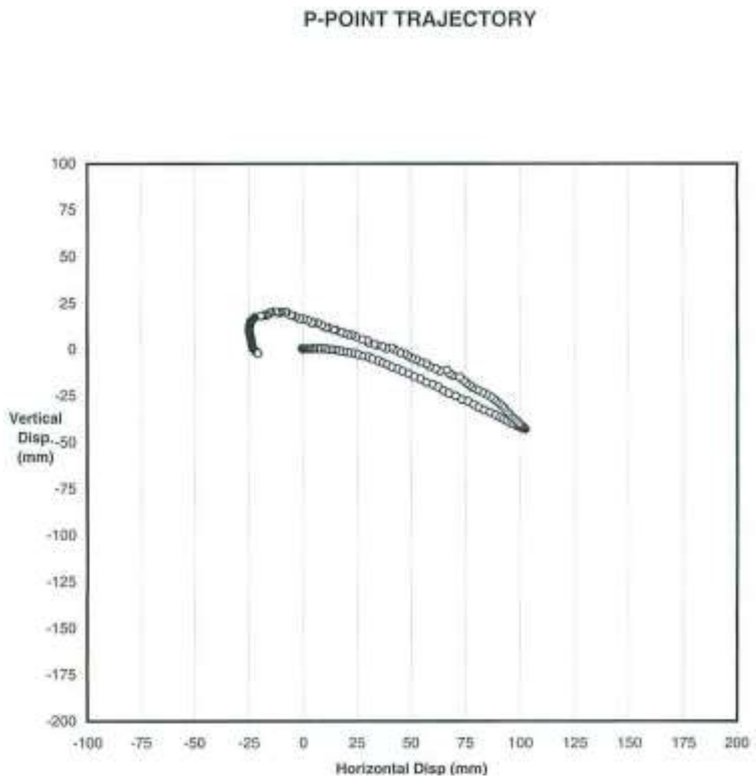



Figure 7.7. S11012 P-Point trajectory

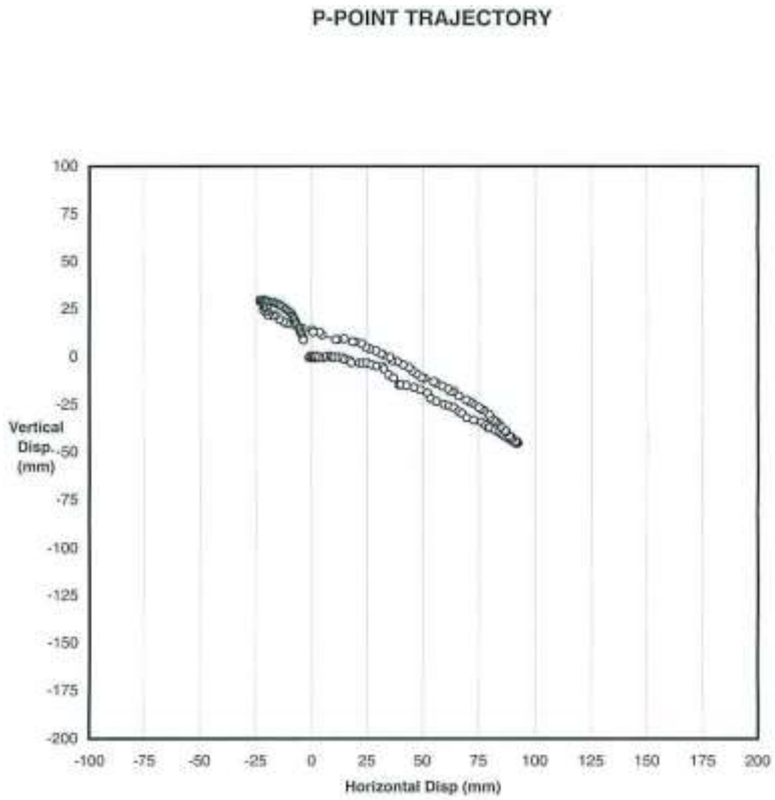
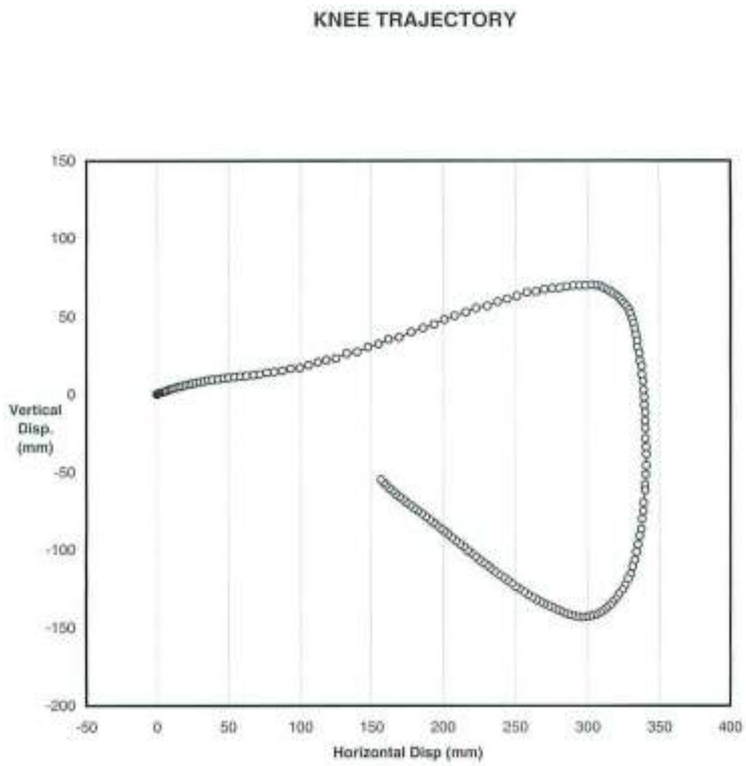



