The Development of a Novel Adaptive Seating System for Children with Neuromuscular Disorders

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Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed……..… Date……..

Abstract

Adaptive seating systems are reputed to provide a number of benefits to children with neuromuscular disorders. The objective of this project was to design and develop a novel adaptive seating system that was intended to provide some functional, postural and/or developmental benefits to the user.

The views of individuals who spend extended periods of time with these children who use these systems were sought regarding the current state and provision of the technology. These findings were used, along with the existing knowledge available in the literature, to develop the novel adaptive seating system and related devices. The effects of the novel system on adaptive seating users were then assessed using a repeated measures study design. The use of actigraphy, the measurement of activity using accelerometers, as an indicator of discomfort in sitting subjects was also investigated.

A number of functions of adaptive seating were rated by importance and areas where improvements could be made were identified from the views of parents and teaching staff. A novel design for an adaptive seating system was produced and a prototype fabricated. The novel backrest featured in the system was shown to perform to a level comparable with standard systems for the measures tested. In a separate study, sitting activity as measured by actigraphy, was shown to increase over time and levels of movement in different chairs corresponded to some extent with subjective discomfort ratings given by normal subjects.

There are still aspects of adaptive seating design that could benefit from further attention. The use of actigraphy may have some potential for the indication, and perhaps objective measurement, of sitting discomfort in both normal subjects and subjects with neuromuscular disorders. In a small study, the prototype system featuring a stimulus reducing backrest appeared to give comparable results in terms of short term benefits to the user, and the information gained did allow further improvements to be made to the design.

Contents

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My colleagues in the Bioengineering Unit have made the past few years an outright pleasure (however much my liver disagrees). I wish them all the very best on their future endeavours.

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Glossary of terms

ADO – Active Dynamic Orthosis

ARCOS – Association for the Rehabilitation of Communication and Oral Skills

AT – Assistive Technology

BtA – Botulinum Toxin type A

BOM – Bill of Materials

CAD – Computer Aided Design

CFS – Contoured Foam Seat

CMS – Custom Moulded Seat

CNS – Central Nervous System

CP – Cerebral Palsy

CP-50 – Category Partitioning scale

CVA – Cerebrovascular Accidents

DOH – Department of Health

DPC – Distinct Postural Change

EMG - Electromyographic

FMECA – Failure Mode, Effects and Criticality Analysis

GMFCS – Gross Motor Functional Classification System

ICF – International Classification of Functioning Disability and Health

ICM – In-Chair Movement

IQR – Interquartile Range

MRI – Magnetic Resonance Imaging

NHS – National Health Service

NRES – National Research Ethics Service

NTM – Neuromaturational Theoretical Model

PDS – Product Design Specification

PTFE – Polytetrafluoroethylene

QFD – Quality Function Deployment

RCT – Randomised Controlled Trial

SCI – Spinal Cord Injury

SD – Standard Deviation

SDR – Selective Dorsal Rhizotomy

SPCM – Seated Postural Control Measure

STMD – Systems Theory of Motor Development

TPC – Transient Postural Change

UEC – University Ethics Committee

WESTMARC – West of Scotland Mobility and Rehabilitation Centre

WHO – World Health Organisation

1 General Introduction and Objectives

Adaptive seating systems are prescribed to individuals with moderate to severe disabilities that have led to postural control problems when sitting. These devices aim to provide postural management to the user and as a result improve their quality of life and increase independence. A more complete definition of this approach is '*the customised prescription and application of seating support devices based on therapeutic principles'* (Washington et al, 2002). Seating systems are often prescribed to patients with severe neuromuscular disorders, such as those arising in subjects with cerebral palsy (CP), Duchenne muscular dystrophy or Fredreich's ataxia (Clark et al, 2007).

The project described in this thesis is based around the design of a novel adaptive seating system and arose out of a link between the Bioengineering Unit at Strathclyde University and the clinical engineering department at Addenbrooke's Hospital, Cambridge. One of the doctors at the hospital, an ophthalmologist named Paul Meyer, had designed an adaptive seating system for his daughter, Rebecca, who has CP. The clinical engineering department thought the system was worth some further investigation and, through their contacts in Glasgow, a project based around the system was set up at Strathclyde, and this thesis is the result. Although the route taken by this project altered compared to that which was initially envisaged, it should be noted that a number of aspects of the development of the system presented here were heavily informed by the adaptive seating system developed by Dr Paul Meyer (please see chapter 4 for more details).

The main objective of this project was to develop a novel design for an adaptive seating system for children with neuromuscular disorders, and this thesis presents the work carried out to achieve this. The overall hypothesis for the project was that the novel system would be comparable or better in terms of its effect on the user's posture, function and comfort when evaluated against currently used adaptive seating

systems. The null hypothesis was that the novel system would perform worse than currently available seating systems.

A number of pieces of work were carried out to achieve the project's objective and a brief description of each follows.

An investigation of parents' and teachers' views on adaptive seating provision and technology (chapter 3)

To support the development of the novel system and identify problems with currently prescribed seating, it was decided - in addition to interviewing seating clinicians and manufacturers - to investigate the views and experiences of the people who live and work every day with children who use adaptive seating, namely the parents of these children and teaching staff at special needs schools, along with making observations of the children themselves. The full methodology and results of this investigation are presented and discussed in chapter 3 of this thesis.

Design of novel adaptive seating system (chapter 4)

The development of the novel seating system itself (including the design and fabrication of the prototype used for testing purposes) and the methodologies used in its design have been described in chapter 4. From the work carried out in chapter 3, it was identified that a device that could be used in conjunction with the seating system and would assist in moving the user from a seated to standing position could be of benefit, and a design for this device is also included in this chapter. Supplementary materials including engineering drawings and documents relating to the design process have been included as appendices.

Design of active dynamic wrist orthosis (chapter 5)

Due to limitations related to time and cost that were inherent in the project, it was not possible to fully explore all of the ideas that were proposed for inclusion in the novel

adaptive seating system. One of the most promising of these ideas was the use of active dynamic control for the support elements of the seating system, a feature that would allow the forces applied by the support surfaces to be varied in response to the user's own movements. It was decided to fabricate a simple demonstration device based around a wrist orthosis and the design and testing of this is described in chapter 5.

The potential for actigraphy to be used as an indicator of sitting discomfort (chapter 6)

In reviewing the literature on adaptive seating systems and the methods used to assess them, it became clear that there was scope for additional tools to be developed to help provide more information on the effects the systems were having on their users, especially for measurements related to comfort. With this in mind it was decided to investigate whether data generated through actigraphy, which is the measurement of movement using accelerometers, could be used as a proxy for levels of sitting discomfort. A full description of the method and the testing carried out to investigate it is given on chapter 6.

Testing of novel adaptive seating system (chapter 7)

A prototype of the design developed in chapter 4 was fabricated for the purposes of evaluation. The methodologies used to test the system and the results from these experiments are described in chapter 7, along with a discussion of the results.

To assist in visualising how the different aspects of the project inform each other and relate to the overall objective of the project, please refer to Figure 1.1 on the following page.

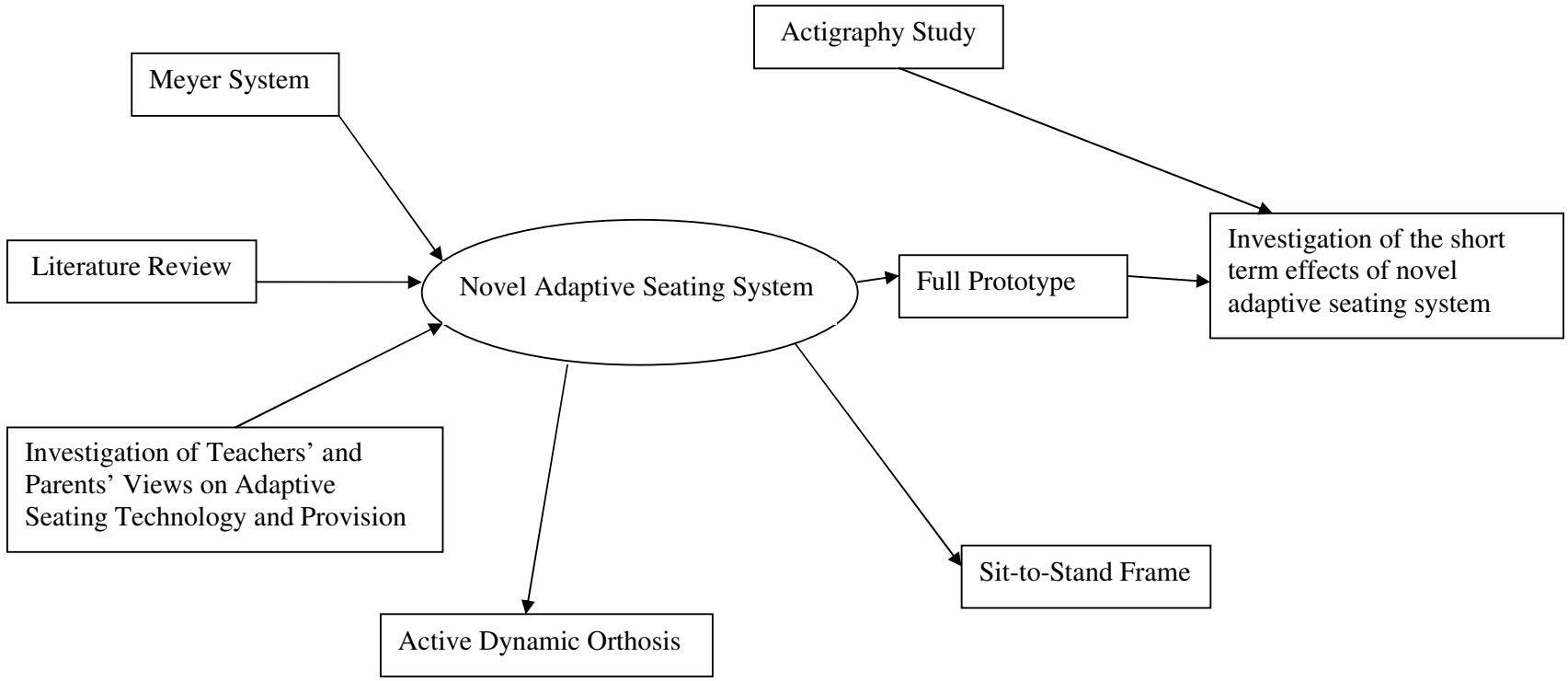


Figure 1.1 – Layout of project

2 Literature Review

2.1 Search strategy and outline of review

The initial searches for this review were carried out in September 2006 using the thesaurus terms 'adaptive seating', 'positioning', 'wheelchair' and 'cerebral palsy' in a number of internet databases including Medline, Science Direct, the Cochrane Library and Google Scholar. Catalogue searches of the University of Strathclyde and National Centre for Prosthetics and Orthotics libraries were also performed, and reference lists in articles were examined for related articles. Further searches were carried out at various points during the course of the project, including searches focused on more specific areas, for example 'upper-extremity function', 'infant development', 'pressure measurement', 'discomfort' and 'muscle tone'. This chapter is intended to provide an overview of the state of the science for the subject areas covered in this thesis.

This review first covers the origins of adaptive seating and gives some brief information about its development and the people who use these systems. Expanding on this, the framework given by the International Classification of Functioning, Disability and Health (ICF) (WHO, 2001) has been used to present an overall description of the patients adaptive seating is most commonly prescribed to and the effects that seating can have on these individuals. Furthermore, aspects relating to adaptive seating that, for the purposes of this thesis, require expansion beyond the information given in the ICF section – namely: dynamic support systems; sitting discomfort; and assessment of adaptive seating interventions - have been elaborated upon in separate sections at the end of the review.

2.2 The history of adaptive seating

Prior to the development of the adaptive seating systems as would be recognised today, people with severe disabilities would almost certainly have been confined to bed in some kind of residential care institution. Individuals were kept in what would be, by today's standards, considered unacceptable conditions (Webster, 1996). The institutions that these patients lived in were poorly maintained, under-funded and consisted of large dormitory-type environments where residents were often not even allowed to keep personal possessions. To add to this, the care that was provided by staff was little more than control (Watson & Woods, 2005). By the 1960s the way that these people were being treated became something of a national scandal in the UK and the USA.

Around the same time, what today would be considered 'standard' wheelchairs were becoming more available, but it was quickly realised that these were not suitable for the more physically impaired users. The basic design of standard wheelchairs has changed very little since their post-war conception and the sling backrest and seat that allow the chair to be folded for transport or storage purposes are simply inadequate in terms of the support provided to users with anything less than normal sitting abilities (Harms, 1990).

Perhaps surprisingly, it was mainly due to the impact of the drug thalidomide in Europe and Canada that adaptive seating has come into the form which would be recognisable today (Figure 2.1) (Watson & Woods, 2005). During the aftermath of this crisis there was a surge of enthusiasm aimed at making better provision for the children born with congenital limb deformities as society and governments realised that it was part of their duty to try to improve the quality of life for these children. In the USA, development of special seating systems was driven mainly by returning war wounded from Vietnam who had suffered spinal cord injuries. This directed research on that side of the Atlantic towards developing innovative solutions for preventing tissue trauma due to pressure. Over time, and through the joint goal of trying to de-institutionalise people with severe handicaps on both sides of the Atlantic, these different research tangents gradually grew closer and adaptive seating in its present form came into existence. Over the past 50 years considerable progress

has been made with adaptive seating and in the field of assistive technology (AT) in general (Hoenig et al, 2007).

Figure 2.1 – A modern adaptive seating system (from Wenzelite Re/hab, New York, USA)

In the Western World, members of the population who have cerebral palsy (CP) make up a significant proportion of adaptive seating users, and it is this group that has been the focus of this project. Approximately 25% of CP patients have no walking ability and will spend the majority of their waking hours in a seating system (Evans et al., 1990). In addition, a significant proportion of the remaining population who have only limited walking ability will be prescribed a seating system. There are numerous other, smaller patient groups with conditions such as Duchenne muscular dystrophy or Friedreich's ataxia that could also potentially find developments in adaptive seating technology beneficial.

2.3 The international classification of functioning, disability and health

In recent years there have been efforts made to provide a more unified approach to adaptive seating prescription and research (McDonald et al., 2004). Arguably the most important of these efforts have been focused around the International Classification of Functioning, Disability and Health (ICF) developed by the World

Health Organisation (WHO, 2001). The ICF aims to link the at times opposing medical and social models of health care delivery. Figure 2.2 shows an adapted version of the interactions between the various components of the ICF in relation to the provision of adaptive seating.

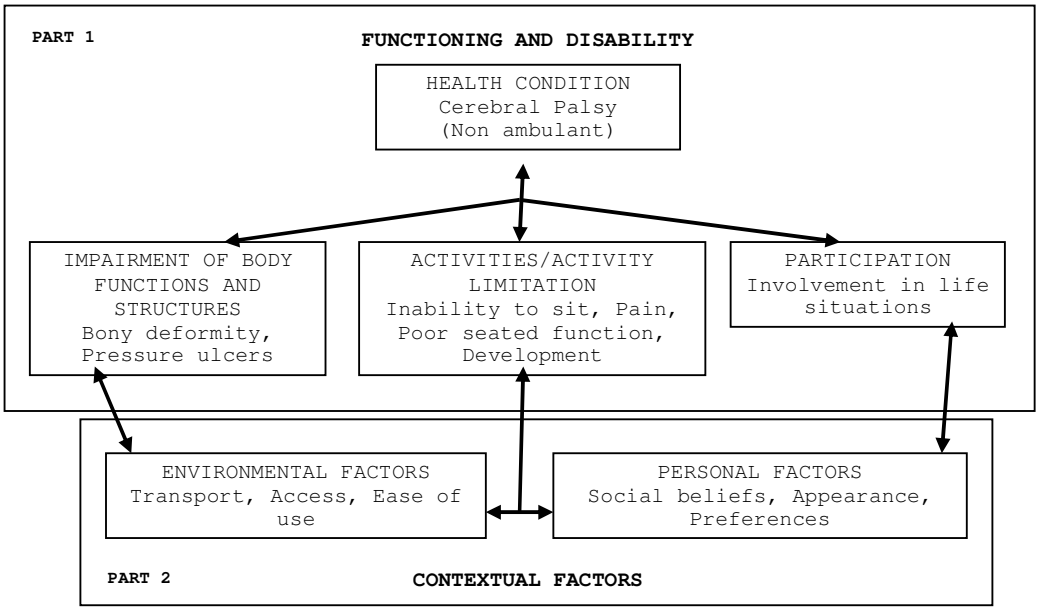


Figure 2.2 – An adapted model for viewing the interactions between different components of the ICF when applied to the provision of adaptive seating systems for children with cerebral palsy (McDonald et al., 2004).

Part one of the ICF relates to 'Functioning and disability' and contains concepts that are universally applicable across different cultures. It is divided into four sub divisions: 'Health condition' in this case is cerebral palsy; 'Impairment of body functions and structures' covers skeletal deformity and pressure ulcers; 'Activities/activity limitation' relates to sitting and functioning while sitting; and 'Participation' refers to general involvement in life situations. Part two, 'Contextual factors' are factors that should be seen more in the context of the individual's life than those in part one. It includes 'Environmental factors' which in this case relates to transport, access to building etc; and 'Personal factors' which covers appearance and preferences. In the following sections the adapted ICF will be used as a framework to describe the use, effects and provision of adaptive seating and the research associated with these factors.

2.3.1 Health condition: cerebral palsy

Cerebral palsy is the common term for a group of developmental and motor impairment syndromes that are non-progressive and have resulted from an injury to the immature central nervous system (CNS). It has an incidence of around 2.5 births per thousand and in the developed world is the principal cause of severe physical disability in children (Koman et al., 2004). Its prevalence has remained steady for the past 30 or so years as reductions in birth complications due to medical advances have been balanced out by an increasing survival rate for premature, low birth weight children (Stavness, 2006). The primary impairments which relate to the patient are motor, sensory and/or cognitive. Secondary impairments are very wide ranging but include skeletal alignment, muscle force production and aerobic capacity. Despite the injury to the CNS being non-progressive its effects on the developing child are most definitely not.

2.3.1.1 The motor development of infants

Before going further into the symptoms and treatments of CP, it is worth taking some time to discuss the way infants develop, the two main theories that have arisen to explain this, and how this relates to adaptive seating prescription for CP patients.

Often the first sign that a child has some kind of cerebral impairment is the failure to achieve certain motor milestones, e.g. by nine months of age a normally developing child should be able to sit unsupported without falling over (Sheridan, 1997). To understand fully the processes going on behind reaching these milestones the two main theories that attempt to explain how infants develop motor skills will be briefly covered. They are-

- The neuromaturational theoretical model (NTM)
- The systems theory of motor development (STMD)

2.3.1.1.1 Neuromaturational theoretical model

The NTM is a fairly well established theory of motor skill development. The crux of this theory is that changes and developments in motor skills result solely from the maturation of the central nervous system (Darrah et al., 2003). The suggestion is that the blueprints for motor skills are all embedded in the cerebral cortex, pre-programmed, and are waiting to be initiated as cues - perhaps in the form of sensory or muscle developments - occur. There are four assumptions closely associated with this theory-

- Movement moves from primitive reflex patterns to voluntary controlled movement
- Motor development progresses in a cephalocaudal direction (control is first gained at the head, then shoulders, then trunk etc.)
- Movement is first controlled proximally, then distally
- The sequence of motor development is consistent among infants, and the rate of motor development is consistent for each infant (the rate refers to the time taken to progress from one skill to another).

This theory of genetic pre-programming does seem to be supported by the fact that the vast majority of infants do tend to reach certain motor milestones around the same time and in the same order.

2.3.1.1.2 Systems theory of motor development

The STMD model is a more recent development and its roots lie in principles that have been derived from developmental psychology. In basic terms these state that when elements of a system work together, certain behaviours or properties emerge that cannot be explained or predicted from the elements separately. It is also sometimes known as dynamic systems theory. In the systems model, the sensory and motor inputs are not regarded as two separate entities but as one system that has an impact on both input and output. Coincidently, as with the NTM there are four main assumptions stated by the theory-

- Motor behaviours are a product of all contributing sub systems.
- Movements are influenced by the task.

- Systems exhibit self organising, autonomous properties (there may be additional mechanisms other than the cerebral cortex for the development for controlling motor behaviour).
- Subsystems may develop asynchronously (The factors influencing and changing a motor behaviour may not develop at the same rate. Thus any of the factors can become rate limiting preventing a specific motor goal being developed. For example, primary stepping in babies has been shown to be lost due to biomechanical factors, for example gravity limits the child's progress in learning to walk as the increase in the fat to muscle ratio in the early months of life prevents the infant from continuing stepping when held upright. This was shown in experiments that used weights to prevent primary stepping, and water submersion to reinstate it (Thelen et al., 1984).

Systems in this theory are described as complex, synthesized structures comprising the infant, the environment and the functional task. Three different levels of constraints have been identified-

1. Organismic constraints (physical and neurological characteristics).
2. Enviromental constraints (mainly gravity but also temperature, noise, lighting restrictive clothing).
3. Task constraints (established motor behaviours may be altered by specific tasks).

2.3.1.1.3 The implications of these theories for the prescription of adaptive seating

Although the two theories are not entirely incompatible, therapeutic approaches tend to be in line with the NTM. For example, therapists strive to achieve symmetrical posture in their patients to inhibit the influence of asymmetrical tonic neck reflex. Head control is facilitated before pelvic control, and proximal stability is achieved before distal mobility is anticipated (Assaiante et al., 2005). NTM however, by stating that motor development is entirely pre-determined, must therefore limit the benefits of any intervention procedures. According to this theory, changing

environmental and task constraints should have no effect on the progress of motor development, precisely what therapists are attempting to do.

By considering the use of adaptive seating through these theories it can be seen that the NTM suggests that adaptive seating may benefit the child by promoting proximal stability in order to lead to better distal functional control, normalising the resistance of muscles to stretching and decreasing the influence of primitive reflexes (Washington et al., 2002). Dynamic systems theory proposes that adaptive seating aims to influence the starting conditions of the movement and by limiting the body segments that are free to move or restricting the degrees of freedom that they have. This is achieved by constraining body segments i.e. with knee blocks and footrests, or changing the alignment of body segments relative to each other and gravity (Roxborough et al., 1994).

2.3.1.2 Symptoms

The wide range of symptoms (the most common of which are described in the following sections) that fall under the banner of CP often make strict definition of different types difficult. Clinically accepted definitions for different levels of physical involvement in CP patients include: hemiplegia (involvement of ipsilateral arm and leg); diplegia (leg involvement); quadriplegia (all four limbs involved); and also whole or total body involvement (where severe quadriplegic involvement is combined with reduced cognitive ability and pronounced learning disabilities). There are different classification systems in use in some clinics such as the gross motor functional classification system (GMFCS) which are based on overall motor function rather than affected limbs (Palisano et al., 1997). Around 70% of children with CP also have some sort of learning difficulty related to their condition (Evans et al., 1985).

2.3.1.2.1 Spasticity

Spastic hypertonus of muscles is often one of the most debilitating symptoms of CP (Flett, 2003). It is defined as ‘a velocity-dependent increase in the stretch reflex’

(Lance, 1980) or 'an increase in the stiffness of a muscle as it is stretched rapidly' (Pountney et al., 2000). It does not occur in all variations of the disease and can also be caused by other diseases or injuries that affect the nervous system such as cerebrovascular accidents (CVA). The lives of those afflicted can also be affected through joint contractures, pain and a reduction in the effectiveness of remaining viable motor units (Gormley, 2001). This leads to large reductions in quality of life for sufferers through the inability to perform tasks and often unrelenting discomfort. There is a strong link between spasticity and muscle shortening (Carr et al., 1995), although all muscle shortening is not necessarily a result of spasticity.

A general clinical rule is that children with spasticity should be treated for it by the age of five or six, before joint contractures have the opportunity to develop (Boyd & Graham, 1997). Decreasing or eliminating spasticity allows subjects to use whatever motor control they do have more effectively and lets them lead a more fulfilling life (Flett, 2003).

In its most simplified form, the series of events that lead to muscle overactivity and also muscle weakness are as follows (Gracies, 2001)-

- Damage is caused to the central motor pathways
- This disturbs the descending pathway's functions and leads to paralysis of affected muscles
- Damage is also caused to the circuitry involved with reflex responses, resulting in the permanent loss of these reflexes
- In the acute care environment, patients are placed in a lying position. Thus, some of the affected muscles are immobilized in a shortened position, often including extensors of lower limbs, and internal rotators and flexors of upper limbs. The lack of loading on these shortened muscles leads to loss of muscle mass and of sarcomeres (leading to shortening). This process is very acute, with studies showing only 24 hours of unloading caused up to a 60% reduction in muscles fibre length (McLaughlin, 1981).

- During the following weeks the damaged nervous system goes through some intensive re-organisational activity as redundant fibres degenerate and higher centres attempt to find new ways of eliciting movement.

Excessive amounts of antagonist muscle co-activation is seen in subjects with CP (Brogren et al., 1998). However, it should be noted that when considering an agonist-antagonist set of muscles in a spastic patient, both of the muscles may be relatively weak when compared to normal subjects, but when compared to each other the overactive antagonist generates torque which is not sufficient to oppose that generated by the more overactive agonist (Gracies, 2001).

2.3.1.2.2 Skeletal deformities

These imbalances of forces around a joint can lead to the development of deformities (Morrell et al., 2002). The majority of skeletal deformities are initiated during childhood, while the subject is still growing. Once adulthood and skeletal maturity is reached the risk decreases drastically as does the need for intervention (Emery & Wedge, 2003). Bone is a very adaptable tissue and abnormal stresses, like those produced by spasticity at joints, will inevitably lead to some degree of remodelling of shape and or composition (Pountney et al., 2000). Equally, the bones of children with severe CP who never gain standing ability are very different in comparison to their standing equivalent in terms of composition and bone density and this is the main reason for the high occurrence of fractures in these children (Henderson et al., 2002): nearly 20% in non-ambulatory children and young adults (Pritchett, 1990). The role of adaptive seating in attempting to treat these deformities is expanded upon in section 2.3.2.1.

2.3.1.2.3 Other common symptoms

Growth retardation is another secondary effect of CP. Children with CP, especially those with quadriplegia tend to be smaller and lighter than their healthy equivalents (Krick et al., 1996). Beyond the nutritional issues a number of possible reasons have been suggested for this retardation of growth, including medication and the reduction

in growth factors originating from bone (Stevenson et al., 1995). This is due to the regulation of these factors being partially controlled by mechanical stress on the bone, and often in CP subjects a number of bones will be non-weight bearing.

Other impairments associated with CP include speech and language disorders (Pennington et al., 2004). Children affected in this way will rarely initiate a conversation and seldom ask questions, a result of reduced development of narrative skills and functional communication (Pirila et al., 2006). Unfortunately, these communication disorders can be mislabelled as learning and intellectual problems (Al-Turaiki, 1996). In addition, breathing, swallowing (and therefore eating) problems are common (Hulme et al., 1987; Nwaobi & Smith, 1986).

2.3.1.3 Treatment and management

Today, as a result of advancements in medicine and care, individuals with CP have the potential to live fuller and more functional lives and, if there are no major secondary complications (for example, to the respiratory system), they could have a lifespan almost comparable to that of a non-affected individual (Strauss et al., 2008). However, it has been shown that there is a strong correlation between the severity of the condition and shortened lifespan (Eyman et al., 1990).

A number of different approaches are used to treat and manage the symptoms of CP. For the most part these treatments are aimed at relieving the symptoms, preventing or correcting deformities, and reducing spasticity. Treatment can be split into three reasonably well defined areas: pharmacological; orthotic/physio/occupational therapy; and surgery.

2.3.1.3.1 Pharmacological interventions

The wide range of symptoms encompassed by cerebral palsy has led to an equally broad spectrum of drugs being developed to treat them, each with different indications and contra-indications. They can be split, to an extent, into those that are administered orally, intramuscularly and intrathecally, but it is beyond the scope of

this review to go into any great depth for this particular area so only two of the most commonly used are described here: baclofen and botulinum toxin A (BtA).

Baclofen is an interesting example. It is a gamma-aminobutyric receptor agonist used to treat spasticity but its short half life means that to be effective it requires almost continuous administration. To solve this problem implantable pumps have been developed that can be programmed to deliver set doses of the drug over certain periods of time and clinical trials have shown promising results (Emery, 2003).

BtA is a neuromuscular blocking agent that is gaining popularity for the treatment of spasticity (Lukban et al., 2009). More commonly known as Botox®, it has been popularised in recent years as a form of cosmetic treatment. In the case of CP the drug is injected into muscles to balance the forces across spastic joints. Its action predictably wears off as the neuromuscular junction is reactivated, which makes this treatment much more controllable than treatment with alcohol or phenol, which have more side effects (Koman et al., 2004). However, the evidence for the overall efficacy of BtA remains somewhat inconclusive (Ade-Hall & Moore, 2000; Wasiak et al., 2004).

The use of less localised pharmaceuticals, taken orally, may induce some improvement in a patient's posture and reduce discomfort but they are unlikely to improve their functional ability (Gracies, 2001). Often this is due to the drugs' antagonist effect on the motoneural excitability of both agonist and antagonist muscle groups. It is for this reason that more focused treatments, directed at specific muscles, are favoured.

2.3.1.3.2 Therapeutic interventions

Physiotherapists and occupational therapists often work together to provide or maintain the health and skills that allow individuals with CP to participate in all aspects of their lives. These skills can be for self-care activities such as feeding, dressing and grooming, play and fine motor tasks like writing and drawing. Occupational therapy can also in some cases aim to address cognitive and perceptual

disabilities. The adaptation of equipment such as seating can also fall under the banner of occupational therapy as these devices try to promote greater functional ability and independence for the patient.

Orthotic treatments such as static and dynamic splints may be used to try and control the development of joint contractures. Static splints in particular can be poorly tolerated by some patients if used for extended periods of time and in some occasions they can lead to pressure sores (Taylor et al., 2003). They also, by nature, limit motion and can contribute to learned misuse of affected limbs. Another orthotic treatment is serial casting. It is a technique which involves making plaster or plastic casts around the affected joint to gradually train it into the correct alignment. The casts are revised every week or so for a set length of time, with each revision moving the joint slightly further towards the desired position (Rose et al. 2010).

More in depth information on the use of seating as an orthotic device is given in section 2.3.2.1.

2.3.1.3.3 Surgical interventions

The increase in the risk of complications related to surgery on patients with underlying neuromuscular disorders means that it is generally considered to be the last resort as a treatment (Sarwahi et al., 2001). When considering surgery for children it is best practice to delay the surgery until absolutely necessary. This is because the fact that they are still growing makes the long term results of the operation difficult to predict (Graham & Fixsen, 1988). Contraindications for surgery on CP patients include epilepsy, impaired general health and respiratory problems (Terjesen et al., 2000). In some instances there are clearly defined indications when surgery is required, for example, if the patient's underlying condition has led to scoliosis, then the aim of any treatment is to prevent the Cobb angle from reaching >40º by the time skeletal maturity is reached (Burgoyne & Fairbank, 2001). Several commonly used spinal surgery techniques (instrumentation and fusion) mean that after the surgery the patient loses all flexibility of the spine.

Orthopaedic surgical techniques have been the mainstay of surgical treatment for many years now (Koman et al., 2004). These include tendon transfer, tendon lengthening, arthrodesis, neurectomy and osteotomy. Although successful in many cases, to the author's knowledge there have been no randomised controlled trials that have identified which technique(s) are the most effective and there are no clear guidelines on the best technique to use in specific situations resulting in the decision generally being left to the surgeon's discretion.

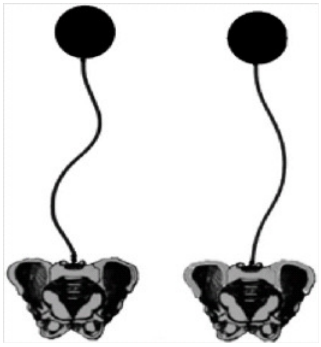
Another surgical technique worth noting is selective dorsal rhizotomy (SDR), which is used to treat spasticity. The procedure involves a laminectomy to be carried out at L2-L5 and the stimulation and transection of selective posterior rootlets or arbitrary transection of a specific proportion of rootlets. SDR is now considered the procedure of choice for the treatment of spasticity in selected patients with permanent long term improvements being shown (Steinbok, 2007), although the surgery still needs to be followed up with a programme of long term physiotherapy to improve muscle strength for best effect (Nordmark et al., 2008).

2.3.2 Assessment of body functions and structures

The procedure for fitting a patient with CP or similar neuromuscular disorder with an adaptive seating system is quite a complex task involving a number of specialists including physiotherapists, occupational therapists and bioengineers. Physical assessment of the individual provides the information that will guide the whole process (Healy et al., 1997). Loss of range of motion at joints, spasticity, hypotonia, dyskinetic movement etc are all noted, and provision has to be made for these problems. During the assessment the subject's reflex activity and reactions in different situations has to be observed, for instance is there a hypertonic response when the patient is excited? An assessment of the patient's sensory status is also necessary as this will affect the components of the system that will be prescribed. Any medication that the patient is taking that could have transitory effects on, for example, abnormal muscle tone, should be noted.

2.3.2.1 Deformities and using adaptive seating to attempt orthotic correction

Table 2.1 – The classification of scoliotic curves in cerebral palsy (Lonstein & Akbarnia, 1983)

Group 1	Group 2
Features- -Lumbar and single or double thoratic curves (resembles idiopathic scoliosis) -Minimal or no pelvic obliquity	*Features-* - Large C-shaped thoracolumbar or lumbar curves - Distinct pelvic obliquity
	

The potential for adaptive seating to be integrated with the orthotic management of certain conditions was quickly realised. Knee blocks, thoracic pads, pelvic stabilisers and neck supports are all common options that are available with most modern seating systems (Ham et al., 1998). The main conditions that seating based orthoses are used to treat are skeletal deformities such as scoliosis (see Table 2.1). Neuromuscular scoliosis occurs in 25% of all individuals with CP, and this rate rises to close to 75% in quadriplegic cases and those with severe involvement (Thomson & Banta, 2001). These are the cases that are most likely to require the use of an adaptive seating system. For individuals with Duchenne muscular dystrophy, the incidence of scoliosis rises to 90% (Kinali et al., 2006). Kyphosis and lordosis of the spine are also commonly associated with neuromuscular disorders and many patients will present with some combination of these symptoms.

Scoliosis can be split into two types, those with pelvic involvement and those without. The actual curvature of the spine is evaluated by its Cobb angle, which is

measured by identifying the two vertebrate that are maximally tilted away from each other, then drawing lines along the uppermost edge of the top vertebrate and the lower edge of the lowest vertebrate. A perpendicular line is subsequently drawn from each of these lines in such a manner that the two perpendicular ones intercept. The angle between the perpendicular lines is defined as the Cobb angle (see Figure 2.3) (Cobb JR, 1948).

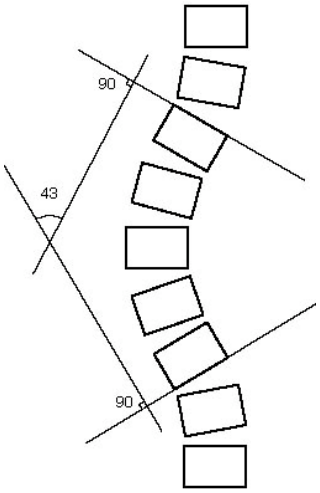


Figure 2.3 – How the Cobb angle is measured

In the short term, and while the spine is still flexible, large, but generally only temporary reductions of the Cobb angle can be produced by the application of lateral trunk supports in a three point force system: the technique normally used to treat scoliosis in adaptive seating. As a consequence of the application of these supports, it has been suggested that a more erect sitting posture can be achieved. A study by Holmes et al (2003) using skin markers to assist in measuring the Cobb angle showed a mean 35º reduction in Cobb angle across 16 cerebral palsy patients when comparing the unsupported curve of the spine to the supported one. It should be noted that this study only measured the change in Cobb angle in the frontal plane. Repeating this experiment, Mao et al (2006) used X-rays to allow a much more accurate measure of the change in the position of each vertebra (see Figure 2.4). The results showed a mean correction in the Cobb angle of 26.16º across a sample of 17 subjects. Interestingly, x-ray images were also taken in the sagittal plane, and these showed a reduction in the lumbar angle of the spine when lateral forces were applied.

It was suggested by the authors that this may be due to a reduction of the rotational deformity of the spine (scoliosis is often coupled with 3D deformities) when the corrective forces are applied.

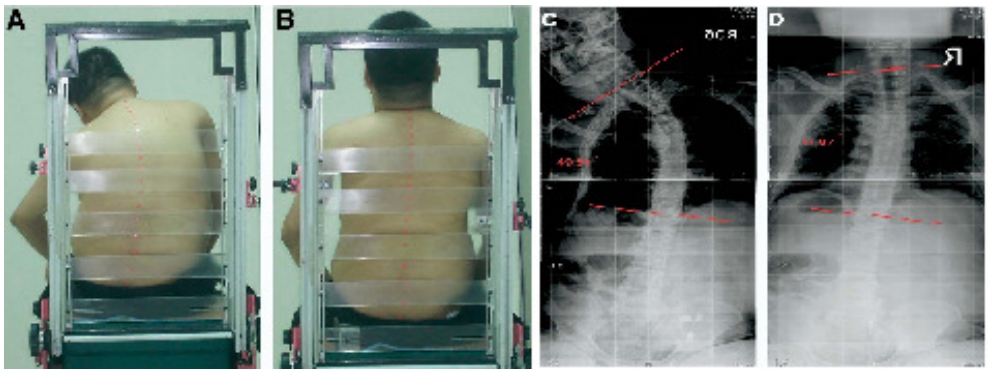


Figure 2.4 – Patient with scoliosis including x-ray of spine before and after correction using three point force system (Mao et al., 2006)

It should be stressed however that bracing of the spine, whether through seating or spinal orthotics, is generally considered a stabilizing treatment rather than a corrective one. The purpose of bracing is to attempt to allow the maximum growth and maturation of the spine before surgery is required or to prevent surgery being required (Burgoyne & Fairbank, 2001). A general rule is that curves which are kept below 30 degrees rarely progress after skeletal maturity (Weinstein, 1994), therefore orthotic interventions would be considered fully successful if they achieve this. By providing the patient with a more erect posture, things like their functional ability, breathing and eating ability can be improved.

Regarding the long term effects, to the author's knowledge no studies have been carried out that look at adaptive seating as a management technique for skeletal deformities. However, bracing by spinal orthoses, such as a thoraco-lumbar-sacral orthosis, is another commonly used technique for treating spinal deformities. In the most comprehensive single study to date, 86 patients (5 to 33 years old) with severe spastic quadriplegia and who wore a spinal brace had the progression of their scoliosis closely monitored (Terjesen et al., 2000). The findings showed that although wearing the orthosis reduced the initial Cobb angle by an average of 25º,

the mean progression of the Cobb angle was still 4.2º per year (4.7º for under 15s). Comparing this to the natural (untreated) progression rate found by (Saito et al, 1998) of 4.5º in under 15s these findings support claims by Miller et al (1996) that orthotic treatments will rarely succeed in halting the progression of a curve, and indeed may be ineffective in many cases for slowing the progression. However, it is believed that lack of compliance may potentially have clouded these results, as the braces are designed to be worn >10 hours during the day and at night, a great deal to ask of any child. Once subjects in this study reached the age of 15 the correction that could be achieved by the brace was reduced significantly, and the rate of progression of the curve also slowed. This is in accordance with the commonly held view that spinal curves are relatively flexible until the end of the growth phase and there after become quite rigid and structural. Larger curves may continue to progress after skeletal maturity, but this is thought to be due more to the effects of gravity than to any muscle imbalance (Stokes, 1997).

It is worth noting however that a meta-study analysing the efficacy of non-surgical treatments for adolescent idiopathic scoliosis (ADI), which is often considered a more correctable form of scoliosis, did find some support for bracing (Rowe et al., 1997). The analysis showed that observation only had a (weighted) 49% success rate, wearing a brace for 8 hours per day 60% (not significant compared to observation only), 16 hours a day 62% (again not significant compared to observation only) and 23 hours a day 93% of subjects were judged to have had the progression of their scoliosis halted by the brace. This review only covered studies from the 1975 and 1993, and the way the Cobb angle was measured in many of the studies led to high error margins (±5 degrees) and opportunities for bias. In addition, there were problems with some of the studies reviewed in terms as what was considered a successful treatment, with this varying from keeping the progression under 4.5-10°. These types of spinal brace are, by necessity, very tight fitting and as such can cause quite severe skin and respiratory problems and can also sometimes affect gastric function (Tsirikos & Spielmann, 2007). Care should be taken when extrapolating findings from this type of bracing and from the ADI-type scoliosis to

the type of support associated with adaptive seating due to the different forces applied, although some useful information can be inferred.

Hip dislocation is a relatively common problem in CP subjects. The combination of a poorly developed femoral head and a shallow acetabulum (often as a result of the child not gaining standing ability meaning the forces that are required for the correct development of the bone are not applied) means that the joint will be unstable and strong pull from the spastic hip adductor muscles will eventually cause subluxation of the joint unless counter measures are taken early on in the child's development (Crouchman, 2000). In adaptive seating, knee blocks and sacral pads are often used to try and improve hip and pelvis position. A recent study comparing the use of a seating system with a sacral pad and knee block to one without for CP children did conclude that although there were no postural benefits from the additional supports they may help to improve hip position (McDonald & Surtees, 2007).

2.3.2.2 Decubitus ulcers

For healthy individuals the act of sitting is far from a static process with many conscious and unconscious movements being made in response to signals from various senses. This process works to maintain levels of comfort and prevent damage to tissue. If the senses that detect and communicate these signals are damaged - as they often are in conditions like CP or spinal cord injuries (SCI) - then the risk of decubitus ulcers developing is increased. Ulcers range in severity, all the way from a skin rash to areas of tissue necrosis that can extend all the way down to the underlying bone. They are generally split into superficial and deep types, with the recently defined deep tissue injuries (DTI) (Black & National Pressure Ulcer Advisory Panel, 2005) being the more serious and difficult to treat (Bouten et al., 2003). Ulcers are also sometimes categorised into four groups, from stage 1 (least severe) to stage 4 (most severe) (Shea, 1975). Treating decubitus ulcers has been estimated to cost the health services in the UK £755 million annually (Stinson et al., 2003), with each individual case being quoted as costing an average of £12,300 although it is difficult to account for all of the incurred costs (Shapcott & Levy, 1999). The ulcers can be very painful for the patient, depending on their level of

sensation, and wheelchair or adaptive seating users who develop them may have to be confined to bed until the injury has healed sufficiently and even then the chance of a recurrence is high (Watier et al., 2000). These high costs, both financial and personal, that result from a condition that would appear to be inherently preventable has led to a great deal of interest in this area in terms of understanding how the ulcers develop and methods to prevent them occurring.