Figure 7.8. S11013 P-Point trajectory




7.9. S11012 Knee trajectory

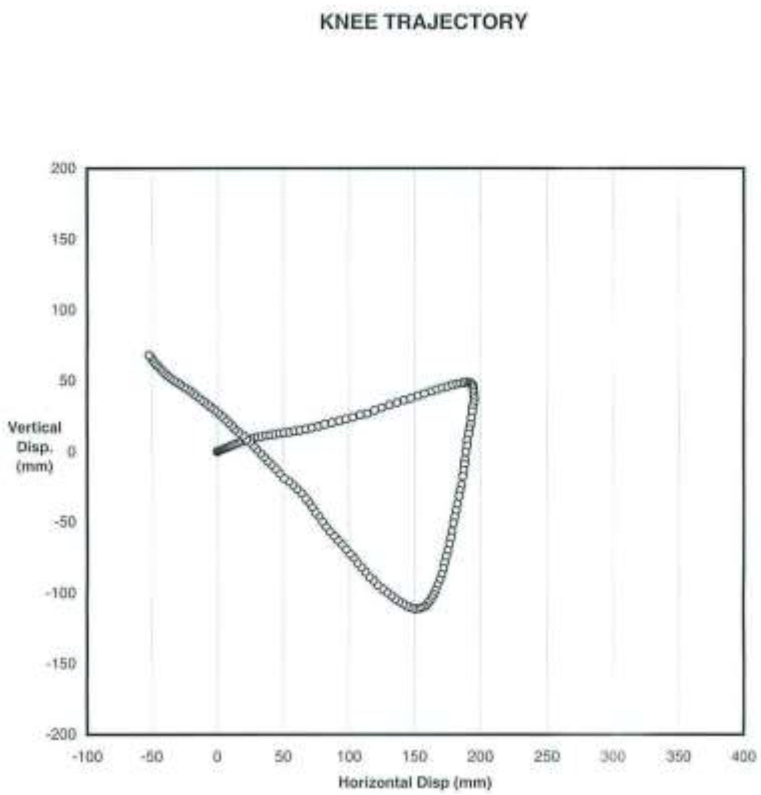



Figure 7.10. S11013 Knee trajectory

Table 7.4. Comparative table of max and min trajectory data collected in crash tests S11012 and S11013

| | Value in mm | Test | |
|---|---|---|---|
| | | S11012 | S11013 |
| Head trajectory | Max horizontal | 300 | 363 |
| | Min horizontal | 49 | -120 |
| | Range horizontal | 349 | 483 |
| | Max vertical | 17 | 59 |
| | Min vertical | -166 | -203 |
| | Range vertical | 183 | 262 |
| P-Point trajectory | Max horizontal | 102 | 93 |
| | Min horizontal | -25 | -23 |
| | Range horizontal | 127 | 116 |
| | Max vertical | 20 | 30 |
| | Min vertical | -43 | -46 |

| | | | |
|---|---|---|---|
| | Range vertical | 63 | 76 |
| Knee trajectory | Max horizontal | 341 | 195 |
| | Min horizontal | 0 | -41 |
| | Range horizontal | 341 | 236 |
| | Max vertical | 70 | 56 |
| | Min vertical | -143 | -111 |
| | Range vertical | 213 | 167 |

Figures 7.11 shows both seats post test with particular focus to the shoulder region. In both cases there was deformation of the Matrix sheet from the force of the occupant restraint. The deformation was more severe in test S11012.

Figure 7.11. To the left seat S11012 and to the right seat S11013.

The Matrix sheet suffered the same type of deformation around the pelvic region. The seat S11012 was folded inwards towards the user from the loading created by the occupant restraint during the test. There was more deformation on the S11012 seat than the S11013.


Figure 7.12 S11012 Seat on crash test rig post test


Figure 7.13 S11013 Seat on crash test rig post crash test.

Figures 7.12 and 7.13 show the ATD after the crash test. In the S11012 test the pelvic belt has been lodged in the ATD abdomen as seen in Figure 7.12. The images also show that the diagonal part of the occupant restraint has moved over the throat producing a suffocation risk. Figure 7.13 shows the ATD in test S11013 where the pelvic belt and diagonal occupant restraint has remained in place. The ATD in test S11012 would have suffered internal damage from the pelvic belt and occupant

restraint.

In both cases the pelvic belt had pulled through the mounting points attached to the frame of the seating making them looser than when fitted at the start of the test.

The raw data, test rig images, video footage and full Millbrook's crash test report can be found in Appendix D – Crash test report.

## 8.0 Discussion

As the research suggested, by anchoring the pelvis securely as achieved with test S11013 the excision data for horizontal and vertical movement of the head was more than test S11012 (Visvikis 2008). The range of movement for test S11013 can be seen in Table 7.4, graphical representation and full list of data points can be found in Appendix D – Crash test report.

As it can be seen from Table 7.4, the range of horizontal head movement for test S11013 was 134mm more than the S11012 test. This would increase the risk of user impact with the vehicle interior. The trunk support location was rated “good” see Table 7.2. If this was better in both cases this head movement can have been reduced. As suggested in the research the pelvic support is important and with improved pelvic restraint torso restraint needs to be improved as well.

The horizontal movement of the knees was approximately 30% greater in test S11012 than S11013. Both tests passed the criteria set within ISO 16840-4, see Appendix D- Crash test report for excursion. Both seats failed in the overall testing due to the failure in frame S11012 and deformation in frame S11013. Given that the sufficient space, as specified in ISO 10542-1:2001 has been allocated around the wheelchair, the horizontal head movement data indicates that the head should not impact on the vehicle interior.

The video footage of test S11012 shows submarining under the pelvic belt. The belt was lodged in the ATD abdomen post test. The pelvic belt on the S11013 test remained in place. As suggested by the research the reduced contact of the occupant restraint increases the risk of submarining and abdominal injury. Abdominal injury could cause serious internal injuries to organs and internal bleeding which can lead to death (Leung Y 1982). The S11013 test shows that the measures taken during this project are vital to reducing abdominal injury.

The ATD excursion for both tests was within the pass criteria of ISO 16840-4 but

S11012 submarined under the pelvic belt increasing the risk of serious or fatal injury. This indicates that the standard needs to be improved. The tests show that the pass criteria for ISO 16840-4 is too high and that just concentrating on the excursion data can place users in serious harm.

The movement forwards as seen in the S11012 video footage (Appendix D of this report), in Figure 7.9 and Table 7.2 could be the reason for the S11012 seat frame failure. The pelvic restraint was unsuccessful in keeping the ATD back in the seat. The ATD centre of gravity had moved forwards and during the forwards rotation phase (Adams TC 1992) additional loading on the front of the seat could have caused the failure presented in Figure 7.3. The pelvis of dummy did not move forwards in as much in test seat S11013 and there was less damage to the seat. This indicates that occupant restraint is not only important for user restraint to prevent injury from seat ejection and submarining but also for wheelchair integrity. If the seat completely failed and came off the wheelchair base, injuries incurred could be fatal.