2.3.2.2.1 Initiating factors

Although these types of injury are commonly described as pressure sores, this is not strictly an accurate definition as there are a number of factors that can, individually or in combination, lead to their development. Heat (Finestone et al., 1991), moisture and chemical environment (Clever et al., 2002), and friction have all been shown to play some role. It is however generally agreed that shear forces and unrelieved pressure are the two main contributing factors (Salcido & Popescu, 2009).

2.3.2.2.1.1 Shear forces

Shear forces, whether sustained or transitory, are an important initiating factor for superficial ulcers especially in individuals who have a poor sitting posture that results in a tendency to slide down the seat. The shear stresses are thought to 'kink' the vessels supplying nutrients and removing waste products from the tissue, resulting in the supply of nutrients and the removal of waste products being halted (Zhang, 1994). Efforts are thereby made when prescribing a seating system to ensure that the user does not generate these shear forces when in their seating system, although how this is achieved is dependant on each individual's case. No completely satisfactory sensor currently exists for the measurement of shear stresses, although a number of attempts have been made (Goosens et al., 1997).

2.3.2.2.1.2 Unrelieved pressure

Arguably the most important initiating mechanism for the development of the more serious deep tissue ulcers is unrelieved pressure, which again is thought to occlude the vessels in the tissue. It has been shown that there is an inverse relationship

between tolerable pressure levels and the length of time the pressure can be applied before resulting in discomfort (Mehta & Tewari, 2000). Users of normal wheelchairs are often taught simple pressure reliving exercises such as 'lateral leans' and 'push ups' which are intended to prevent sores developing (Ferguson-Pell & Cardi, 1992). Interestingly, a recent study (Coggrave & Rose, 2003) that featured a novel tissue oxygen measurement technique (a $TcPO_2$ electrode) suggested strongly that, for a sample of 46 spinal cord injury (SCI) patients, the standard 15-30 second pressure lifts (known as 'push-ups') were ineffective in comparison to forward and lateral leans at raising tissue oxygen levels at the ischial tuberosity. This work suggested that almost two minutes of lift was required to return oxygen levels to the unloaded level. However, for subjects who have lower physical or cognitive abilities the use of these self applied exercises is often not possible, and different pressure relieving techniques have to be employed.

2.3.2.2.2 Identifying those at risk

As well as these localised risk factors, there are also systematic factors that can help to identify those most at risk. These factors include age, arterial disease, poor nutrition and, most relevant to this project, it is widely recognised that decreased mobility and reduced sensation puts individuals at high risk (Vohra & McCollum, 1994). Individuals with pelvic obliquities are also deemed to be at high risk with greater loading being placed over the lower of the ischial tuberosities (Moreau et al., 2002). Risk assessment scales such as the Waterlow Pressure Sore Risk (Waterlow, 1985) are designed to predict who is most at risk of developing these ulcers, however these vary widely in their effectiveness and are often most ineffective when looking at specific populations (Anthony et al., 1998).

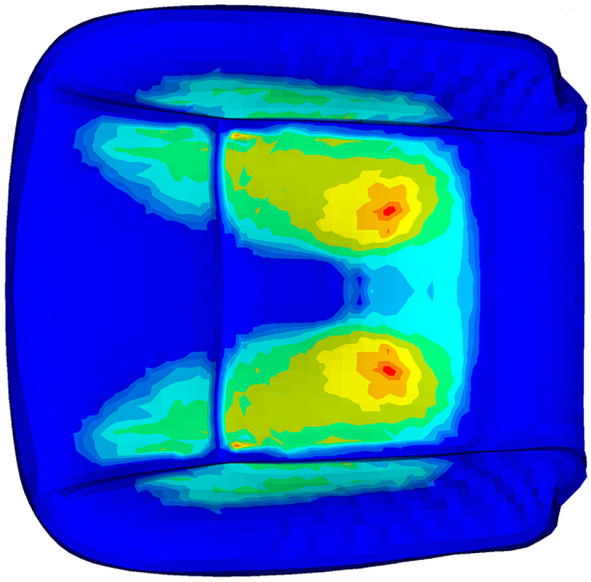


Figure 2.5 – A typical pressure distribution pattern at the interface between subject and seat (www.woelfef.de).

A major component of a standard seating assessment now revolves around trying to ensure that the system will not lead to pressure sores. Traditionally this would involve close monitoring of the skin condition by the user and/or their carer with a typical guideline stating that the skin should be checked for redness and the other initial signs of pressure sore development every 30 minutes (Shapcott & Levy, 1999). Currently there are moves towards using more objective measurement techniques, specifically pressure distribution measurement systems, which are now being regularly used, both clinically and for research purposes. These systems consist of an array of pressure sensors that can be based around pneumatic, resistive or capacitive technologies and arranged in a grid and in the form of a mat. The mat is placed over the surface (usually the seat cushion) that the clinician or researcher is interested in and a computer output displays the pressure measurements which, depending on the resolution (number of sensors per unit area in the mat), can provide a useful and accurate picture of the pressure distribution (see Figure 2.5). The output can be in the form of numerical data, a three-dimensional grid or, most commonly for clinical purposes, a colour-coded pressure map (Stinson et al., 2002). This map allows the clinician to easily demonstrate the effects of pressure relieving strategies on interface pressures to the patient. Other tools such as high frequency ultrasound

are also being investigated as a potential early warning system to detect pressure sore development (Quintavalle et al., 2006).

2.3.2.2.3 Computational modelling of ulcer development

Some work has been carried out using finite element (FE) modelling to investigate the mechanisms involved in the pathogenesis of decubitus ulcers. Computer models have suggested that the internal compressive stresses in the deep tissue under the ishical tuberosities can be up to three times greater than the surface interface pressure (Oomens et al., 2003; Ragan et al., 2002) i.e. the pressure measured by the pressure mat systems mentioned earlier. In possibly the most important study to date, Linder-Ganz et al (2007) used weight bearing and non-weight bearing magnetic resonance imaging (MRI) scans of the buttocks of six normal subjects in order to find boundary conditions for their FE models, and thus investigate the stresses and strains involved with sub dermal tissues. Their findings suggest that the stresses and strains in the gluteus muscle were 32kPa and 74% respectively compared to an interface pressure of 17kPa. This information is important in order to increase our understanding of the aetiology of pressure sore development, and from it more effective ways of preventing them occurring may arise.

2.3.2.2.4 Preventing sores developing

A number of strategies have arisen from clinical experience in order to try and reduce the occurrence of pressure sores for complex seating users. The main aim of these strategies is to achieve a more even pressure distribution and redistribute body forces away from prominently bony areas to areas with more tissue bulk and there are a number of different methods used to try and achieve this. These include novel materials such as foams or gels used in the seat to spread pressure distributions across larger areas (Apatsidis et al., 2002) and seat cushions that contain different air pockets whose pressures can be varied to alter pressure distributions at set intervals (Rosenthal et al., 1996; Rosenthal et al., 2003). However, despite these efforts, decubitus ulcers remain a considerable and very current problem.

2.3.2.2.5 Tilt and recline seating systems

It has been realised that no matter how well supported the trunk and well positioned the vertebrae, it is unacceptable to keep any static seated position maintained for long periods of time (Graf et al., 1995). Maintaining the same position in a seating system can lead to decubitus ulcers and the loss of functional independence, not to mention the pain and discomfort these conditions may induce (Lacoste., 2003). Tilting and reclining mechanisms have been incorporated into some adaptive seating systems to try and alleviate these problems.

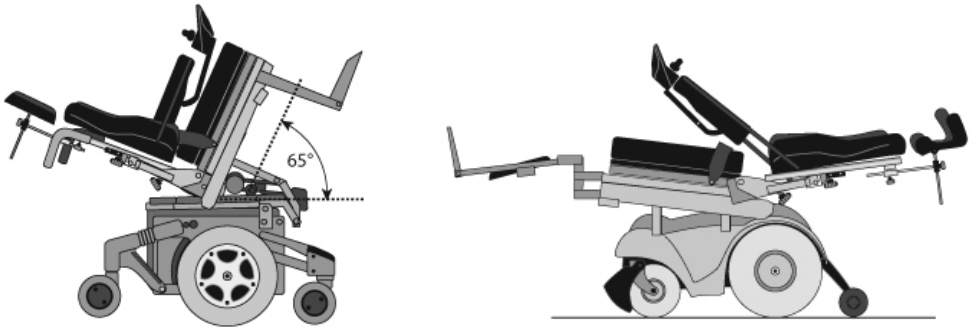


Figure 2.6 – Tilting adaptive seating system (left) and reclining adaptive seating system (right) (http://msktc.washington.edu)

Tilt and recline (also known as repositioning) seating systems are those that have the ability to allow the variation of the user's posture with respect to gravity either through tilting the overall angle of the system and/or the seat-to-back angle (recline) (see Figure 2.6). The ability to make an adaptive seating system tilt or recline has been shown to be beneficial to a number of users (Fermin & Wellard, 2002) and there are numerous systems on the market that provide this function, both in powered and manual forms. The additional mechanisms required to allow the seating system to tilt and/or recline does increase the overall size and weight of the wheelchair, thus reducing its range and manoeuvrability (Deway et al., 2004).

2.3.2.2.5.1 Evidence for the use of tilt and recline systems to prevent decubitus ulcers and other benefits

Although tilt and recline mechanisms were primarily incorporated to improve user comfort they have been reported to be used for a wide range of additional functions. Lacoste et al (2003) questioned 40 users of tilt and recline systems to investigate what they felt were the benefits. They discovered that as well as comfort and resting other functions that were popularly cited were: helping to drain urinary bladder; stability; climbing pavements; pain relief; and gaining access under tables.

In the most comprehensive review to date it was concluded that posterior tilt of 20° or more can reduce pressure at the interface under the pelvis (Michael et al, 2007). The authors made note of the general poor quality of research in this area, especially in groups with progressive neuromuscular or neurological disorders, and emphasised the need for high quality future studies with more standardised outcome measures. In clinical terms, some disagreement still exists over the best angle of tilt for maximising user comfort and reducing pressure. Recommendations suggest angles of up to 65º are required to effectively relieve pressure temporarily (Coggrave & Rose, 2003) but research into the 'real world' use of these types of systems found that in terms of reducing perceived discomfort users can find benefit from much smaller angles of tilt and recline (Ding et al., 2007; Seeger et al., 1984). This finding - that tilt angles of less than 30° tended to be used more often and were considered more comfortable than those greater than 30° - suggests that pressure distribution may not be as closely related to perceived discomfort as generally assumed, or that other factors influence the subjects' discomfort at larger angles of tilt.

The potentially beneficial aspects of tilt and recline systems in terms of abnormal muscle tone reduction is another area that has been under-investigated. This is probably due to the difficulty in interpreting the results from electromyographic (EMG) measurements and other measures of muscle tone. One limited study (Nwaobi, 1986) investigated the tone reduction caused by tilting the seat between 0 and 30º and found some evidence that tonic muscle activity in the lower back extensors, hip adductors and ankle plantar flexors of CP patients can be affected by their seating position and is actually increased by tilting from 0 to 30º from vertical.

Some limited experimental work has also been carried out on the functional effects of tilt and recline. A recent review of the work in this area declared the current work on the subject to be inconclusive, although the authors did note that there were some indications that neutral and anterior seat inclines do positively affect function in CP children when opposed to when the seated position is posterior inclined (McNamara & Casey, 2007). The review also noted evidence for positive and negative effects on postural sway for spastic and hypotonic CP when sitting on an anterior incline.

2.3.3 Activities/activity limitations

2.3.3.1 Postural support

The techniques which are currently employed for the positioning of these individuals are based on principles that have been developed in clinical practices over the past few decades. However, the complexity and wide range of symptoms involved with neuromuscular diseases means that it is very difficult to predict what responses can be induced or inhibited by seating designs. Maintaining a good posture for the user could arguably be considered the most important aspect of adaptive seating, as it is from this that many of the benefits are thought to arise (Chung et al., 2008). Research into this field, perhaps because of the difficulties with the conditions involved and isolating the effects of individual interventions, tends to be qualitative and retrospective in nature. Very few high quality randomized studies with controls have been carried out.

Postural control is defined as the control of the body's position in space in order to obtain stability and orientation (Brogren et al., 1998). To achieve this control we use integrated sensory input from the visual, somatosensory and vestibular systems. These inputs then activate specific neuromuscular responses. For example, in the case of a simple standing the centre of gravity is maintained within the stability limits of this position. In subjects with neuromuscular disorders this process is interrupted and muscle activation patterns are altered.

2.3.3.1.1 Evidence for functional benefits

In a small study (Washington et al., 2002) investigated the effects of a contoured foam seat (CFS) on children with neuromotor impairments. These seats were customised for each of the infants and consisted of a foam block which had areas carved out of it plus some lateral trunk supports (see Figure 2.7) The effects that were specifically looked for were postural alignment and the ability of the child to interact with toys. Results showed that the CFS gave a sustained improvement in postural alignment when compared to standard highchairs. The study suffered from having a very small sample size of only four participants. The authors offered several hypotheses as why the CFS improved postural alignment including-

- Pelvis is kept in a neutral position that limits its degrees of freedom, thus allowing the infant to concentrate on controlling other body segments, mainly the trunk in this case (this refers back to the dynamic systems theory of infant development).
- The surface of the highchairs allowed forward or lateral pelvic movement which may have led to pelvic obliquity or asymmetric weight bearing whereas the CFS had a non-slip cover.

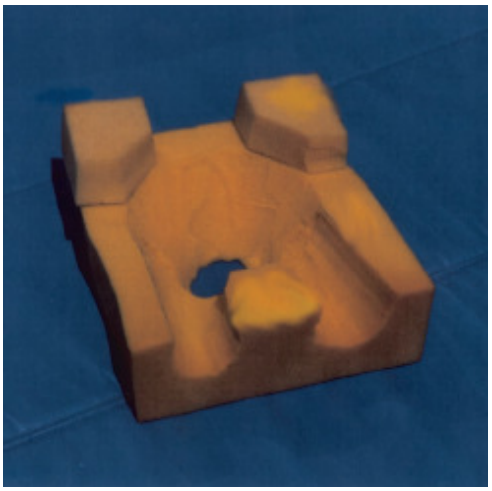


Figure 2.7 – Contoured foam seat (Washington et al., 2002)

Targeted training is a technique that can help to explain the use of adaptive seating systems as a means to improve function. Aimed primarily at children due to their

greater levels of neuroplasticity - i.e. the ability of the nervous system to adapt to changes within and outside of the body (Gordon et al., 2006; Pountney et al., 2000) - it is based around the principle that control of movement is learned through the repetition of movement combined with feedback from proprioception and the joints themselves. Learning to simultaneously control a large number of free joints places heavy demands on the neuromuscular system and, in the case of CP children where this system is damaged, it will inhibit the learning of new motor skills. Targeted training attempts to allow the subject to learn how to control only one or two joints at a time. Equipment is used to immobilise non-targeted joints and control is ideally gained from the neck down (an idea that relates to the neuro-developmental principles laid down in the neuromaturational theory of motor development) and, although the literature is limited, the technique would appear to have some potential (Butler, 1998). By supporting the limbs and trunk adaptive seating may provide inherent functional benefits to the user along the lines of targeted training.

2.3.3.1.2 Evidence for mental benefits

It has been suggested that postural support systems may improve mental performance in pre-school children with CP (Miedaner & Finuf, 1993). It is thought that this may be due to the child being relieved of the neuromuscular sensory load that had been placed on them by their postural instability, thereby enabling them to concentrate better on mental tasks. Dexterity and grasp movements were also found to be more precise when in the supported position.

2.3.3.1.3 Evidence for other benefits

The effects of sitting posture on pulmonary function have also been investigated. It has been demonstrated that in normal subjects sitting posture has a significant effect on the lung capacity and expiratory flow (Lin et al., 2006), a finding which reinforces conclusions drawn from earlier work claiming that the use of adaptive seating has a positive effect on pulmonary function in CP subjects (Nwaobi & Smith, 1986). However, in a study of 19 subjects with Duchenne muscular dystrophy or Friedreich's ataxia which compared the use of a standard wheelchair to an adaptive

seating system, no improvement in pulmonary function was found (Clark et al., 2004). This study did however note some improvements in upper limb function and sitting posture. Hulme et al (1987) found that multi-handicapped children who used adaptive seating improved their eating and drinking abilities, although there was no control group and insufficient detail was given in the paper to determine how the authors had separated the effects of the seating system and the natural functional development of the child so this result should be used with caution.

The beneficial aspects of adaptive seating in terms of abnormal tone reduction have been under-investigated. Some types of orthoses, such as the neurophysiological ankle foot orthosis (NAFO) (Thom, 1994), have been studied to see if they improve abnormal muscle tone. The theory behind this type of neurophysiological approach, when related to the treatment of motor disorders, is that motor control performed by the central nervous system is heavily influenced by peripheral cutaneous receptors and muscle proprioceptors. This means, hypothetically at least, that by altering the inputs to the CNS from the peripheral receptors, it may be possible to alter motor output to a more normal pattern which can then be learned as a repeated action. Work in this area has tended to be on a case-by-case basis due to the difficulty in applying a stereotyped treatment across a large sample.

2.3.3.2 Custom moulded seats

In individuals where skeletal deformities have developed to a level where accommodating them in an adaptive seating system with a standard seat cushion and backrest is no longer possible, custom moulded seats are required. A number of different methods exist to achieve a suitable mould of the subject, ranging from simple hand carved approaches where a block of foam is gradually shaped to fit the physical presentation of the patient, to more complex systems which require a mould of the subject to be taken which is then scanned into a computer program, alterations to the shape made, and then the file to be transferred to a 3D milling machine for fabrication of the seat. To the author's knowledge, no studies comparing the efficacy of these methods exist. Brienza et al (1999) did describe a method for producing custom-contoured cushions using interface pressures but this study only featured

elderly and SCI wheelchair users. Another investigation, which looked some of the materials used in custom-contoured seats, suggested that foams are more effective at reducing peak interface pressures and provide a better overall pressure distribution (Apatsidis et al., 2002).

2.3.4 Participation, environment and personal factors

For children especially, the importance of engaging in activities and having social interactions are essential aspects of the child's development (Asbjornslett & Hemmingsson, 2008). Research however, suggests that CP children, especially those with physical disabilities, are less involved in leisure activities than their healthy peers and that the activities they are involved in tend to be more passive and lack variety (Shikako et al., 2008). The physical and mental effects associated with neuromuscular disorders often lead to problems in the patient's ability to participate in educational, social and vocational activities. Suggestions that therapists should consider a mix of environmental, child and task related factors to improve participation have been made (Egilson & Traustadottir, 2009), although other work has shown that neither the amount of support given nor the environment are statistically related to the student's level of participation and that the own perception of the factors that could limit participation play a more important role (Eriksson, 2005).

Patients can come up against a number of obstacles thrown up by the environment (Palisano et al., 2003) they find themselves in which can reduce the levels of participation that they are able to achieve. Increasing efforts are being made to improve accessibility in all aspects of the physical environment, the primary example being The Disability Discrimination Act 2005 and its predecessor from 1995. In terms of transport there are a number of regulations regarding the way wheelchairs and seating systems can be used, namely ISO 7176-19:2009 (Wheelchairs for use as seats in motor vehicles), and ISO 16840-4:2009 (Seating systems for use in motor vehicles). These standards are based on work reported in the literature on the testing and modelling the crashworthiness of various aspects of seating systems (Bertocci et

al., 1996; Bertocci et al., 2001; Kang & Pilkey, 1998; Karg & Springle, 1996; VanRoosmalen et al., 2001).

As well as the more easily observable effects of adaptive seating (attempted correction of deformites and posture, improvements in functional abilities etc) it is important not to forget about the personal and psychological aspects of providing seating systems for individuals. As seating users will often spend the majority of their waking hours in their system it can play an important role in their day to day life. A recent study looking at the effects adaptive seating devices had on the day-to-day lives of CP children and their families concluded that the devices "had a meaningful, positive impact on child and family life" (Ryan et al., 2009). It should be noted that due to the methodology of this trial and the nature of the intervention a placebo-type response cannot be ruled out.

There are a number of alternative adaptive seating systems available. These include the Bambach Saddle Seat (Loughton, UK), the Association for Rehabilitation of Communication and Oral Skills (ARCOS) saddle seated wheelchair (Malvern, UK), and kneeling chairs. Designs which make use of a saddle type seat seem to have come out of observing the beneficial effects of horse riding, a common activity for CP children attending special needs schools, on the sitting posture of CP individuals. Children who have little to no sitting ability on normal chairs are often found to be able to ride a horse with a normal saddle and no or little help from carers.

The Chailey Heritage Clinical service has developed a specific approach to postural management. It is based upon preventing the development of deformities while improving the ability of children with reduced motor skills to participate more actively in life (Pountney et al., 2001).

Introduction of devices such as communication aids, computers or toys are beginning to become more common as modular additions to a standard seating system. Depending on the individual's abilities the selection of switches and control systems is an important part of the design process to allow the patient to get the most out of

their system. Head, knee, shoulder and foot controls are all potential options if the use of the hand is not possible.

2.4 Sitting discomfort

The minimisation of discomfort is of paramount importance to an individual sitting in a seat. It is therefore an area of great interest to chair manufacturers and the automotive industry who wish to show customers that their products cause minimal discomfort (Andreoni et al., 2002), and also to the healthcare industry; where discomfort caused by wheelchairs and beds can be important in terms of the overall quality of life of the individuals who depend on such devices for mobility and more. However, it is not always an easy task for researchers to relate comfort to specific biomechanical variables (de Looze et al., 2003). Individuals without any neuromuscular problems will instinctively search for a sitting posture which allows task execution to be performed easily and efficiently, as well as the posture that results in the lowest expenditure of energy, within biomechanical and physiological limits (Kolich, 2007). Thus, a sitting posture at any given time represents the outcome of often very dynamic internal and external constraints, and also of any task which is being carried out, making it a highly complex problem with a large number of variables. Although research has been carried out in this area (for example a standard set of biomedical causes of seating discomfort was developed for the automotive industry (Viano & Andrzejak, 1992) and a model for applying biomechanics to seat design has been produced (Mehta & Tewari, 2000)), it remains to be seen whether or not such a distinctly subjective experience as sitting discomfort can fully be described using biomechanical variables alone.