The seats were cast using an ATD of “normal” anatomy. As a result of this the seats were relatively orthogonal and did not include any anti-submarine features. The current practice is to slightly tilt back to create a ramp at the front of the seat. This slight amount of ramp may have improved the results. The test results also show that neglecting to do this could increase the chance of injury to the user.

## 8.1 Conclusion

The objectives of this project as highlighted in Section 2.2, have been listed below;

The hypothesis was to show that neglecting to consider occupant restraint in custom seating will have a detrimental effect of the user safety in the event of an accident. In showing this 3 objectives where suggested.

1. To produce a seat which replicates the general design of custom seating within the NHS and crash test it using ISO 16840-4.

2. To produce a seat which improves the design of custom seating with respect to the occupant restraint path and crash test it using ISO 16840-4.
3. To compare the crash test data to determine if the new design is an acceptable suggestion to improve occupant safety in transport.

Referring back to the projects objectives, objectives 1-3 have been achieved. Two seats where produced and tested. The data collected shows that the improved design reducing the risk of submarining while the excursion of the head increases but not so much that impact of the vehicle interior is possible thus proving my hypothesis.

The seats did not have optimum restraint for the torso which has affected the results. This project shows that optimum restraint is required to give the user the best chance of escaping injury in the event of an accident. Ideal occupant restraint as per ISO 7176-19 is required to prevent user injury from ejection, strangulation and submarining but also to prevent the failure of the wheelchair.

The benchmark seat did not perform as well as the improved design seat. The improved design prevented abdominal injury, potential strangulation and seat failure but the head trajectory would suggest that some injury in the form of whiplash. This highlights the importance of achieving an “Excellent” rating for the shoulder aspect of the occupant restraint.

Due to the data collected during testing, condition of the seats and ATD post test it is safe to conclude that the improved design of removing material around the pelvic region is an appropriate solution to the problem. The new design did improve the occupant restraint and from the findings of this project would be a suitable solution to be put into place across the NHS for custom seat design. A further improvement would be to reduce the back rest height.

The conclusions from this project are more applicable to users of “normal” anatomy. The users of custom seats often have abnormal anatomy so it could be argued that the results have limited relevance. This project does show that the pelvic belt needs to have good contact and the torso needs to have good contact as per ISO 7176-19 Annex D. The research shows that the back of the chair needs to be in an upright position. If these aspects can be improved it can be assumed that the possibility of injury can only be reduced in the event of an accident. While attempts can be made to improve the seating to accommodate occupant restraint, this is more challenging when presented with a user with significant levels of postural deformity rather than the orthogonal ATD this project was based around.

The postural belt was pulled through the mounting clamps on the seating system. The belts where looser after the test showing evidence that they are not satisfactory occupant restraint and should not be solely relied on during transportation.

## 8.2 Recommendations

The recommendations that follow are guidelines that should be attempted when producing a custom seat which have been developed from the conclusions of this investigation. By keeping these suggestions in mind, a seat safer for transport can be manufactured. Achieving the best possible seat to allow for occupant restraint may not always be possible for all medical conditions but the seat may be able to be improved slightly greatly reducing the possibility of injury in the event of an accident.

1. If the client requires the seat to be reclined during normal use, consider the use of a two part seating system that will allow the seat to be used with recline and then can be raised to a 90 degree angle from the seat to back during transport. This may not always be possible for all users.

2. Use ISO 7176-19 Annex D to rate the occupant restraint path of the finished seat. If there is potential to increase the score allocated then make the

modifications where possible. The higher the score, the better the occupant restraint will perform which produces a lower possibility of injury.

3. Ensure the occupant restraint over the torso is within the optimum region as suggested in ISO 7176-19 Annex D.

4. If the custom seat can not be modified to achieve an "excellent" rating using ISO 7176-19 Annex D because it would reduce the effectiveness of the medical device, inform the user of the risk during transportation as required by the Directive 2001/83/EC of the European Parliament.

## 8. 3 Further work

- Research into how abnormal anatomy or skeletal deformities affect occupant restraint in terms of excursion during dynamic testing and loading from occupant restraint

- Study into the effects of back rest height on occupant restraint. During the test conducted in this project, the back rest height was too tall. The back rest height forced the belt to rest against the neck of the ATD raising the risk of potential injury. The occupant restraint could have been improved in this area but a study could be completed to determine how much of an affect the back rest height is.

- Possible effects of Occupant restraint on custom seating when interfaced with standard wheelchair bases. The wheelchair may affect the occupant restraint. The wheelchair could deflect the WTORS reducing its effectiveness and placing additional loading in places that are not designed to withstand it resulting in product failure. The stiffness of chairs has also been proven to be a possible risk during an impact which could be investigated.

- The work in this project could be completed again with the above suggestions and with an instrumented dummy to study the loading of the occupant restraint. This would then be related back to any available medical studies completed on loading and injury in the human body. Further work would also be required since wheelchair users tend to have a lower bone density.

- The affects of other special seating on occupant restraint such as modular seats and other custom seats. The effects of removing material around the pelvis could be investigated with respect to weakening in the seats. During this study a better overview of seating across the UK could be considered rather than the limited region within this project.

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## Appendix A –Custom seats

Contoured carved foam

Client is sat on segregate chair on top of bean bag

↓

The air is removed from the bean bag until it is firm but malleable. The person making the cast moulds the bag so it matches the seats prescription.

↓

The bean bag is then set on a platform and traced with a milling machine. The machine generates an exact copy of the bag in foam.

↓

The foam is placed on the surrogate chair again and the client is sat in the foam. This is to check that the mould was correct and if there are any adjustments to be made to reduce casting errors. The provision and location of any belts or shoulder harnesses is discussed

↓

A cover is made for the foam. Rigid plastic/alluminum backing is attached to the foam. The interface brackets are attached to the backing

↓

Seat is interfaced to the wheelchair base. Back and seat will be separate units. They are adjusted with the client present until they conform correctly to the anatomy. Foam can be cut away or the alignment on the wheelchair base can be adjusted until the client is comfortable.

| Advantages | Disadvantages |
|---|---|
| • Made in two parts – two part nature allow good pelvis access for the occupant restraint system<br>• Can be made to be width adjustable<br>• Delicon has experience in manufacturing car seats for children<br>• Seat can be cut and checked with client on day of casting reducing possible errors | • Only small amount of adjustment available until recasting is required<br>• Can be hot – solid foam is not very breathable<br>• The seat and back might be incorrectly aligned making the client uncomfortable |

Moulded seat insert (MSI)

Client is sat on segregate chair on top of bean bag

↓

The air is removed from the bean bag until it is solid.  The caster help to mould that the bag so it matches the seats prescription.

↓

The bean bag can be copied in Plaster of Paris.  Plaster cast the taken back to manufacturer workshop.

↓

The cast is placed in a box and "box forming" (a plastic heat forming process) is used to create a solid plastic seat in one piece.  The inside is then padded.

↓

A cover is made for the foam and casing.  A frame is constructed from tubing so that the seat can be interfaced to the wheelchair base.

↓

Seat is interfaced to the wheelchair base.

| Advantages | Disadvantages |
|---|---|
| • Seat in one part.  As long as mould is correct seat will be properly aligned.<br>• Plastic structure firm and can hold client securely | • Only small amount of adjustment in the thin padding available until recasting is required<br>• Can be hot –  foam and plastic is not very breathable<br>• Made in one part – one part nature tends to have high sides obstructing the pelvis from the occupant restraint system. |

Matrix

Client is sat on surrogate chair on top of bean bag (client can also sit directly on Matrix and have it formed around them which will bypass next two stages)

↓

The air is removed from the bean bag until it is solid. The caster help to mould that the bag so it matches the seats prescription.

↓

The bean bag is copied in Plaster of Paris. Plaster cast the taken back to manufacturer workshop.

↓

The cast is used with a sheet of Matrix which is adjusted and fixed into the shape of the plaster cast. The Matrix is then covered in foam.

↓

A cover is made for the foam and sheet. A frame is constructed from tubing so that the seat can be interfaced to the wheelchair base.

↓

Seat is interfaced to the wheelchair base.

| Advantages | Disadvantages |
|---|---|
| • Can be made in one or two parts – two part nature allows good pelvis access for the occupant restraint system<br>• Plastic structure firm and can hold client securely<br>• Cast can be stored in case the seat needs to be reproduced without recasting the client.<br>• Seat can be easily adjusted and more scope for adjustment than any other custom system. | • When made in one part – one part nature tends to have high sides obstructing the pelvis from the occupant restraint system.<br>• Can be too firm |

Lynx

Client is sat on segregate chair on top of bean bag.  (client can also sit directly on Lynx and have it formed around them which will bypass next two stages)

↓

The air is removed from the bean bag until it is solid.  The caster help to mould that the bag so it matches the seats prescription.