2.4.1 The balance between comfort and discomfort

The true definitions of comfort and discomfort have been the subject of some debate in recent years. For a long time researchers considered comfort states to be part of a continuous scale, with extreme discomfort at one end, a neutral state for the mid

point, and extreme comfort at the other end (Shackel et al., 1969). Recent work however has suggested that comfort states are primarily associated with aesthetics, whereas discomfort is more closely related to biomechanical and physiological factors (Zhang et al., 1996). Obviously comfort and discomfort are not completely unrelated, as even the most aesthetically pleasing chair, if it causes pain to the user, will not be considered comfortable. This line of reasoning led Zhang et al (1996) to produce their hypothetical model of the relationship between comfort and discomfort in seating. In it, comfort is defined as being related to a state of well being and the plushness of the seat; and discomfort is defined as poor biomechanics, fatigue and restlessness. The model suggests that comfort cannot be achieved through the absence of discomfort, but the presence of discomfort *can* reduce the overall level of comfort. The work presented in the later chapters of this thesis is focused mainly on sitting discomfort as influenced by biomechanical factors.

2.4.2 Measurement of sitting discomfort

Sitting discomfort is generally assessed using subjective rating scales, of which there is a wide range (in terms of both approach and reliability) available. Finding a useful means of objectively measuring sitting discomfort is one of the greatest challenges facing seating researchers today (Andreoni et al., 2002). A number of techniques have been investigated with varying success, including-

- EMG activity of spinal muscles (Babski-Reeves et al., 2005; Bennett et al., 1989; El Falou et al., 2003; Makhsous et al., 2003)
- Intra muscular pressure in para-spinal muscles of the lumbar region (Konno et al., 1994). (Lower back pain has been related to poor lumbar spine posture when seated (Wilder & Pope, 1996), but it is difficult to make useful measures of spinal posture without altering the seat itself (Carcone & Keir, 2007))
- Spinal shrinkage (Leivseth & Drerup, 1997; McGill et al., 1996; Van Dieen & Toussaint, 1993; van Dieen et al., 2001)
- Postural angles (Dunk & Callaghan, 2005; Na et al., 2005)

- Pressure maps at the body seat interface (both by the measurement of peak pressures and by the analysis of centre of pressure (COP) behaviour) (Fenety et al., 2000; Gyi & Porter, 1999; Porter et al., 2003)
- Verification of the anthropometric sizing of the seat through the description of interfacing surfaces of seat and body (Kolich, 2003; Zhoa & Tang, 1994)

2.4.3 Dynamic measurements and in-chair movement

A recent study which looked at dynamic body pressure distribution in sitting subjects managed to show a significant correlation between body pressure variables and subjective discomfort ratings (Na et al., 2005). This suggests that dynamic pressure distribution data is a more useful tool for the assessment of seated discomfort than data obtained from static measurements. The use of dynamic measurements relates back to a suggestion by Branton (Branton P, 1969) that sitting should be viewed as a behaviour, rather than a posture, and as such should be described on a continuous (dynamic) basis. This is supported by the assertion that any sitting posture, no matter how well positioned the spine is or how uniform the distribution of pressure, cannot be maintained for any significant period of time without becoming uncomfortable (Graf et al., 1995). Branton's original work studied the patterns of postural shifts of train passengers on long journeys, and this led to 'in chair movement' (ICM) being used as a measure of discomfort after a study showing a link between increases in discomfort and increases in ICM and fidgeting was carried out (Fenety et al., 2000). Interest has also been shown in the use of non-verbal communication in the form of movement and postural shifts as an indicator of discomfort and boredom (Bull, 1987). The assumption on which these and other studies using ICM or similar postural variables are based is that subjects will increase the frequency and/or magnitude of their movements, at a conscious or unconscious level, as time passes, in a manner that is influenced by their level of discomfort (Fenety et al., 2000).

2.5 Stretch and dynamic support

2.5.1 Joint contractures and muscle stretch

Neuromuscular disorders such as CP and stroke can result in muscle imbalances around the patient's joints and, if left unchecked, these imbalances can lead to a reduction in the range of motion of the joint, deformity, and ultimately to the complete dislocation of the joint (DeLuca, 1996; Tafti et al., 2008). It is the generally held consensus for neuromuscular diseases that it is only muscle imbalance or spasticity at a joint that can lead to contractures, whereas with injury scar tissue contraction plays a major role (Gracies, 2001). It is understood that chronic spasticity will lead to muscle shortening, which leads to joint contractures, which in turn leads to increased spasticity (Gracies et al., 1997). This feedback loop, if uninterrupted, will over time lead to severe joint contractures and skeletal deformities. Stretch may be used to interrupt this cycle, and therefore it can be considered to have an intrinsic anti-spastic effect. Stretch is also very important in stimulating the growth of muscle fibres (Coutinho et al., 2004). Therefore, regular and varied stretching of the muscles and other soft tissues around the joint to ensure that range of motion is conserved is considered to be one of the most effective non-surgical method of preventing these problems developing (Gracies, 2001).

Stretching plays a major role in clinical approaches to the prevention and treatment of contractures (Bressel & McNair, 2002; Trembley et al., 1990). Physiotherapists working with patients with contractures will spend the majority of their sessions carrying out stretching exercises and parents and carers will also be taught techniques that will allow them to perform manual stretching exercises on the individual under their care that will help to keep joints flexible and prevent contractures occurring.

Disagreement exists in the literature over the amount of muscle tension required to produce a beneficial increase in range and functionality. A school of thought exists that believes that splinting a joint on maximum stretch may result in increased spasticity (Bobath, 1979) but this hypothesis has not been shown in any controlled studies and is opposed by research showing the inhibitory effects of full stretch on muscle overactivity (McPherson et al., 1985). As well as this, some work has been

done comparing fixed angle, cyclic, and constant torque stretching with significant improvements in range of motion being shown for all approaches. Constant torque stretching was suggested to being the most effective method although differences between methods were not statistically significant (Bressel & McNair, 2002; Yeh et al., 2005).

Research into the stretching of spastic muscles does not support short time acute stretching, either for preventing contractures or increasing the range of motion of a joint (Pin et al., 2006). In their classic study of the soleus muscle in children with CP, Tardieu et al (1988) showed that at least six hours of stretching was required per day to avoid joint contractures. This supports the findings from studies showing that serial casting is an effective intervention to improve joint range of motion due to its ability to provide a long slow stretch over time (Brouwer et al., 1998; Cottalorda, et al., 2000). It is important to note however that serial casting is only considered appropriate when muscle hypoextensibility is caused by an imbalance at the joint rather than the lack of muscle growth (Palisano et al., 2004).

It is not feasible for physiotherapists to spend such long periods of time carrying out stretching exercises. Therefore, to bridge the gap, the majority of these cases are prescribed a static orthosis, normally a plastic moulding of the joint and surrounding parts of the limb that when worn locks the joint in one position. Although helping to prevent the deformity from worsening and in some cases providing functional benefits (for example ankle-foot orthoses to improve gait (Woo, 2001)), static orthoses have a number of disadvantages including lack of acceptance, impediment of spontaneous function, aggravated disuse, skin damage and breakdown and pain (Gracies et al., 2000).

2.5.2 Dynamic orthoses

Dynamic orthoses, where the moment being applied around the joint by the orthosis is given a dynamic element by the use of a spring or similar component, try to achieve continuous stretch of a muscle whilst not requiring the joint to be immobilized. To understand why dynamic orthoses could potentially have

advantages over static orthoses, more detailed examination of the pathology of spastic muscles is required. Spastic muscles can be considered to have a dynamic and a static element, where the static component is muscle shortening and the dynamic part is abnormal tone and imbalance (Scheker et al., 1999). By applying a constant stretch to the shortened muscle over a long period of time, a dynamic orthosis addresses the static component of spasticity. This theory perhaps suggests that dynamic orthoses will be at their most effective when applied in combination with therapies that treat abnormal tone. This is echoed in the claim by Gracies et al (2000) that for a treatment aimed at improving function to have maximal efficacy it should address both muscle overactivity and muscle shortening.

Dynamic orthotic devices provide a therapy similar to serial casting in that they can provide a slow stretch over an extended period of time. However, they have several important advantages over casting treatments. For serial casting to be effective the patient has to have the targeted joint re-cast in a new position at least every few weeks. This requires repeated hospital visits and a relatively labour intensive process involved with making the new cast, whereas dynamic orthoses can be designed to provide a constant stretching force over a wide range of joint movement, negating the need for repeat visits. Conversely, there is still debate over whether this reduction in time at the hands of a therapist is a good thing or not given the lack of feedback from mechanical devices. Treatment with dynamic orthoses, as with seating, is an under researched area and there is a distinct lack of high quality randomised trials with controls that would adequately determine its efficacy.

Some dynamic (or lively) support systems have been developed and are in use. These include the contracture correction device (CCD) from the Orthotic Research and Locomotor Assessment Unit (ORLAU) (Oswestry, UK), the 'Dynasplint' (see Figure 2.8) (Dynasplint Systems Inc. Severna Park, Maryland), and the Ultraflex system (Ultraflex Systems Inc. Pottstown, Pennsylvania). Literature on the effectiveness of all of these systems is limited although the small trials and case studies that have taken place have indicated that the devices show some promise

(Charlton et al., 1999; Farmer et al., 2005; Keeping & Major, 1999; Nuismer et al., 1997).

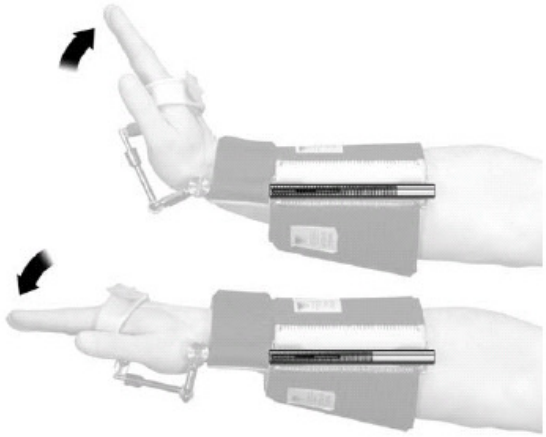


Figure 2.8 – Dynasplint orthosis (Farmer et al., 2005)

The effect of Lycra® based orthotic garments on hemiplegic CP sufferers has also been investigated. Originally developed as a treatment for burn injuries, these have now been made available in the form of splints for the limbs of individuals with neuromuscular disorders. Three companies in the UK currently supply lycra splints, Second Skin (Edinburgh), Tyco Healthcare (Gosport), and Gilbert and Mellish (Birmingham). The stretching properties of Lycra mean that garments/devices incorporating the material can be considered to be dynamic orthoses (Blair, Ballantyne, Horsman, & Chauvel, 1995). The flexibility of the material allows for a considerable freedom of movement and intimate skin contact is maintained without the risk of developing decubitus ulcers and its porosity means that user comfort is not reduced because of heat or humidity. Additional plastic supports can be attached to the outside of the material to increase the level of support if necessary. Initial results have been limited mainly to small scale studies and case reports, but, as with the previously described dynamic orthoses, the treatment appears to show some promise (Matthews & Crawford, 2006; Nicholson et al., 2001; Rennie et al., 2000; Watson et al., 2007). However, there are a number of contraindications and functional problems with these garments which must be noted. Problems with subjects

becoming too warm whilst wearing the garments, difficulties in washing and drying, toileting problems and difficulties putting the garment on have all been reported (National Horizon Scanning Centre, 2002; Nicholson et al., 2001). Contraindications are respiratory problems and intractable peripheral cyanosis (Blair et al., 1995). Full body suits and garments that are designed for individual limbs are available, with costs ranging from £55 for simple garments all the way up to £1800 for a complex body suit (National Horizon Scanning Centre, 2002).

A study of nineteen young CP subjects who took part in a therapeutic regime that involved the use of a dynamic brace combined with neuromuscular electrical stimulation (NMES) that was intended to reduce spasticity in the hand and wrist was carried out by Scheker et al. (1999). In a qualitative assessment of hand function all subjects showed improvement. It should be noted that the authors also suggest that the treatment is a long term one, as a subject who was taken off the programme early began to show signs of regression. This is supported by results suggesting that the effects of the treatment will reverse in as little as 12 months if it is discontinued. It has been suggested that this can be prevented by using standard static night splints to maintain the improvement in range of movement (Cottalorda et al., 2000).

Dynamic orthoses can be used on almost any body part. Although not strictly dynamic in the way previously described, Lou et al (2005) produced a "smart" orthosis intended to be used with sufferers of scoliosis. This orthosis was capable, using an air bladder connected to a motorised pump and controlled by a microprocessor receiving feedback from a force transducer, of adjusting the tightness of the orthosis. Although it was only tested on four subjects, results in terms of how much the orthosis was worn (although the influence of simply taking part in the study and having a novel orthosis must be taken into account here) and, more importantly, the forces it applied by the orthosis were maintained at a much more consistent level with subjects using their orthosis at the prescribed tightness 16% more often than previously.

Although seating systems which use dynamic type supports for the backrest and headrest exist and are available there is no existing evidence for their effectiveness, nor have there been any short term studies published. Anecdotal evidence from centres developing the dynamic seating systems however, suggests that they reduce the amount of time users spend in extended positions, tolerances to the system improved (compared between static and dynamic versions of the same system), and ability to remain in their system.

A novel seating device in the form of a thoracic lumbar sacral orthosis made out of a non-rigid SIDO®frame (note: the abbreviation was not defined in the paper) was reported to allow the user "to bend forward or rotate the trunk to some extent" (Vekerdy, 2007). No further details were given on the range of motions achieved or the properties of the materials used, however the paper described positive outcomes in subjects when comparing feeding and postural items between it and their standard system. In many cases semi-dynamic elements have been consistently presence in seating design since its conception through the use of certain materials for supports and padding.

2.6 Assessment of seating systems

It is standard practice when investigating the efficacy of a medical device or intervention to thoroughly assess for their effect on a medical condition or physiological measurement. Ideally, a double-blind, randomised and controlled methodology which will negate or account for the influence of factors such as experimenter bias or the placebo effect should be used to achieve this. In the case of medical interventions for individuals with chronic disabilities, especially seating interventions, things get a bit more complicated. (Springle, 2007) gives this example:

"If one were trying to determine the medical benefits of a standing wheelchair, several practical barriers exist alongside the methodological challenges. For

example, changes in physiology due to standing will take time, but the differences in use of the standing feature may delay or even mask the impact in some people. Further complication arises from the need to recruit and study enough users of standing wheelchairs – a device with a low prevalence of use."

Longitudinal studies on the effects of adaptive seating systems, on children especially, are difficult to organise due to concurrent treatments that may be being administered, thus confounding the results. Halting these concurrent treatments, whose efficacy may have already been established would be unethical.

Despite this, a number of tools do exist that try to measure the effects of interventions on CP subjects. Functional measurements for example can be made in terms of range of movement in a joint, or as the ability to carry out a task. Popular tests for measuring function include the Quality of Upper Extremity Skills Test (QUEST) and the Seated Postural Control Measure (SPCM), both of which provide an objective standardized measure of functional ability. These tests involve the subject being asked to carry out a number of functional tasks, including lifting objects of different sizes and estimates of the range of motion of key joints when performing functional tasks. There seems to be a trend in emerging assessment tools in that they are moving towards more global measurement tools, such as those based around health-related quality of life (Bjornson & McLaughlin, 2001). Quality of life can be defined as the presence of physical, mental and social well being (Krick et al., 1996). These tools tend to be based around questionnaires that are to be answered ideally by the patient, or if this is not possible by their primary caregiver.

2.7 Conclusion

This review has covered the pathology of CP, the development and intended effects of adaptive seating and the evidence for these effects. A recent systematic review of the literature related to adaptive seating concluded that "Future studies on the effects of adaptive seating should describe participants with standardized classification

systems and employ stronger research designs" (Chung et al., 2008). The current literature is very limited in terms of both the overall quality of the studies and the clinical relevance of the work. This can be attributed to some extent to the lack of focus in research areas associated with seating, the difficulty in recruiting subjects and indeed in making generalisations about such diverse subject groups as the CP and other neuromuscular disease populations. The significant interactions in this group between variables such as age, parental participation, IQ etc can all have masking or confounding effects on the findings from these types of studies.

This review has also briefly covered the state of the science relating to sitting discomfort and the use of dynamic support, both of which have been the subject of further investigation later in this thesis.

3 An investigation of teaching staff members' and parents views on the current state of adaptive seating technology and provision

3.1 Introduction

The purpose of this part of the research was to support the development of the novel adaptive seating system by finding additional areas where improvements could be made beyond those that have been identified from the literature and from discussions with seating experts.

3.1.1 Background and aims

It is recognised that the views of the parents of children who use adaptive seating systems can often be opposed to those of clinical professionals (McDonald et al, 2003). Parents tend to be more concerned about functional and day-to-day management issues whereas clinicians are more concerned with postural management, and this gap can lead to difficulties in prescribing clinical treatments. For example, if an orthotic treatment is prescribed that causes the subject to feel uncomfortable and show signs of distress, then it is the individuals who work and live with them for extended periods every day who will have to deal with this. This may go some way towards explaining the low levels of compliance that are reported in some studies (Miller et al, 1996). An effective adaptive seating system should both improve the day to day quality of life of the user and as well as provide long term benefits to their development. The existing literature for adaptive seating tends to be focused mainly on clinical outcomes. With this in mind, the aim of this part of the project was to investigate the true day-to-day use of adaptive seating systems in the educational and home environments, as perceived by teaching staff and parents, and to identify areas where improvements could be made, specifically in terms of safety, reliability and technology. Significant differences between the opinions of the two groups were also tested for.

3.2 Methods and Materials

3.2.1 Methods

3.2.1.1 Preparation for investigation

Preparation for this study took the form of a literature review and visits to four local special needs schools in the central Scotland area (UK). These schools were identified as having several adaptive seating users among their pupil population. The school visits involved spending time with the children in their normal educational environment and observing them and their teaching staff carrying out the tasks and activities that are performed in the classroom every day. During these visits, teaching staff took part in brief and informal discussion groups (consisting of the thesis author and two or three members of staff) where they were questioned about their views and experiences with adaptive seating systems. Special attention was paid to the problems they mentioned and potential solutions that were suggested. These comments were all noted and the information gathered from the visits helped to form the basis of the questionnaires for this investigation.

3.2.1.2 Subjects

Three schools out of the four that were visited agreed to take part in the survey. Participants were split into two groups: teaching staff at special needs schools who worked with children who use an adaptive seating as a result of a neuromuscular disorder; and the parents of children with a neuromuscular disorder who used adaptive seating equipment and attended these schools. Teaching staff members were required to have worked with these children for at least six months. Parents had to have had a child who had regularly used at least one piece of adaptive seating equipment for at least six months.

3.2.1.3 Ethics

Ethical approval for this study was obtained from the departmental ethics board at the Bioengineering Unit, University of Strathclyde (reference no. UECO708/09).

Questionnaires were sent out to special needs schools in the central Scotland area with permission for the research to be undertaken in these locations first being obtained from the relevant local education authorities. It was emphasised in the cover letter included with every questionnaire that participation was entirely voluntary.

3.2.1.4 Data analysis

Descriptive analyses were conducted (n, percentage and standard deviation) for all applicable data. Due to the nonparametric nature of much of the data, the Mann-Whitney test was used to test for significant differences between the two groups in the relevant sections and Fleiss's kappa was used to determine overall rater reliability. Relevant respondent comments were also reported.

3.2.2 Materials

3.2.2.1 Questionnaires

Two closely related self-administered questionnaires were designed for this study, a teaching staff version and a parent version (see appendix A). These questionnaires were designed with reference to survey development texts (Czaja & Blair, 2005; Fowler, 2002) and were made up of a mix of open, closed and rated-response type questions. They were designed to be completed in around ten minutes in order to minimise time demands on busy teaching staff and to encourage a high response rate. Both versions contained the same questions with the exception of a section asking for personal details about the staff member or the child. Three successive drafts of each questionnaire were prepared with amendments being required in turn by senior teaching staff at the schools taking part in the survey and the Bioengineering Unit departmental ethics board at the University of Strathclyde.

The areas which were investigated were-

- The perceived importance of the different functions of seating systems. It was decided to limit the number of functions to be assessed to the ten which,

after extensive reviewing of the literature and the aforementioned discussions with teaching staff, were believed to be key in adaptive seating technology. The functions chosen were - *child interacting with others; the prevention of deformities; mobility (indoors); mobility (outdoors); child's well being and self esteem; child being accepted by peers; postural support; positioning child for eating; positioning child for cleaning/hygiene tasks;* and *providing comfort.* The functions were required to be as general as possible, as, for example: in some cases it has been suggested that pulmonary capacity can be improved through improved sitting posture (Lin et al., 2006) but this was considered to be applicable to too few adaptive seating users to make it viable for inclusion.

- The time spent transferring child between and to and from seating systems on an average day.
- Satisfaction levels with the way adaptive seating systems cope with the growth patterns of their users.
- Descriptions of any accidents that had been witnessed which involved an adaptive seating system.
- Descriptions of any repairs or adjustments which had been carried out on an adaptive seating system.
- Satisfaction levels with the speed at which new or replacement models are issued.
- Teaching staff were asked for type of school (nursery, primary or secondary), job title and time spent working with children with special needs.
- Parents/guardians were asked for the type of school their child attended, how long they had been regularly using adaptive seating systems, and what type of system they currently used.