↓

The bean bag is copied in Plaster of Paris.  Plaster cast the taken back to manufacturer workshop.

↓

The cast is used with a sheet of Lynx which is adjusted and fixed into the shape of the plaster cast.  The Lynx is then covered in foam.

↓

A cover is made for the foam and casing.  A frame is constructed from tubing so that the seat can be interfaced to the wheelchair base.

↓

Seat is interfaced to the wheelchair base.

| Advantages | Disadvantages |
| --- | --- |
| • Seat in one part.  As long as mould is correct seat will be properly aligned.<br>• Plastic structure firm and can hold client securely<br>• Seat can be easily adjusted Seat can be easily adjusted and more scope for adjustment than any other custom system. | • When made in one part – one part nature tends to have high sides obstructing the pelvis from the occupant restraint system.<br>• Can be too firm |

## Appendix B – Custom seat examples.

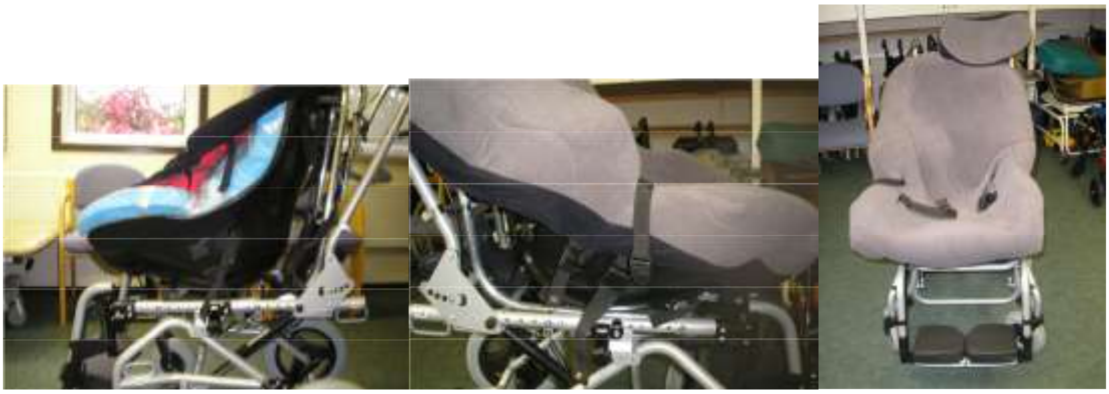
Seat 1: Matrix seat. Sides have been raised for user postural control resulting in sides too high to allow for good occupant restraint contact

Seat 2: Foam carved seat. The sides are too thick and/or high.

The similar issues arise with the following seats.

Seat 3: Moulded seat insert.

Seat 4: Carved foam

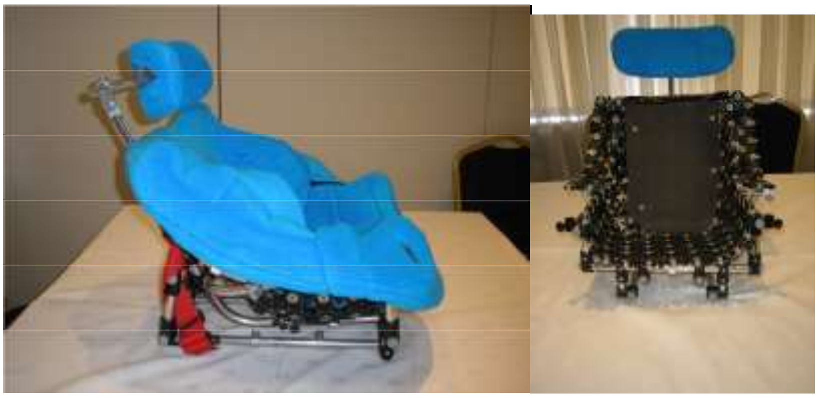


Seat 5: Moulded seat insert

Seat 6:  Matrix

Seat  7 ; Moulded seat insert

Seat 8; Moulded seat insert



Seat 9 Matrix

Seat 10: Moulded seat inert some attempt has been made to improve the occupant restraint contact but further work could have been completed

Seat 11. Carved foam

Seat 12: Matrix

Seat 13: While the sides have been reduced the plastic shell would prevent the occupant restraint from achieving a good contact.

Seat 14: Matrix

# Appendix C – ISO 7176-19 Annex D scoring tables

**Table D.1 — Overall ease of belt positioning**

| Rating | Description | Score |
|---|---|---|
| Very difficult | Lap and/or shoulder belt webbing and hardware shall be placed through narrow spaces in the wheelchair armrest or between the wheelchair armrest and wheelchair backrest | 0 |
| Difficult | Some placement through wheelchair openings is required but not through tight spaces | 2 |
| Easy | Wheelchair provides for placement of both pelvic and shoulder belts without having to place or insert webbing and hardware through wheelchair openings or around obstructions | 4 |

**Table D.2 — Pelvic belt contact**

| Rating | Description | Score |
|---|---|---|
| No contact | Belt is held away from ATD's pelvis because of wheelchair structures | 0 |
| Minimal contact | Belt barely contacts the front of the ATD's pelvis | 1 |
| Good contact | Belt contacts a good portion of the front of the pelvis but does not contact near the sides of the pelvis (i.e. at the hips) | 2 |
| Excellent contact | Belt makes good contact with the front and sides of ATD's pelvis | 3 |

**Table D.3 — Shoulder belt contact**

| Rating | Description | Score |
|---|---|---|
| No contact | Belt is held away from ATD's torso because of wheelchair structures | 0 |
| Acceptable contact | Belt makes minimal contact with the front of the ATD's chest | 1 |
| Good contact | Belt makes good contact with the ATD's chest, but does not contact the shoulder | 2 |
| Excellent contact | Belt makes good contact with both the chest and shoulder of the ATD | 3 |

**Table D.4 — Pelvic belt contact locations**

| Rating | Description | Score |
|---|---|---|
| Poor location | Belt contacts ATD above the pelvis and over abdomen | 0 |
| Acceptable location | Belt contacts ATD on the upper part of pelvis | 1 |
| Excellent location | Belt contacts ATD low on the pelvis and/or at the thigh-abdominal junction | 2 |

**Table D.5 — Shoulder belt contact locations**

| Rating | Description | Score |
|---|---|---|
| Poor location | Belt passes laterally to the ATD's shoulder | 0 |
| Acceptable location | Belt contacts ATD's neck | 1 |
| Excellent location | Belt crosses middle of ATD's shoulder | 2 |

**Table D.6 — Pelvic belt angle**

| Rating | Description | Score |
|---|---|---|
| Poor angle | Projected side-view angle is less than 30° to the horizontal | 0 |
| Good angle | Projected side-view angle is between 30° and 45° to the horizontal | 1 |
| Excellent angle | Projected side-view angle is between 45° and 75° to the horizontal | 2 |
| Use an inclinometer to estimate the side-view projected angle of the pelvic belt after installation on the ATD. | | |

**Table D.7 — Pelvic belt clear paths to anchor points**

| Rating | Description | Score |
|---|---|---|
| Poor | Belt contacts wheelchair resulting in a change in belt angle greater than 30° | 0 |
| Good | Belt contacts wheelchair resulting in a change in belt angle of less than 30° | 1 |
| Excellent | Belt path is straight to anchor point and does not contact wheelchair | 2 |

**Table D.8 — Pelvic belt contact with sharp edges**

| Rating | Description | Score |
|---|---|---|
| Poor | Belt makes contact with sharp edges on the wheelchair that could cause wear and failure of webbing material | 0 |
| Good | Belt does not make contact with sharp edges but comes with 25 mm of sharp edges | 1 |
| Excellent | Belt does not come within 25 mm of sharp edges on the wheelchair | 2 |

## D.4 Overall rating

Determine an overall rating of the wheelchair with regard to its accommodation and fit of vehicle-anchored pelvic

and shoulder belts by totalling the scores from Tables D.1 through D.8. Assign a rating based on the total score as follows:

A = excellent = score of 17 — 20

B = good = score of 13 —16

C = fair = score of 9 — 12

D = poor = score of 0 — 8

## Appendix D – Crash test reports

Please refer to attached wallet. Two CD's marked S11012 and S11013, with Millbrook's crash test report including film footage of crash tests.