An additional section was also included to allow further comments regarding any other problems respondents would like to see addressed and improvements they would like to be made. Parents were encouraged, where possible, to discuss the questionnaire with their child.

3.2.2.2 Full packs

Teaching staff were given a questionnaire pack which included a questionnaire, a letter explaining the purpose of the research and a stamped, addressed envelope for returning the completed questionnaire. These were distributed by the head teacher of the school (or by a senior member of staff delegated by the head teacher) to those staff who worked regularly with adaptive seating users. Parent questionnaire packs included the same items but with a parent version of the questionnaire replacing the teaching staff version. These packs were distributed to the parents via the documentation the children would normally take home from school (i.e. their diaries or letters from the school).

3.3 Results

3.3.1 Teaching Staff

The teaching staff members who completed and returned the questionnaire represented a cross section of the people who work in modern special needs schools, covering the full range of pupil age groups. In total, there were 33 teaching staff respondents from the 60 questionnaire packs that were sent out to schools (a response rate of 55%) and this group included teachers, physiotherapists, nursery nurses, occupational therapists, learning assistants and speech therapists. The staff had a mean experience level of 6.9 years (SD 5.4 years).

3.3.1.1 Rating of functions

Table 3.1 shows the ratings given to the functions of adaptive seating systems by teaching staff members.

3.3.1.2 Transfer time

The estimated time spent transferring students to and from their seating systems during the course of a normal day was found to be 63 minutes (SD 45 minutes).

Table 3.1 – Functions of adaptive seating, rated by importance by teaching staff at special needs schools and with the relative observed agreement (Pr(a)) noted. Subjects were asked to rate the importance of the function, the options being: 1 - of no importance; 2 – of very little importance; 3 - somewhat important; 4 - very important; 5 - extremely important.

Rank	Function	Ratings					Pr(a)
		1	2	3	4	5	
1	Postural Support		1			32	0.939
2	Providing comfort		1		1	31	0.881
3	Positioning child for eating tasks		1		3	29	0.775
4	Preventing the development of deformities	1			3	29	0.775
5	Child's well being and self-esteem	2		1	3	27	0.672
6	Child interacting with staff and other pupils	1		1	6	25	0.6
7	Mobility (indoors)			4	8	21	0.462
8	Mobility (outdoors)		1	3	9	20	0434
9	Positioning child for hygiene tasks		1	8	6	13	0.35
10	Child being accepted by other pupils	3	1	9	5	15	0.29

3.3.1.3 Accidents

10 of the respondents (30%) reported having seen or being involved in an accident that involved a child using an adaptive seating system. Incidents reported included-

- Chair tipping over after hitting a kerb while going round a corner downhill.
- Several respondents reported having been injured when they had been run into by chairs; main injuries were bruised ankles caused by wheels and footplates, sometimes due to faults with the braking system.
- Faults with tilt-in-space functions- chairs tilting backwards or forwards too quickly (JCM chair from JCM Seating solutions Ltd, Peterborough, UK) or in an uncontrolled manner causing injury to the occupant of the chair.
- Worn straps allowed child to undo safety belt and subsequently fall out of chair.

3.3.1.4 Coping with growth patterns

9% of staff were not at all satisfied with the way adaptive seating systems cope with the growth of the child, 12% were somewhat satisfied, 49%, 24% and 6% were quite satisfied, very satisfied and extremely satisfied respectively.

3.3.1.5 Repairs

Of the 12 teaching staff member respondents (36%) who reported having to carry out repairs on adaptive seating systems, the majority of items mentioned were regularly performing basic maintenance such as tightening brakes and tightening nuts and bolts that had come loose. Five respondents (15% of the total sample) reported having to adjust and replace postural supports.

3.3.1.6 New or replacement models being issued

In total, 12% of teaching staff members were not at all satisfied with the current provision of new or replacement adaptive seating systems, 27% somewhat satisfied, and 40%, 18%, and 3% were quite satisfied, very satisfied and extremely satisfied respectively.

3.3.2 Parents

The children of the parents and guardians who completed the study attended a range of nursery, primary and secondary special needs schools and had used an adaptive seating system for a mean of 6.4 years (SD 4.8 years). In total, there were 17 suitable respondents from this group, from a total of 32 questionnaire packs that were distributed to schools (a response rate of 53%). Out of all the parent respondents, seven knew the make and/or model of seating system their child used. There were four CAPS II systems (Active Design, Birmingham, UK) reported to be in use, plus one Jenx Whale (Jenx Ltd, Sheffield, UK), one JCM Star X (JCM Seating Solutions

Ltd, Peterborough, UK) and one Lomax (model unknown) system (Lomax Mobility, Dundee, UK).

3.3.2.1 Rating of functions

Table 3.2 shows the ratings given to the chosen functions of adaptive seating systems by parents.

Table 3.2 - Finctions of adaptive seating, rated by importance by parents and guardians of children attending special needs schools. Subjects were asked to rate the importance of the function. The choices were: 1 – of no importance; 2 – of very little importance; 3 – somewhat important; 4 very important; 5 extremely important.

Rank	Function	Ratings					Pr(a)
		1	2	3	4	5	
1	Postural support					17	1
2	Providing comfort				1	16	0.882
3	Postitioning child for eating tasks				3	14	0.691
4	Preventing the development of deformities				4	13	0.618
5	Child interacting with carers and others				5	12	0.559
6	Child's well being and self-esteem			2	2	13	0.588
7	Positioning child for hygiene tasks			1	4	12	0.529
8	Child being accepted by peers			1	5	11	0.478
9	Mobility (outdoors)			2	4	11	0.456
10	Mobility (indoors)			3	4	10	0.397

3.3.2.2 Transfer time

The estimated time parents spent transferring their child to and from their seating systems during the course of a normal day was found to be on average 86 minutes (SD 55 minutes).

3.3.2.3 Accidents

Parent respondents reported one accident. This was considered by the parent to be a relatively minor incident and involved the hip strap catching the child's stomach.

3.3.2.4 Coping with growth patterns

In total, 12% of parents were not at all satisfied with the way currently prescribed adaptive seating systems coped with the growth patterns of children, 29% were somewhat satisfied, and 35%, 18% and 6% were quite satisfied, very satisfied and extremely satisfied respectively.

3.3.2.5 Repairs

Almost half of the parent respondents (47%) reported having to perform minor repairs on their child's seating system including: tightening brakes; fixing footrests; and adjusting postural supports including harnesses.

3.3.2.6 New or replacement models being issued

Of all parent respondents, 24% were not at all satisfied with the current provision of new or replacement adaptive seating systems, 29% were somewhat satisfied, and 35%, 12% and 0% were quite satisfied, very satisfied and extremely satisfied respectively.

3.3.3 Rater agreement and comparison between groups

Overall reliability of agreement as measured using Fleiss's kappa was 0.085 for the teaching staff group and 0.015 for parent group. The relative observed agreement (Pr(a) in Tables 1 and 2) may prove more insightful with the functions rated to be most important tending to gain the highest levels of agreement. Performing the Mann-Whitney test to compare ratings between teaching staff and parent's views found only one item to be rated significantly differently, the "child being accepted by his peers" function ($\alpha = 0.05$). Using the same test on the coping with growth

patterns and provision of new or replacement systems ratings found no significant differences between the two groups' satisfaction levels.

Table 3.3 – Additional comments by both teaching staff and parents. If known, the seating system in question has been noted

Complaint	Comment
Time taken to replace or repair chairs	'For children who are severely physically disabled [seating systems] can take a long time to arrive and repairs or alterations can be slow – thus having a major impact on the child's quality of life' 'There is often a long wait for wheelchair assessments for our local service' 'Very slow to provide new seating as child grows' 'Children have to wait for too long to get new seating systems' 'The amount of time that we have to wait when new seating is required is very slow' 'Such a long waiting list. You have to think long before you need the chairs' 'New seating systems take too long to get ready. A new one is not ordered until the child has outgrown the old one and then it can take up to a year for the new one to arrive' *Caps II*
General faults	'Hydraulics frequently breakdown' 'Brakes jamming on whilst moving' 'Brakes seem to brake [sic] often' 'Also we wish chairs could be made with covered screws and bolts so we did not have to do it ourselves. Our daughter has lots of involuntary movements' *Jenx Whale*
Non-carer friendly chairs	'School chairs especially can be cumbersome and difficult to push causing damage to backs and knees of staff (less of a problem in nursery and primary: smaller chairs but also newer models)' 'Hard to push' '[It] has a million nooks and crannies and is really difficult to clean' *Jenx Whale* 'Difficult to clean. Easy [to] clean and remove covers would be good'
Easy for unqualified individuals to make changes to set-up of systems	'Adjustments made by OT are easily 'undone' by less skilled/careful carers staff members > poor positioning a risk esp[ecially] when eating and drinking'
Aesthetics	The style of a lot of seating is not very nice to look at. There is not a good choice of buggies out there. Some kids/parents do think about what other people think when they look at ugly seating'

Other	'Staff/parental perception of chair can be a bigger hindrance than the chair itself. Differences between chairs and keeping various agencies up-to-date can also cause problems'

3.3.4 Additional findings

A number of specific complaints and comments were also given by the respondents and have been noted in Table 3.3.

3.4 Discussion

Adaptive seating has a number of purposes in the treatment and alleviation of neuromuscular disorders (Clark et al., 2004; Mao et al., 2006; McDonald et al., 2003). The findings of the current study show that the functions of adaptive seating thought to be most important were similar for both teaching staff members and parents. Providing support, providing comfort, positioning for eating and preventing the development of deformities were the most highly ranked functions and were all consistently rated as extremely important by the majority of respondents, a finding that does not fully support findings that parents are generally more concerned about the more functional aspects of adaptive seating compared to therapists (McDonald et al., 2003). In addition, the fact that rater agreement for these functions was the highest in these groups would tend to further confirm the groups' awareness of both the long and short term goals of using adaptive seating. The high ranking of the providing support and preventing deformities suggests that parents may be becoming more aware of the intended long term benefits of adaptive seating. In a previous survey of forty adult adaptive seating users which looked specifically at tilt and recline systems, comfort was shown to be the most highly rated objective of use (Lacoste et al., 2003), a finding which is backed up by the results from this investigation (postural support and the prevention of deformities were not given as an option in the earlier study). Differences between the two groups' rating of the functions was also of interest as it was believed that this may give additional insight into the groups' perceptions of adaptive seating. For example, teaching staff would

generally be expected to, over time, come into contact with a larger number of adaptive seating users than parents, and it was thought that this would perhaps give them a different opinion on some of the areas investigated. In fact, the only function that was found to be statistically different between the two groups was "child being accepted by peers" which was rated more highly by parents than by teaching staff, a finding that suggests parents have a slightly greater concern for their child's overall place in society.

It has been shown that over one hour of teaching staff's time per day is taken up by transferring pupils between and to and from seating systems. This is to some extent due to the health and safety requirements put in place to prevent injuries to the staff and the individual being lifted ("Health and safety matters for special educational needs: moving and handling", 2006). As well as taking up a large proportion of staff time, this finding suggests that the child may be missing out on valuable teaching time while staff are busy transferring them or their classmates. Parents reported spending a similar amount of time on transfers. There would seem to be some potential in this area for improvement, mainly in terms of developing equipment which could reduce the overall time required for transfers.

A number of points were brought up that could be of use both to seating services and to seating manufacturers. Of those who responded, 36% of teaching staff and 47% of parents declared that they had carried out repairs to seating systems. The fact that they are carrying out these repairs is in itself a worry, especially if the systems have been set up to treat a specific condition and supports are being repositioned by individuals - however well intentioned – who do not have the necessary training or experience to carry out the task. Some repairs, such as tightening the brakes, are of lesser consequence but the fact that a number of respondents made comments complaining about these problems (Table 3.3) does suggest that perhaps more reliable components or regular servicing is required for some systems. Accidents that involved seating systems were also reported by 32% of the teaching staff but by none of the parents (this is possibly due to the fact that teaching staff members come into contact with a far greater number of children in seating systems). Most of these

incidents resulted in relatively minor injuries to a member of staff (usually no more than a bruise) rather than the user but several more serious accidents were mentioned, including a child falling out of a seat and faulty tilt-in-space mechanism tipping a child backwards too quickly. This suggests that perhaps there are some safety issues which may need addressed. Comments were also made about chairs being "cumbersome" and "hard to push", a problem that has been previously noted ("Moving Forward: Review of NHS Wheelchair and Seating Sevices in Scotland", March 2006), and should be addressed in future systems. The ranking of the various functions of adaptive seating in terms of importance could also be of interest to designers when they are developing new systems.

A number of respondents felt strongly that there were problems with the speed at which new or replacement systems are being issued, more so with the parents with almost half describing themselves as being either 'not at all satisfied' or 'somewhat satisfied', the two lowest available ratings. This is reinforced by a recent government survey on wheelchair and seating provision where it was found that 37% of the respondents had to wait over six weeks to be issued a new chair ("Moving Forward: Review of NHS Wheelchair and Seating Sevices in Scotland", March 2006). A similar proportion of respondents in this survey expressed dissatisfaction with the way seating systems cope with growth patterns of their young users and an additional six comments were complaints regarding the time spent waiting for assessments, repairs and having to think well in advance of time about new seats, by which time the user's condition may have changed and the replacement seat might no longer be appropriate. These additional comments would appear to emphasise the strength of feeling on this matter, and were from both parents and teaching staff. Providing equipment that copes better with the growth of its user could help to reduce the pressure on seating services as well as improving the comfort of the child (Cox, 2003).

The dissatisfaction felt by a proportion of the respondents about the time taken to repair and replace systems raises concerns, especially because the children are at an important stage in their development. Reducing their mobility and having them

using an inappropriate system at this stage could potentially cause problems in later life.

This study has several potential limitations. A distinction was not made between seating systems that are provided by the National Health Service (NHS) and those which are purchased privately, (although it should be noted that the majority of pupils at the schools visited had had their chairs supplied by the NHS). The relatively small sample size, combined with the low number of parents who were able to tell us the type of seating system their child used meant that it was not possible to specify if problems tended to be related to specific makes of seating system. There is the opportunity for some response bias in this study, perhaps especially in the parent responses where those parents who are completely happy with their child's seating system are less likely to take the time to complete and return the questionnaire. As always with research in this area, each adaptive seating user is a distinct case and it is difficult to draw conclusions which can be applied across a large proportion of the population. Findings should be used with caution and in conjunction with advice from experienced individuals and the other evidence from the existing literature. However, despite this and the fact that the results presented here are mainly descriptive, it is believed that they still hold some clinical relevance and could be useful in the development of new adaptive seating systems.

3.5 Conclusion

The work presented in this chapter raises some important points about the current state of adaptive seating as viewed by the individuals who live and educate these children on a daily basis. There remains definite scope for improvements to be made in this field. Devices which reduce the time demands of transferring the users to and from their systems would be beneficial, especially in the educational environment. Systems which can more effectively accommodate the often non-linear growth patterns of users could also be a welcome development. The number of both teaching staff and parents taking part in this survey who have had to carry out repairs

to a seating system is a cause for concern and would suggest that more attention should be paid to the development of new safety measures and procedures. The opportunity remains for studying the same items investigated here in adult adaptive seating users and their carers, and future research should include the development of new systems designed to perform better in these areas.

4 Design Methods and Results – Novel Adaptive Seating System

4.1 Introduction

In the preceding chapters of this thesis, a number of aspects relating to current adaptive seating technology and provision which may have some scope for improvement were identified. This chapter describes how, by drawing on these findings and by considering the "Meyer system" (described in the following section), the main objective of this project, the design of a novel adaptive seating system, was accomplished.

At all stages of the process standard design methodologies were used (mainly adaptations of those described in French (1992) and Pahl & Beitz (1984)). Briefly, a short design brief was prepared, stating the main aim of the device in a single sentence. Following this, an objectives tree was produced which divided the aim into more specific objectives relating to aspects like function and performance, reliability etc. This was then expanded into a detailed product design specification (PDS) which defined the requirements of all aspects of the system. Concepts were generated for the individual functions the seating system was intended to perform and were assessed using an evaluation chart made up of the key requirements drawn from the PDS (expanded upon in section 4.3.3). This process was repeated over several iterations of concepts and overall combinations of concepts until the optimum design was identified.

For reasons of conciseness it would be inappropriate to go into the full details of all the processes carried out at the various stages of the system's development. Therefore, the design processes have only been loosely portrayed here with some complete examples of the documentation produced being included in appendix B. In addition, in order to give the reader an accurate picture of the system, the main iterative stages of the development of each main assembly unit have been described along with the final solutions, and the reasons for choosing these solutions.

All of the 3D modelling presented in this chapter was carried out using the computer aided design (CAD) software Solid Edge V14 (Siemens PLM Software, Plano, Texas, USA).

4.2 Background

At conception, this project was intended to be based entirely around the development of an adaptive seating system that had been designed by Dr Paul Meyer, a practicing ophthalmologist at Addenbrooke's hospital, Cambridge (please see chapter 1 for details on how the project came about). Dr Meyer's daughter, Rebecca, now aged 21, has quadriplegic CP and has used some form of adaptive seating from an early age. As she was growing up, Dr Meyer became dissatisfied with the seating systems that were available for her and he set about constructing one of his own design, based around the principles that he believed worked best for Rebecca. At the time of writing Rebecca will have used this system or a variation of it for close to 12 years. Dr Meyer believes that the system contributed significantly and positively in Rebecca's development and provided her with a number of functional and postural benefits.

Figure 4.1 – A fully rendered 3D CAD model of the Meyer adaptive seating system. It is shown here in manual mode and without the custom moulded cushion that the user sits on.

Based on these claims, during the initial stages of the project a 3D CAD model of the Meyer system was created in order to gain a full understanding of how it was fabricated and assembled. This model is shown in Figure 4.1. At first glance the system appears to be a rather radical departure from current standard seating systems, but in fact the majority of the basic elements remain: there is a backrest to support the trunk; a detachable powered base; it has the ability to tilt or recline; and there is a custom moulded cushion which has been produced from a cast of the patient as the seatbase (not shown in Figure 4.1). The backrest is unarguably the most novel feature of the design. It supports the user's trunk with mainly angled lateral forces rather than standard posterior support in an attempt to reduce hip extensor tone by reducing stimuli to the posterior surface of the trunk (Figure 4.2). It is also intended to be dynamic in nature, i.e. it is pivoted at a point below the seatbase and the forces applied by the user in hip extension are balanced using shock cords. Thus, when varying extension forces are applied the angle of the backrest to the seatbase alters.

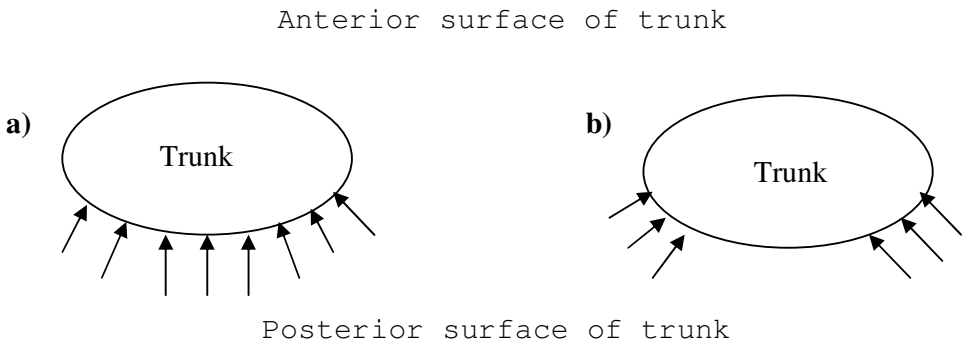


Figure 4.2 – Forces applied to trunk in a) standard seat and b) Meyer support

The system was constructed using only basic tools in Dr Meyer's garden shed, and as a result certain aspects of the design are fairly ramshackle and would be inappropriate for a commercial product. During the initial analysis of the design, a number of these issues that would need to be addressed as part of the development process were identified. These included-

- *Aesthetics*: the importance of the overall look of the seating system should not be underestimated. The psychological effect that its appearance can have on the people who come into contact with it and their subsequent reactions can have a strong effect on the user's self esteem. Indeed, the user being accepted by his/her peers was shown to be considered an extremely important function of adaptive seating by the majority of respondents in the parent and teaching staff investigation (chapter 3).
- *Material choices*: the Meyer system is primarily constructed from stainless steel tubing and brass connecting blocks. With weight playing an important role in the system's mobility and range, not to mention affecting its user friendliness with respect to the carer being able to push, manoeuvre and lift it (into a car boot for example), materials with better strength to weight ratios such as aluminium alloys and plastics need to be considered. Certain elements of the stainless steel frame which are put under relatively low stresses could also be re-designed and/or replaced with lighter materials.
- *Designing for manufacture*: complex tubular frames such as the ones used in the Meyer system need to be designed with computer numerical control (CNC) pipe-bending machines in mind if they are to be built cost effectively and in large numbers. More standard components need to be incorporated in order that fabrication times and machining costs can be reduced.
- *Safety concerns*: Safety issues and conformation to British and international standards have to be addressed ("BS ISO 7176: Wheelchairs" is perhaps the most relevant). A number of potential finger traps were identified that must be removed from the design. Originally, there was some discussion about designing and testing the system with a view to making it suitable and legal for use as a car seat, however the cost of the safety testing required to achieve this meant that it was not feasible.
- *Incorporation of additional features*: provision should be made for attaching standard supports such as knee blocks and various safety belts and harnesses plus other, more functional features like work surfaces, umbrellas, computer interfaces.

- *Powered option for tilt and recline features*: in order for the tilt or recline functions to be activated by the user without requiring the help of a carer powered options should be introduced.

After discussion with a number of experienced seating clinicians however, it became apparent that there were a number of additional issues with the Meyer system that went beyond the basic design factors mentioned above. Firstly, dynamic backrests – initially thought to be an original feature - are already available in certain adaptive seating systems where they are used to help deal with abnormal muscular tone and spasms (see the Zitzi Delfi from Anatomic Sitt AB (Norrköping, Sweden) for example). Second, Dr Meyer's belief that the system could improve posture and prevent deformities occurring must unfortunately be treated with a degree of scepticism since Rebecca required spinal fusion surgery when she was 15 to prevent any further progression of her scoliosis. Of course, it is not possible to tell by this single case whether the seating system had any effect, positive or negative, on the progress of the scoliosis, but since, as discussed in chapter 2, one of the main aims of any intervention of this type is to prevent the need for surgery, it would appear to be unlikely that there was much, if any, slowing effect. During the course of these discussions it also quickly became apparent that due to the nature of the conditions these systems have to accommodate it would be highly unlikely that any one system could provide an "across-the-board" solution that would be highly beneficial to all of these users. Indeed, it was thought that there could be difficulties involved with finding even a small but suitable population to test the Meyer system on.

Looking at the system from a biomechanical perspective, there are also some potential problems that need to be addressed. The reduction in the overall surface area of support given by the backrest, notwithstanding the proposed neuromuscular benefits, could potentially lead to skin breakdown on the posterior surface of the trunk due to concentrated areas of pressure and shear forces. In addition, attempting to influence the neuromuscular system in this manner can have unpredictable results, and current practice would suggest that maximising the area of support provides the most benefit in terms of tone reduction. The lack of support at the lumbar region of

the spine could also lead to problems in the long term if the user if an upright posture cannot be maintained and slouching occurs. There may also be issues in the short term if there is any rotational movement associated with hyperextension of the hips as the backrest is not designed to accommodate these.

In light of these issues, and with the more general findings from the literature review and the parent and teacher study in mind, the aim of the project shifted from the original objective of developing the Meyer system to coming up with a more distinct and widely applicable design, although some of the aspects of the Meyer system were to be retained. The key remaining feature was the stimulus reducing backrest (see section 4.3.5.6), although the overall design of the backrest was distinctly altered. Dr Meyer should also be credited with the suggestion for having the seatbase able to tilt in both the coronal and sagittal planes, although again it was quickly discovered that several existing seating systems had this feature (Dicianno et al., 2008).

4.3 Development of novel seating system

4.3.1 Design brief

In its simplest form, the design brief for this objective of the project was stated as follows:

"To design a novel adaptive seating system, primarily for children with neuromuscular disorders, that aims to improve posture, increase functionality, and reduce discomfort".

4.3.2 Product design specification

Drafted near the beginning of the design process, the product design specification (PDS) outlines what the novel system is intended to do and the criteria that it should meet. Prior to writing this document, an exploration of the needs that had to be met

was carried out and this work is presented in the form of an objectives tree (Cross, 1989) in appendix B. Building on this, a problems/solutions tree was devised, and then a quality function deployment chart (Ullman, 1997) produced. This document allows user requirements to be related to quantified technical requirements that can be used to evaluate design solutions. Reproduced in the following sections is the full and original version of the PDS. During the course of the project certain criteria did change and section 4.3.8 notes and explains these changes and any other objectives set in the PDS that were not able to be met.

4.3.2.1 Function and performance

-Function

- Should provide functional support for users who, as a result of their condition, have restricted breathing
- Should provide functional support for eating/swallowing
- Should provide functional support for social interactions, i.e. gesturing and allowing eye contact to be maintained, thus allowing improved capability to participate in educational or community settings
- Should attempt to reduce anterior/posterior stimuli, thereby potentially reducing gross motor response
- Must allow users who are non-ambulant or have reduced ambulation greater mobility, thereby resulting in increased independence
- Should help to improve control of or provide structural support for users who have difficulty controlling their head and trunk
- Should attempt to prevent the development of new skeletal deformities and attempt to stabilise or slow the development of existing deformities, such as scoliosis or similar conditions
- Should allow a user with severely restricted movement of limbs to independently adjust their own comfort in terms of tilting or reclining the system in the sagittal plane. These positional adjustments should not reduce the effectiveness (in terms of positioning) of other supports
- Should assist the user in transferring from sitting to standing

- Should be a modular unit which can be used with standard minimally modified powered wheelchair bases
- Should also be able to be used as a manual wheelchair
- If possible should be able to be used as a car seat
- Adjustable elements should be able to be locked in place by carer if the user is required to be held in a stationary position
- Should allow a reduction of the amount of care required from the caregiver
- Should provide support to allow easy transferral of the user to and from the chair
- Should be compatible with standard wheelchair cushions and custom moulded seats

-Performance

- Should attempt to prevent the induction of decubitus ulcers
- Should be designed to maximise the users freedom of movement and maximise their function, particularly of their hands and arms, dependent on their condition
- Should have a level of adjustability that will allow the maximum number of users to be able to use the system and also allow for growth in younger users
- Should provide user with a level of comfort that will not cause them to try and abandon the seating system
- Weight distribution and positioning of system should maximise the efficiency of the powered base in terms of power use and manoeuvrability.
- Conversion from manual chair to powered unit or vice versa should be achievable by a single carer in <1min and should not require the user to be taken out of the system

-Operation

- Should have an unloaded weight of <5kg
- Should be easy to manoeuvre and control, both for the user and for his/her carer

-Service Life

- Should be designed with the expectation that the system will be in almost constant use for 16 hours a day, 365 days a year
- Should have a functional life of >10 years (note: use of the system may be restricted by the development of secondary conditions such as scoliosis which cause skeletal deformities that could prevent the use of this system)

-Availability, Reliability, Maintainability, and Safety (ARMS)

- Components should not suffer any loss of performance e.g. seizing or rusting during periods when the system is not in use.
- Should have smooth, clean contours with no sharp edges or finger traps which could be potentially hazardous to the user or carer.
- Should be able to withstand knocks and collisions (e.g. with door frames) without loss of performance or at least without irreparable damage.
- Should have a mean time to failure of approximately 50,000 hours
- Any electronic components must be electrically insulated

4.3.2.2 Support

-Testing

- Integrity of the structure and reliability of mechanisms will need to be assessed
- Clinical testing will most likely take the form of trials involving an assessment of user interactions with the system and instrumentation of key components of the system to allow analysis of changes to the user's posture, behaviour, pressures distributions etc.
- In terms of commercialisation, the system must conform to specifications stated in regulations governing seating systems (see regulations section) in order for it to be CE marked

-Storage and Packing

- Should reduce down into a compact unit that can fit into a standard car boot, dimensions approximately 1000x750x500mm

-Product Documentation

- Provide setup instructions for rehabilitation centres
- Provide clear, easy to understand operating instructions for the user/carer
- Provide rehabilitation centre or user/carer with list of spare parts that are available

-Installation

- Should require minimal setup from packaged unit, achievable in <1hour with standard tools
- Should be easily secured to a powered wheelchair base unit in <1min. This attachment should be intuitive and it should be obvious when attachment is complete
- There should be comprehensive training for the user, carer and/or family of how to operate the system. This may involve demonstrations and short trials
- In order for the user to develop seating tolerance to the system it may be necessary to introduce the user to the chair gradually and build up the amount of time spent in it over a period of months

-Servicing

- All parts/components should be able to be replaced using standard tools
- A standard procedure for servicing should be developed which ideally should take <30mins
- Servicing should be required at intervals > six months

-Spares

- A range of spares should be available for wear and tear items
- Where possible, standardised components should be used

-Disposal

- Where possible, the system should be made of recyclable materials
- System should be readily stripped down to its constituent components for ease of sorting for disposal and recycling

4.3.2.3 Appeal

-Competition

It is estimated that there are at least 20 different seating systems available worldwide (from discussion with seating clinicians along with internet searches). The systems mentioned here are those that the author came into contact with most frequently during the early stages of the project and are believed to form a representative sample of the most popular systems used in the UK. Significant design features have been noted.

- *CAPS II system from Active Design Ltd* (Birmingham, UK)
  Modular unit, wide range of adjustable but static supports including knee blocks and pelvic supports. No active tilt or recline function.
- *Zitzi Delfi from Anatomic Sitt* (Norrköping, Sweden)
  Designed specifically for children with high and fluctuating extensor tone. A flexible plastic component is used to join the backrest to the main unit of the seat making it a dynamic support system.
- *WATC-06 from Nicecare Co. Ltd* (Taiwan, Republic of China)
  Tilting and reclining ability through pneumatic system, but carer operated. Adjustable but static supports. It is a full wheelchair system, not a modular unit adaptable to current standard chairs. Not particularly aesthetically pleasing.
- *Contoured Advance Seat from Leckey* (Dunmurry, UK)
  Has the option of a single piece or split backrest to accommodate a wide range of users. Base unit allows for adjustable height.

-Customer Requirements

- Must be available at a price that is competitive with currently prescribed systems

- Must require minimal technical maintenance
- Should be able to be easily refurbished for use with another patient

-Market Characteristics

- Seating system should ideally be made available through the NHS but users could have the option to purchase it privately

-User Characteristics

- Users may have severely restricted postural control and reduced movement motor control as a result of conditions such as CP that the system must take into account
- Users may also have developed physical deformities that must be accommodated and/or managed. These deformities may be secondary to another condition i.e. CP can often lead to scoliosis
- Users may have additional symptoms secondary to their condition that may have to be considered.
- Other relevant users who could benefit from the system are those with neuromuscular disorders such as Duchenne's Muscular Dystrophy

Note: It is worth clarifying at this point why the novel adaptive seating system has been designed for use mainly with children. The bones and soft tissues of younger subjects are more flexible and malleable than those of adults (Currey & Butler, 1975; Kubo, Kaneshisa et al., 2001), and it is for this reason that their condition puts them at a high risk of developing skeletal deformities such as scoliosis. If these deformities are prevented or their rate of progression slowed until skeletal maturity, when the bones and soft tissues modulus of elasticity has increased and the patient is at less risk, it may reduce the number of surgical procedures they will need to go through and generally improve their quality of life. Of course, many of the features on the new system, especially the multi-planar tilting base, may also be applicable to adult adaptive seating users and the level of adaptability aimed for would certainly make it possible for adults to use the system as well.

-Aesthetics

- Should appear attractive and unobtrusive to avoid adverse psychological effects on the user and other people
- Should improve the user's self image
- Should appear easy to operate

-Ergonomics

- All user control elements must be simple to operate and should take into account the fact that the user's condition may make it difficult for them to operate standard controls
- All support elements of the system should be designed with reference to the most comprehensive ergonomic data available for CP children. (Work that has been carried out in this area is limited, but the most useful resource that has been found is the study carried out by (Hobson & Molenbroek, 1990)
- All carer interfaces should be ergonomically designed for 5^{th} percentile females and 95^{th} percentile males.

4.3.2.4 Supply

-Project Cost

- The design of the system and fabrication of a working prototype for testing should cost < £4000 (not including the running costs associated with the EngD course)

-Project Time Scale

- Fully functioning prototype of commercialised design built and tested (including some clinical experiments) by May 2009

-Target Selling Price

- Basic system should have a recommended retail price of <£1200 (comparable with CAPS II system)

4.3.2.5 Conformity

-Environment

- Should withstand exposure to operating conditions between -5º and 40º Celsius without any loss of performance

-Effect on Environment

- Current regulations relating to disposal and recycling must be taken into account. Most relevant is perhaps BIP 2117: The waste electrical and electronic equipment directive. Requirements and implementation

-Standards and Regulations

- BS ISO 7176 (for general wheelchair standards)
- BS ISO 10542 (for restraint systems)

4.3.3 Concept generation and evaluation

Before beginning to produce ideas for the novel system, a number of criteria that would be used to appraise the different concepts were identified. By identifying these criteria before concept generation, it prevents bias towards any one idea. The criteria were drawn entirely from the PDS. Functional analysis was then performed to determine the various sub functions that the novel system needed to perform. Separate solution concepts for each sub function were generated and arranged using the morphological chart method (Cross, 1989). These concepts were then evaluated and the most highly rated sub function concepts were combined into a number of viable concepts for the total system. Finally, a variation on the controlled convergence method (Pugh, 1991) was used to evaluate these final solutions and a final concept chosen.

4.3.4 Material and component selection, failure mode, effect criticality analysis and final engineering drawings

Having decided upon the basic concept that would evolve into the final design, the next stages were to carry out the processes required to ensure the system's feasibility, safety, and to allow it to be fabricated.

Strength calculations were carried out for loaded elements and along with weight and other considerations this guided the material selection for each component. Safety factors of four or greater were used in all calculations. Components were selected from supplier catalogues and product documentation used to ensure they had suitable reliability, tolerances etc.

Failure mode, effect critically analysis (FMECA) is a tool that is used to find component or material failures that may occur and the effect that this failure may produce, the frequency of these failures and the criticality that these may have for the user. The process involved is described fully in BS 5760, 'Reliability of Systems, Equipment, and Components'. It was used in this project, before finalising the design and prior to the fabrication of the prototype, mainly to identify a number of weak points in the design that could be a safety hazard.

To facilitate the construction of the prototype a full set of engineering drawings were produced for the novel system. These were drawn with reference to BS 8888:2004 'Technical Product Documentation'. To describe all the relevant parts and assemblies over 100 drawings were required; therefore only the set relating to the tilting mechanism assembly (this assembly was randomly selected) have been included in appendix B.

4.3.5 Final design

The final design (shown in Figure 4.3) was the result of several months work over the course of 2007/8. The following section describes the system broken down into its primary functions and states which assemblies relate to these functions.

Furthermore, due to the overall complexity of the novel design, the system has been broken down into its separate assemblies (the modular nature of the design makes this possible) with a discrete section giving an overview of the development of each assembly and the thinking behind it, plus any major problems that were encountered along the way (see Figure 4.4 for exploded view of assemblies).

4.3.5.1 Key functions

Providing postural support *(see related assemblies: Seatbase, Armrests, Backrest, Footrests, Lateral supports, Kneeblock)*

A number of components of the design combine to provide support for the user. One of the main principles on which the design has been guided by is that of dynamic support, and allowing the chair to move with the user to some extent. The aim of providing this support is to allow the user to have better functionality in their chair as well as longer term benefits.

Preventing deformities *(see related assemblies: Seatbase, Backrest, Kneeblock)*

This is a difficult subject because of the lack of solid evidence for the effectiveness of standard orthotic devices preventing or slowing the development of deformities, never mind one that features a new design.

Reducing discomfort *(see related assemblies: Tilting mechanism, Seatbase, Armrests, Backrest, Footrests, Lateral supports, Knee blocks)*

The ability to tilt the seat base in more than one plane is important for increasing the user's overall level of comfort. As well as this, all the supports have been made as adjustable as possible to increase the options of positions for the user. This ability is especially innate in the backrest.

Mobility *(see related assemblies: Powered base, Front castors)*

The system has a custom designed powered base that can be easily removed and the system changed to a manual system. This can be carried out by a single carer.

Figure 4.3 – Rendered CAD model of final design. It is shown here in powered mode and with all orthotic supports in place

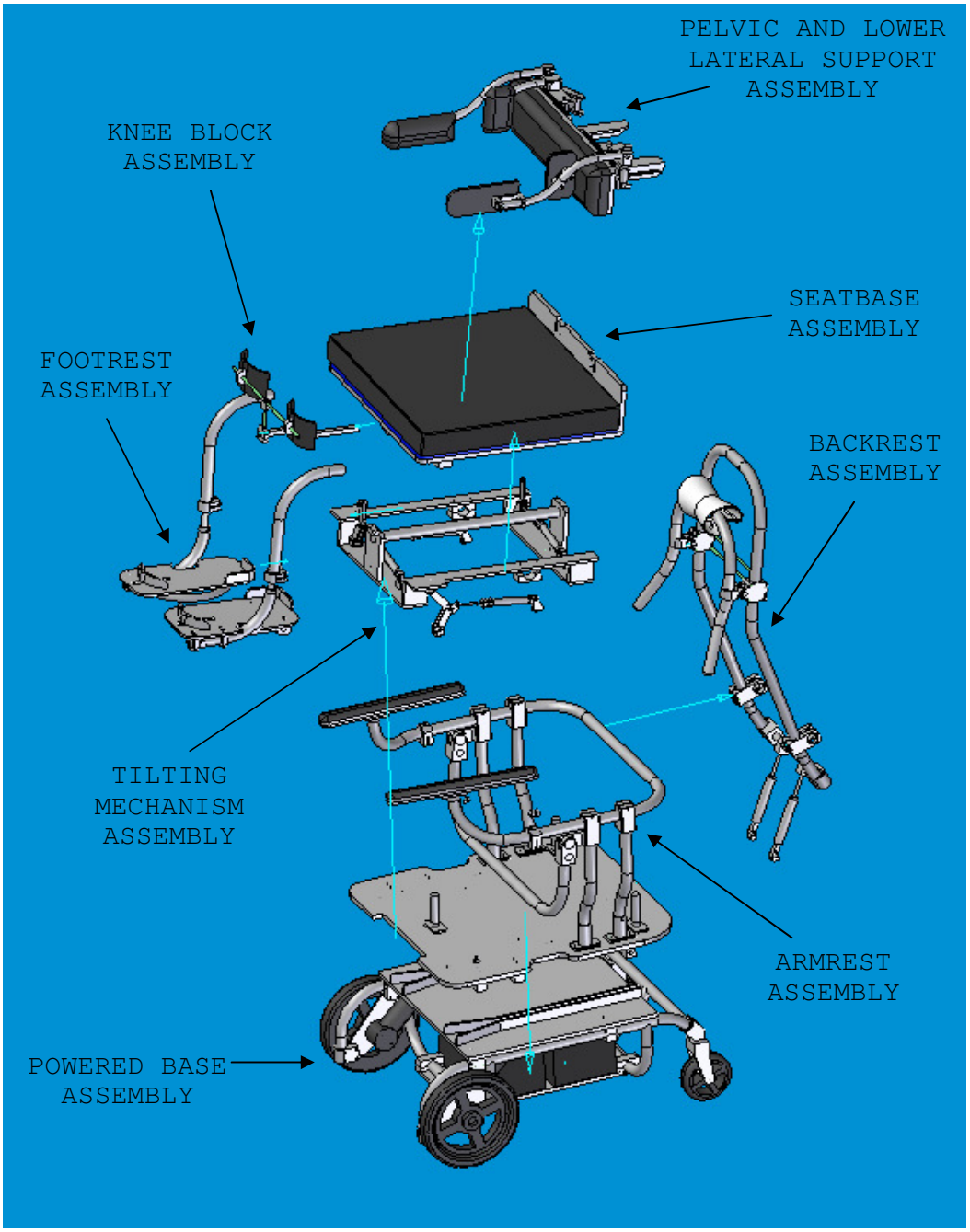


Figure 4.4 – Final design exploded assembly view

4.3.5.2 Powered base

Function: to provide easily controllable mobility to the system without the need for manual propulsion.

Many adaptive seating systems (i.e. the CAPS II (Active Design Ltd, Birmingham, UK) and the Advanced Seating System (Leckey, Dunmurry, Northern Ireland)) come as a modular unit that can be used with a variety of base units, either powered or manual, which provide mobility to the whole system and that can be in various configurations, for example: adjustable in height for the teaching environment. The option of buying in a powered base unit from an existing manufacturer and designing the novel system to suit it was considered, but it quickly became apparent that the retail costs of these units made this course of action unviable. This decision was also influenced by the fact that there was an unused electric wheelchair in the department where the project was based that parts could be scavenged from. Therefore, it was decided to design a simple but functional base unit that would provide motorised mobility to the main seating system. This approach also allowed the unit to be customised to incorporate features that it may not have been possible to modify an existing base to have.

The main objectives for the powered base unit were that it had to be able to be controlled by either the user or their carer; it had to give the system a high level of manoeuvrability; and it needed to be easy to remove from the main system so that the system could be changed to manual mode.

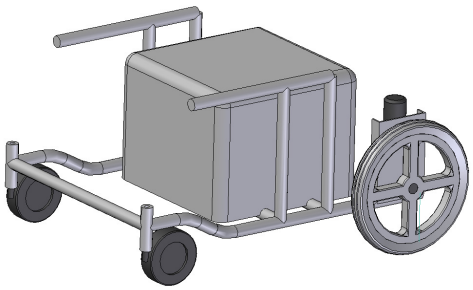


Figure 4.5 – An early version of the powered base unit

Figure 4.5 shows one of the early ideas for the base. It is very basic and probably structurally unsound, although all the key components are in place. It would have been difficult to find suitable casters for this set up. Another slightly more

adventurous solution that was considered at the concept generation stage was a six wheel version of the base with freely rotating casters at both ends and the powered wheels in the middle. It was thought that despite giving the system excellent manoeuvrability it may overcomplicate the system and require modifications to the control system as well as taking the emphasis away from other key areas of the design.

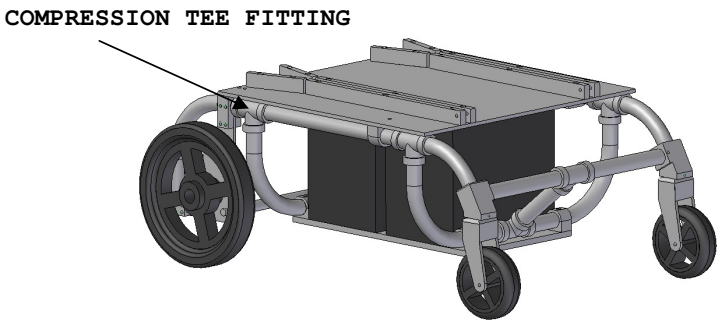


Figure 4.6 – Final design for powered base unit (prototype version; note plumbing fittings to connect tubing)

In the final design for the powered base (Figure 4.6), the default configuration has the driven wheels at the front of the system and the free turning casters at the rear, the opposite set up to the majority of powered chairs. This arrangement allows for more manoeuvrability indoors, i.e. if approaching a table or going up a ramp. The configuration can be quickly reversed to the more standard set up, if required, with only minor adjustments to the base needed.

The positioning of the main system on the base can also be varied. This is important because the rolling resistance encountered by the wheels is a major factor in the energy used to propel the system (Kauzlarich & Thacker, 1989) and thus the battery life and range that can be achieved. By altering the position of the centre of gravity in relation to the two axles, the rolling resistance encountered by the wheels can be altered and an optimum position can be found (Cowan et al., 2009), while of course maintaining the stability required to ensure the user's safety. As the user grows, their sitting position in relation to the system will also change and the location of the main

unit will need to change in order to maintain the optimum position for minimal energy use and this can be easily achieved by adjusting the position of the stoppers on the base.

Although technically part of the armrest assembly, to allow the powered base to be easily removed from the main part of the seating system it was decided to make use of the pneumatic equipment which was in place for the tilting mechanism (see section 4.3.5.3). Three short (25mm stroke) pneumatic cylinders were mounted vertically on the base plate of the armrest assembly (described in section 4.3.5.5), and when actuated, these lift the main system assemblies up off the powered base. This allows the large manual wheelchair wheels to be attached at the back and the fold out casters (section 4.3.5.10) to be deployed. When the cylinders are returned to their retracted position the weight of the remaining assemblies is taken by the back wheels and fold out casters. A gap of around 10mm (depending on the floor surface) is left between the powered base and main unit, allowing the powered base to be easily reversed out from underneath the system using its own power and controls. To change the system from manual to powered mode the process is simply reversed. The switching of mode can be carried out by a single carer whilst the user is still in the seat. One drawback with this aspect of the assembly is that the large manual wheels are kept separate from the main unit, and thus could potentially get lost, or be at a different location when required.

4.3.5.2.1 Modifications for prototype version of powered base

As mentioned previously, to reduce the costs related to the prototype version of the powered base several key components, including the batteries and motors, were scavenged from an existing electric wheelchair owned by the Bioengineering Unit. In addition, a beau-type wheelchair controller was kindly donated by Anderson Medical and Mobility (Loanhead, Edinburgh, UK). The forks, casters and rear wheels are all standard wheelchair components and were sourced from various wheelchair parts suppliers. As well as this, the final design was altered considerably to allow the use of standard plumbing fittings (compression tees mainly) to join the pipework together (Figure 4.6). In a production model these joints would most likely

be welded or brazed, both processes that would require the fabrication of a jig and this would not be cost effective for the production of a single prototype. It was discovered that it was not possible to bend the stainless steel pipe by hand and, given that there was no access to any mechanical pipe bending equipment on site, pre-cast stainless steel bends of 90 and 45 degrees were procured and adapted instead. The possibility of using 22mm copper pipe for the frame was considered to make manual pipe-bending possible, but after carrying out stress calculations it was realised that this material did not have the strength required to support the weight of both the user and the rest of the seating system in a safe and reliable manner.

4.3.5.2.2 Materials used

- 22mm stainless steel pipe (RS Components Ltd, Northants, UK)
- 22mm brass compression tees (RS Components Ltd, Northants, UK)
- Aluminium alloy (RS Components Ltd, Northants, UK)
- Plywood (B&Q, Erskine, UK)
- 12V Batteries (unknown supplier)
- Motors (unknown supplier)
- Caster forks (Greentyre, Middlesbrough, UK)
- 100mm diameter casters (Greentyre, Middlesbrough, UK)
- 250mm diameter wheels (Greentyre, Middlesbrough, UK)
- Beau controller (Anderson Medical and Mobility, Edinburgh, UK)

4.3.5.3 Tilting mechanism

Function: To provide a controllable mechanism that allows the seatbase to be tilted in both the saggital and coronal planes.

Tilt-in-space and recline mechanisms which alter the user's position in the sagittal plane are common to a number of adaptive seating systems (for example the Invacare Spree GT from Invacare (Bridgend, UK)) and systems that tilt in the coronal plane also exist but are not so commonly available. Designing a mechanism which allows

the seat base to tilt in more than one plane was one of the more challenging aspects of the design process, mainly in relation to the space constraints of the overall system.

Initial ideas for this assembly included an angled plate which the seatbase could be mounted on, which, when rotated by an electric motor it would alter the angular orientation of the seatbase and in turn the user. A hydraulic version using the same set up as the pneumatic system that was eventually used was also considered, with an option to have it automatically adapt to the user's posture, i.e. by leaning to one side, fluid would be displaced from some cylinders into others in a controlled manner and this would change the overall position of the seatbase. Changes in position could also be powered by a hydraulic motor. After researching available components, it was decided that using hydraulics would be too expensive and, in addition, they do not have the same innate damping properties that can be produced with a pneumatic circuit. Another idea that was considered was simply using electric motors and rack and pinion mechanisms to drive the tilting system. This approach may present difficulties in gearing but would not require a separate compressor. After an extensive evaluation process it was decided that a pneumatic based system would provide the best solution.

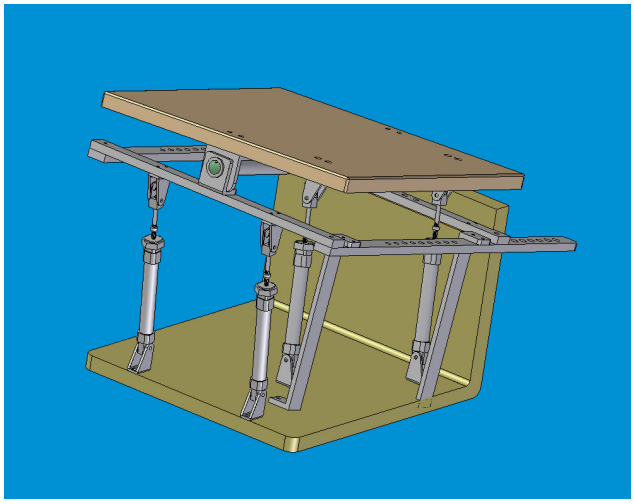


Figure 4.7 – Early version of tilt assembly

A number of configurations for the pneumatic system were considered including the version of the design shown in Figure 4.7. This design would provide the necessary tilting function in both planes but it was ultimately ruled out because of the amount of space required.

In comparison to the earlier version, the final design layout for this assembly features the pneumatic cylinders lying horizontally and connected to scissor mechanisms (shown in Figure 4.8) means that the mechanism is more compact and thus the overall height of the system can be reduced. Polytetrafluroethylene (PTFE) bearings were required to allow the mechanism to move freely and smoothly. A diagram of the pneumatic circuitry used to control the tilting mechanism is shown in Figure 4.9. The assembly is set up such that it can be tilted back 20° and forward 10° in the sagittal plane and approximately 12° to either side in the coronal, but these setting s can be altered by changing some of the components.

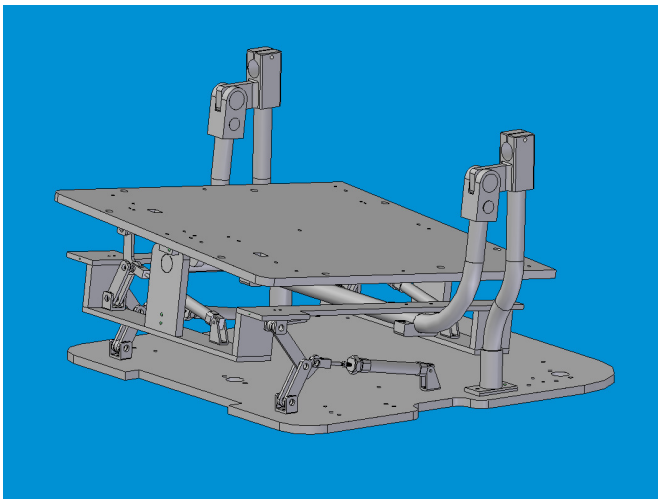


Figure 4.8 – CAD model of final tilt assembly (shown with armrest assembly in place)

The assembly includes an option for the user to be able to control the tilting functions in order to adjust their comfort. This requires compatibility with a range of different interfaces, i.e. joysticks, tilt switches etc, to suit users with different abilities. Some of the tilting functions may have orthotic support functions so it is possible to make

these non-user adjustable. A further aspect to the tilt function is the fact that it can be programmed to automatically tilt at given intervals of time. This is similar in principle to pneumatic mattresses and seat cushions which are designed to alter pressure distributions (McInnes et al., 2008). It could be particularly relevant to individuals who are unable to actively control or actuate the movement of the seatbase.

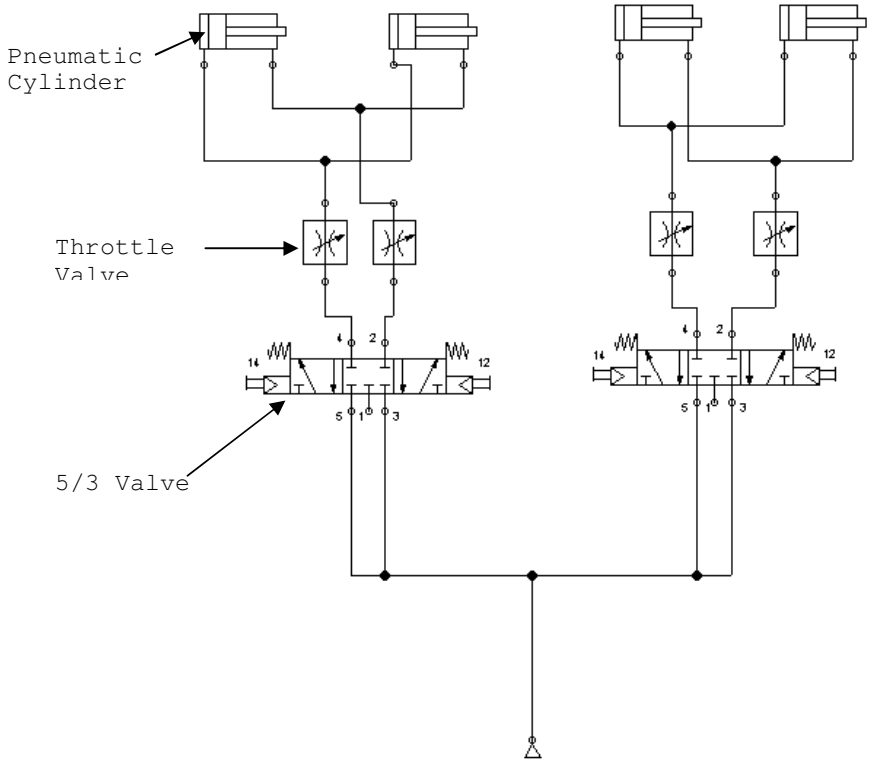


Figure 4.9 – Schematic diagram of pneumatic circuit used to provide coronal and sagittal tilt (drawn with reference to ISO 1219 parts 1 and 2: Fluid power systems and components – Graphic symbols and circuit diagrams)

4.3.5.3.1 Materials used

- Aluminium alloy (RS Components Ltd, Northants, UK)
- 22mm stainless steel pipe (RS Components Ltd, Northants, UK)
- Pneumatic cylinders (catalogue no. C85N10-50, Pneu-Store Ltd, Lanarkshire, UK)
- Mounting joints for pneumatic cylinders (Pneu-Store Ltd, Lanarkshire, UK)

- Pneumatic valves and fittings (RS Components, Northants, UK)
- Compressor (Ruian Royal Air Tools Co. Ltd, Zhejiang, China)

4.3.5.4 Seatbase

Function: To provide a stable base for the user to sit on and to stabilise the pelvis as an aid to posture.

As well as supporting the majority of the user's weight, the seatbase needs to allow for the attachment of other support assemblies like the lateral and pelvic supports and the footrests. The assembly also needs to provide some kind of additional structural support to the whole system and be compatible with most custom moulded seat cushions. In this assembly hygiene is especially relevant and for this reason its components and surfaces should be easy to clean, preferably simply by wiping them.

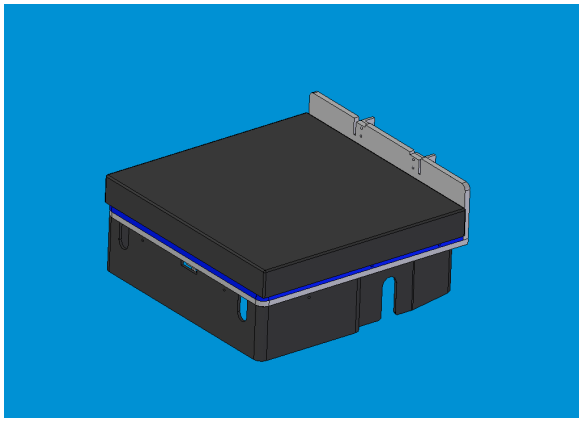


Figure 4.10 – CAD model of seatbase assembly

The final version (Figure 4.10) includes the facility to adjust the hip angle, separately for the left and right hip (Figure 4.11). This means that the pelvis can be stabilised to try and prevent lumbar lordosis of the spine. The ergonomic fit of the base can also be adjusted to suit a range of different users by adjusting the pelvic and lower lateral support assembly (see section 4.3.5.8).

The assembly was designed to suit a fairly standard seat cushion that was kindly donated by Royal Medica (Pozzoleone, Italy). Plastic trims have been added at

several points around the assembly, mainly for aesthetic reasons but they also serve to close off potential finger traps. Acrylic sheet was chosen for this purpose as it is easy to fabricate these types of components out of, plus it is a lightweight material with a smooth and attractive finish.

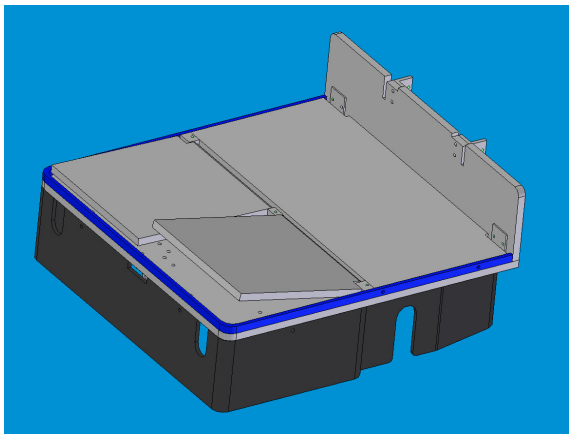


Figure 4.11 – Hip angle adjustment shown

4.3.5.4.1 Materials used

- 12mm plywood (B&Q, Erskine, UK)
- Aluminium alloy (RS Components Ltd, Northants, UK)
- Seat cushion (Royal Medica, Pozzoleone, UK)
- Acrylic sheet (RS Components Ltd, Northants, UK)

4.3.5.5 Armrests

Function: To provide postural support, particularly of the upper limbs, to the user when in the sitting position.

The armrests need to have a large range of adjustment in order to suit a wide range of users. Therefore, even in the earliest design iterations they could be moved backwards and forwards, tilted in and out and rotated around a vertical axis (see Figure 4.12). These degrees of freedom, as well as increasing the whole seating system's ability to suit a wide spectrum of users, mean that they can be moved out of

the way if the user needs to perform tasks where armrests would hinder him/her and to help with getting them in and out of the system.

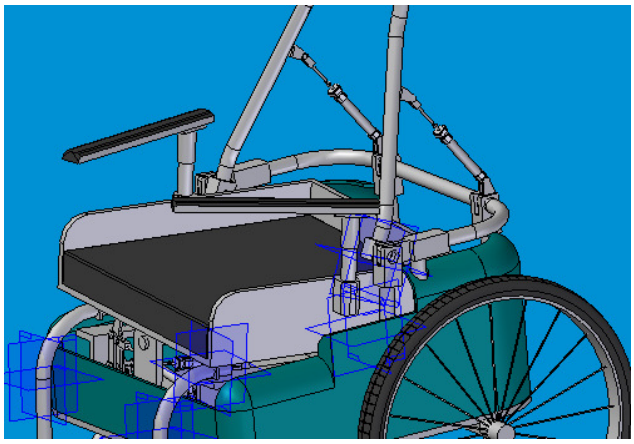


Figure 4.12 – CAD model of early version of armrests

As well as its support function, the final version of the armrest assembly (see Figure 4.13) provides a structure from which other assemblies can be mounted on. Both the backrest and the tilt assemblies are pivoted around parts of this structure. It also provides a potential attachment point for a tray or other accessories.

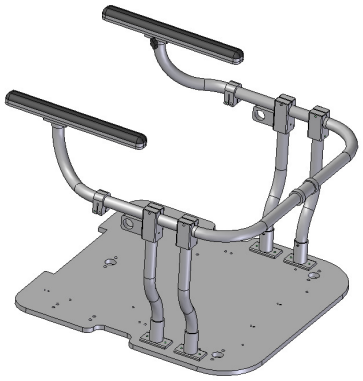


Figure 4.13 – CAD model of final version of armrest assembly

The wheels used when the system is in manual mode (for full description see section 4.3.5.2) are also attached to the base plate of this assembly as are the pneumatic cylinders used to lift the main part of the system off the powered base.

4.3.5.5.1 Materials used

- 15mm plywood (B&Q Ltd, Erskine, UK)
- 22mm stainless steel pipe (RS Components Ltd, Northants, UK)
- 22mm chrome coated copper pipe (RS Components Ltd, Northants, UK)
- Aluminium alloy (RS Components Ltd, Northants, UK)
- Pneumatic cylinders (catalogue no C85N10-25, Pneu Store Ltd, Lanarkshire, UK)
- 20" wheelchair wheel (Skyway Machine Ltd, CA, USA)

4.3.5.6 Backrest

Function: To provide dynamic support to the user's trunk whilst allowing for a recline function.

An important problem for adaptive seating users with high hip extensor tone is that the forces they exert on their chair are so great that they can break their seating system (see chapter 3), not to mention the problems that can result in terms of tissue breakdown that can arise or be aggravated by pushing against a fixed surface for an extended period of time. The shear forces generated by this abnormal tone can, in extreme cases, also lead to the development of decubitus ulcers. Therefore, the principle that the backrest assembly is based is that of supporting the user in a dynamic manner, i.e. allowing them to flex and extend in a natural manner before returning them to their original position. It is important that all the dynamic supports used in this system are adjustable as a balance must be struck between providing enough support to gain functional benefits while still providing scope for some movement.

The backrest also must be extremely adjustable, both because the users whom the system is targeted at are still growing and because of the wide anthropometric variations in this particular group. These users will often not conform to the anthropometric data used for designing standard chairs and seats and although the overall system is not intended to be compatible with those individuals with the most severe deformities, some accommodation for those in the early stages should be provided.

Taking inspiration from the Meyer system, the shape of the backrest support area is intended to reduce stimuli to the posterior of the trunk, replacing it with oblique lateral support forces. This type of backrest has the added bonus that the shape intrinsically centres the trunk of the user when seated in the system. The shaping of the backrest is essential to ensure that enough lateral support is provided. A good shape combined with a solid pelvis which does not move will give good posture while reducing sensory load. A poor overall setup could result in the user slumping in the seat and lead to kyphosis.

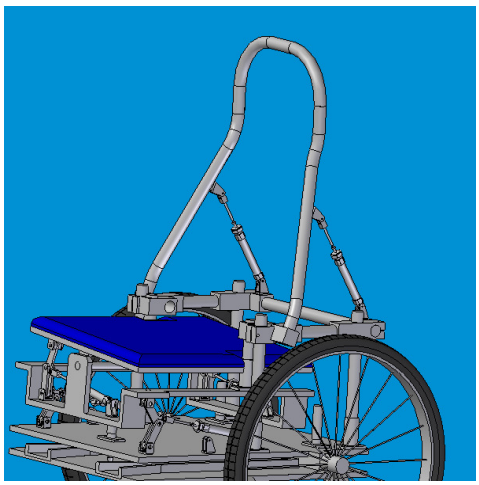


Figure 4.14 – Early version of the backrest assembly

In the early versions of the design, the backrest is given its dynamic functional aspect by using gas springs attached to the main section of the backrest and mounted on the armrest assembly (see Figure 4.14). An alternative to using gas springs was to make the backrest out a flexible plastic material and to design it in such a way that inserts

could be put into the frame at various points in order to alter its stiffness. The use of flexible plastics for these types of applications has been used previously with some success (Vekerdy, 2007). However, the facilities and costs involved with fabricating such a large and complex component made this approach unfeasible for this project. Another idea that was considered was introducing a powered aspect to the dynamic supports in the chair (not just the backrest). These would allow further powered adjustment of posture and also provide stretching forces (see chapter 5 for an expansion of this idea).

The final version of the backrest (see Figure 4.15) has been altered quite significantly from the set up used in the Meyer system. The section in contact with the user remains in its distinctive stimulus reducing support shape but it is now a separate entity which is free to move vertically up and down a separate section of supporting pipework. This new system allows a number of complimentary degrees of freedom which allow the backrest to be adjusted into a position suitable for almost any individual. The ability for the section in contact with the user to slide vertically means that there are no shear forces exerted on the user's back and the position of the headrest is also unaffected by trunk extension. The floating backrest also allows the pivot point for the dynamic support aspect of the assembly to be moved further from the hip joint centre. This helped to circumvent some of the mechanical issues with locating the pivot close to the user's body. Safety harness can be attached to the horizontal bars running across the back of the backrest.

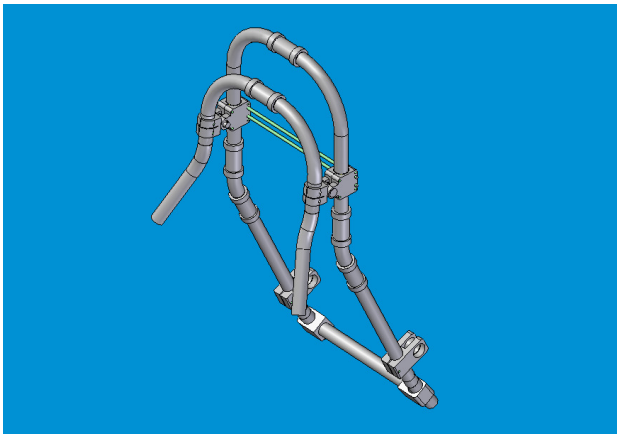


Figure 4.15 – CAD model of final backrest assembly (prototype version)

The backrest is probably the most complicated assembly in terms of fabrication, with a large number of components that have to be made from scratch and pipe sections bent to relatively tight tolerances. For this reason, and as with the powered base, the joints between sections of pipe while intended to be welded or made as a whole have been connected using compression fittings for the prototype of the system for ease of manufacture. A further benefit of using these compression fittings is that compound angle systems can be easily adjusted in terms of angles and length.

The headrest (Figure 4.16) as also a dynamic-type support. Supporting at the sub-occupital level, its helical form which is in part maintained by springs at either side provides the dynamic response. By adjusting the location of the springs the shape of the support can be altered. This could in some cases be used to help compensate for muscle imbalances in the user's neck.

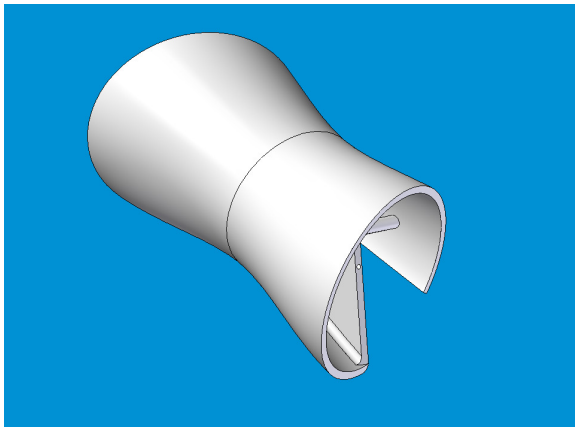


Figure 4.16 – CAD model of headrest

4.3.5.6.1 Materials used

- 22mm chrome coated copper pipe (RS Components Ltd, Northants, UK)
- 22mm brass compression unions (RS Components Ltd, Northants, UK)
- Aluminium alloy (RS Components Ltd, Northants, UK)
- 5mm sheet acrylic (RS Components Ltd, Northants, UK)
- PTFE block (RS Components Ltd, Northants, UK)
- Harness (Edmond Wheelchair Repair and Supply, Edmond, USA)

- Stainless steel compression springs (RS Components Ltd, Northants, UK)

4.3.5.7 Footrests

Function: To provide support to the user's lower limbs when in a sitting position.

The footrests are intended to provide postural support to the user, specifically to the lower limbs. It is important that they are set up correctly as ideally they should take the weight of the legs but not lift the thighs up off of the cushion as this would result in extra pressure being put on the ischial tuberosities. Therefore, especially when dealing with younger users who are still growing it is important that they can be easily and regularly adjusted. The footrests also serve to prevent the legs getting caught beneath the chair or hitting obstacles when manoeuvring as well as providing additional postural positioning. In some dynamic and tilt and recline systems the footrests can extend (i.e. rotate upward pivoted roughly around the knee joint centre) when the backrest is reclined.

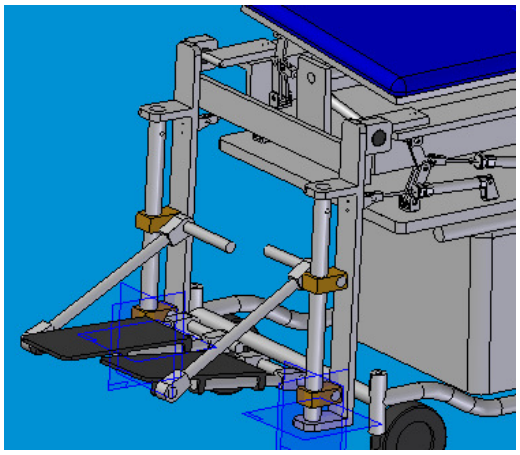


Figure 4.17 – CAD model of early version of the footrest assembly

Shown in Figure 4.17 is a slightly overcomplicated early version of the footrest assembly, although it does have a number of interesting features. The angle of each footplate could be altered individually and their distance apart could also be easily varied. Most interestingly perhaps was the fact that they could be extended by pneumatic cylinders, allowing the user mechanical leg extension which could perhaps have been used to mechanically stretch out the knee joint to help maintain

range of motion or be linked to the recline function such that when the backrest went back the footrests would extend. Aesthetically the design is very rough and unsuitable for use in the final design. After evaluation it was decided that it needed to undergo a great deal of simplification and to have its fabrication time reduced.

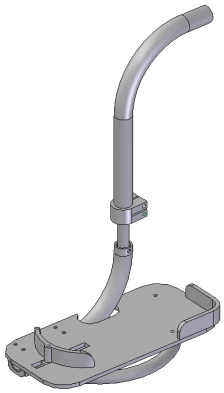


Figure 4.18 – CAD model of final footrest assembly (right hand side)

The final version of the footrest (shown in Figure 4.18) is a more elegant design. Using a simple clamp mechanism it is possible to vary the height of the assembly to suit the length of the lower leg and guides on the foot plate itself can be moved to suit different sizes of feet. The angular position of the footrest can be easily adjusted and attachment points for straps to secure the feet in position are also included.

4.3.5.7.1 Materials used

- 22mm chrome coated copper pipe (RS Components Ltd, Northants, UK)
- 15mm chrome coated copper pipe (RS Components Ltd, Northants, UK)
- Aluminium alloy (RS Components, Ltd, Northants, UK)
- 5mm plywood (B&Q Ltd, Erskine, UK)

4.3.5.8 Pelvic and lower lateral supports

Function: To provide support and stability to the user, especially in helping to stabilise the pelvis.

Providing a stable position for the pelvis and keeping the user within the confines of the system to prevent injury are the main purposes of this assembly. The use of a sacral pad in combination with the knee blocks (section 4.3.5.9) is standard practice in adaptive seating prescription and is intended to apply forces that improve the position of the lower limbs and whole body posture by pushing the pelvis into a neutral position. This assembly again needs to be widely adjustable due to the range of users that the system is targeted at.

Early versions of the assembly (Figure 4.19) featured the supports being fully dynamic. This was achieved by mounting them against springs which were compressed or extended when the user abducted or adducted their hips. This may have required the user's thigh to be strapped to the support, meaning that its movement could be controlled and providing postural control of the legs without the need for knee blocks. It was decided to remove this option from the prototype of the assembly to avoid overcomplicating the system at this stage.

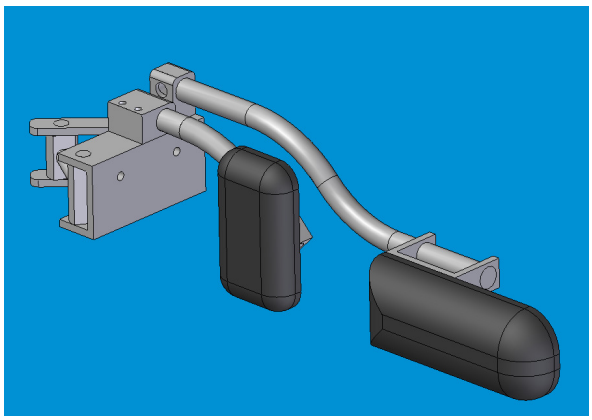


Figure 4.19 – CAD model of dynamic version of lateral support assembly

The final version of this assembly (Figure 4.20) features the ability to vary the distance between the left and right support units (both the lateral and pelvic support on each side should be considered as one unit). This was achieved by mounting sliding devices for the supports on the rear of the sacral pad unit. The assembly as a whole can be easily moved backwards and forwards to accommodate varying hip to

knee lengths. The individual supports on each side can also be adjusted separately by rotating the support arms. Seatbelt or safety harness attachment points are also included in this assembly.

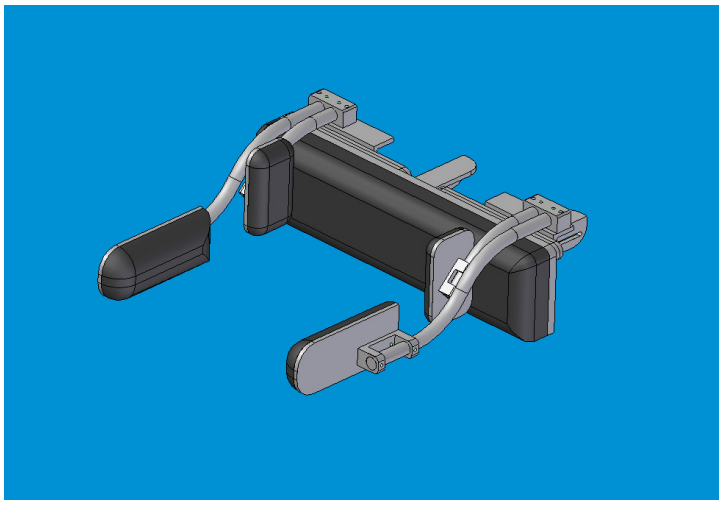


Figure 4.20 – CAD model of full lateral support assembly (used in prototype)

4.3.5.8.1 Materials used

- Aluminium alloy (RS Components Ltd, Northants, UK)
- 15mm chrome coated copper tube (RS Components Ltd, Northants, UK)
- Polyethylene foam rubber 1x2mx10mm (RS Components Ltd, Northants, UK)
- 12mm plywood (B&Q Ltd, Erskine, UK)
- Seatbelt (Edmond Wheelchair Repair and Supply, Edmond, USA)

4.3.5.9 Knee block

Function: To provide orthotic support.

The knee block is intended to provide orthotic support to the user and has to be easily attached and detached from the system to allow the user to get into or leave the system. The knee block, combined with the sacral pad on the pelvic/lower lateral support unit, is intended to control the position of the pelvis and lower limbs. It

needs to be quite sturdy as the user can exert a significant amount of force on it during events such as hyperextension of the hip. As with the powered base, knee blocks are available from wheelchair part suppliers as individual units but again it appeared to be more cost effective to fabricate one from scratch. Again, this also permitted the opportunity to customise the device and incorporate ideas that were not used in current knee blocks.

Please note: several adaptive seating models no longer use knee blocks, preferring instead to concentrate on controlling the hip and pelvis position at the pelvis itself (the Advanced Contoured Seat from Leckey for example). There has been very little work done to produce evidence for choosing one approach over the other but during the course of the project and after much of the design work was carried out new work was published regarding the effectiveness of knee blocks on posture for severe neuromuscular disorders suggesting that they had very little effect on overall body posture (McDonald & Surtees, 2007). However, as this study was not a long term evaluation of the effects of knee blocks in general it was decided to keep the knee block option as part of the final design.

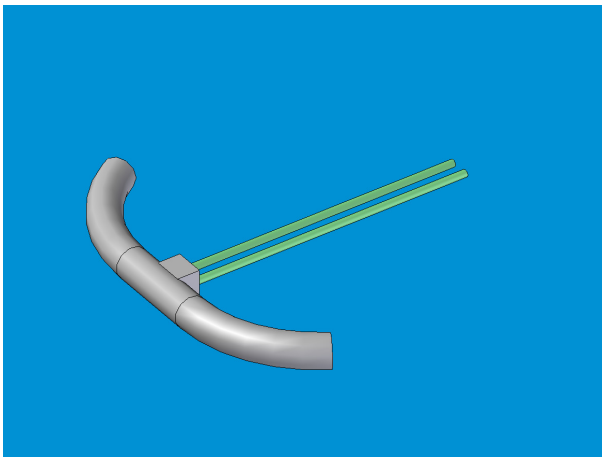


Figure 4.21 – Early version of knee block

Early concepts for this assembly tended to be very simplistic in nature. The early version of the knee block, shown in Figure 4.21, is typical of these designs. This approach was discounted in the end due to a lack of adjustability provided, mainly in

terms of how far apart the knees are, something which severely limits its effectiveness.

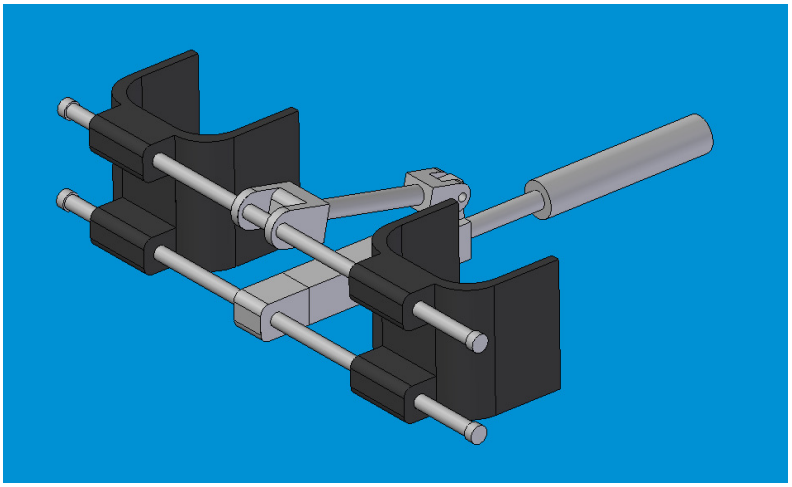


Figure 4.22 – CAD model of dynamic knee block

In keeping with the non-static support principles of the novel system, it was attempted to design a dynamic version of the knee block (see Figure 4.22) that would allow limited movement in the seat. However, it was decided that there is a fine line between allowing some movement for comfort and losing the control benefits gained from having a stable sitting base and it was for this reason that the dynamic knee block was not used as the final design.

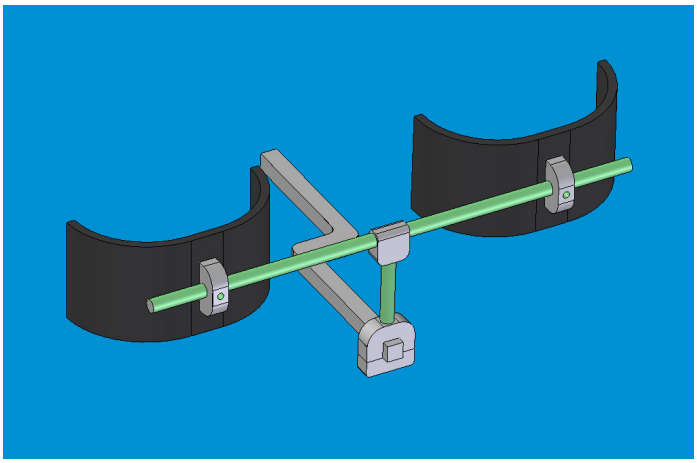


Figure 4.23 – CAD model of static knee block assembly

The final design used for the knee block assembly is shown in Figure 4.23. While being static in nature it is still adjustable in a number of directions. The blocks attach onto the main system using a simple and easy to activate clamp mechanism to allow for quick removal.

4.3.5.9.1 Materials used

- Aluminium alloy (RS Components Ltd, Northants, UK)
- 5mm acrylic sheet (RS Components Ltd, Northants, UK)

4.3.5.10 Front casters

Function: To provide stability and ease of manoeuvrability when the system is in manual mode.

The front casters are used when the system is in manual mode. They need to be able to rotate freely to allow the system to be easily manoeuvred as well as supporting a significant amount of the user's and the system's weight. They should not interfere with the user in any way and should not be positioned such that they may injure the carer.

Initial ideas for this assembly included having a separate unit which could be slid into position by the carer when the system was being changed to manual mode (Figure 4.24). After evaluation it was decided that it would be better to have the front casters attached to the main unit to prevent the risk of misplacing them and, more importantly, to reduce the risk of them being fitted incorrectly which could result in an accident. There were also issues with making the assembly strong enough to bear the weight of the base unit and the seating system without causing problems with attaching them when the user was still in the seat. Another possible solution that was considered in the early stages was to have the front casters permanently attached to the main system and have the detachable powered base providing only the rear wheels for the system. This idea was not used as with the

need for the casters at the back of the system for extra manoeuvrability in powered mode it was no longer possible to use this particular layout.

Figure 4.24 – CAD model of early version of front casters

For the final design (Figure 4.25) it was decided to have the casters permanently attached to the main system (specifically below the bottom plate of the armrest assembly) and to use a folding mechanism that allowed them to be stowed out of the way when they were not in use. By rotating the fold out mechanism 90 degrees it locks the casters in the deployed position. This was identified as one of the weakest parts of the system in the FMECA and the mechanism was improved to produce a higher safety factor.

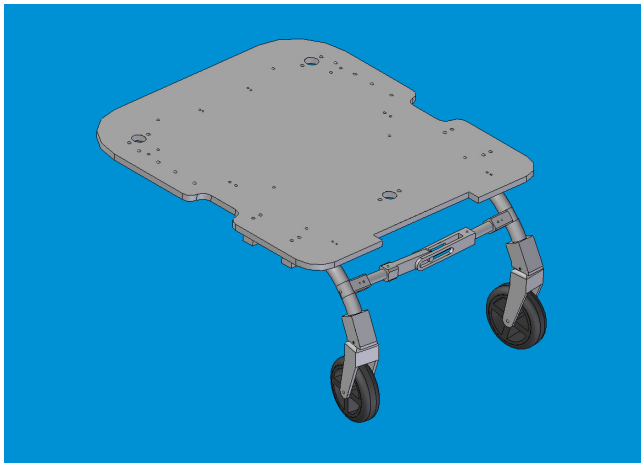


Figure 4.25 – CAD model of final design for front caster assembly

4.3.5.10.1 Materials used

- 22mm stainless steel pipe (RS Components Ltd, Northants, UK)
- Aluminium alloy (RS Components Ltd, Northants, UK)
- Casters (Invacare, Elyria, Ohio, USA)
- Caster forks (Invacare, Elyria, Ohio, USA)

4.3.5.11 Sit-to-stand frame

Function: to assist the user in moving from a sitting to standing position or vice versa in controlled and safe manner.

An area where improvements in efficiency could be made, identified from the results of the parent and teaching staff investigation (chapter 3), was the time taken to transfer children to and from their seating system. This normally requires the use of a hoist or, in the case of older children, the presence of at least two members of staff, and it can be a very time consuming process to make sure all the safety procedures are followed correctly. A child may need to be transferred out of their chair several times a day, i.e. for toilet visits, taking part in physiotherapy sessions, lessons in the swimming pool or for time spent in a prone stander.

It has also been shown that it is beneficial for the development of younger individuals with neuromuscular disorders who spend most of their time in seating system to be put in a standing posture for a significant time every day (Picciolini et al., 2009). It is for this reason that prone standing frames are used so much in special needs schools. Being in the standing position helps the child by placing the forces on their bones and joints that would be encountered by typically developing children, helping both hard and soft tissues to develop normally and gain strength.

A device which could move the subject from their seating system to a standing position, or at least assist the carers in this task may be of some benefit. The device would have to be light, easy to move around and have a high level of safety.

Options including spring loading the device, powering it using a hand crank or powering it some other way were all considered but ultimately discarded. The possibility of integrating the standing frame with the seating system itself was seriously considered. However, not wanting to exacerbate existing weight issues with the seating system plus the appeal of having a frame that could be used for different chairs and situations was the deciding factor in ruling this option out.

Figure 4.26 – CAD model of sit-to-stand frame

The design shown in Figure 4.26 uses pneumatic cylinders to provide the power that assists in helping the user to the standing position. It uses a scissor type mechanism to translate the forces in a suitable manner and raise the user. This design has a wide adjustment range, although, because of safety concerns, in comparison to the main seating system it is not as easily adjustable. The intention is that the device should be powered from the existing pneumatic system on the main seating system, but a further option would be to have a small compressor mounted on the sit-to-stand

frame. As the device is not intended to be used outdoors, this would be powered from the mains supply. It is also debatable how feasible it would be to carry around a pneumatic compressor with or on the device for weight and manoeuvrability reasons, plus this will obviously have a knock on effect on the overall price of the device. The device has casters fitted to the bottom to allow it to be moved short distances, with or without an individual on it. Calculations were made to determine the forces the pneumatic cylinders would be required to generate and these components were sourced on this basis.

4.3.5.11.1 Materials used

- Aluminium alloy (RS Components, Northants, UK)
- 22mm S/S (RS Components, Northants, UK)
- Casters (RS Components, Northants, UK)
- Pneumatic cylinders (catalogue no. C85N10-50, Pneu-Store Ltd, Lanarkshire, UK)

4.3.6 Prototype

Shown in Figure 4.27 is the prototype version of the system. It was fabricated in full at the Mechanical Workshop of the Bioengineering Unit, University of Strathclyde. Time and cost constraints meant that it was not possible to make every component and assembly, so efforts were focused on producing a version of the system that would be suitable for use in the study described in chapter 7. The assemblies that were not fabricated were the tilting mechanism and the fold out casters. To replace the tilting mechanism and keep the seatbase assembly in the correct position, a simple wooden frame was constructed out of plywood and this was fixed directly to the base plate of the armrest assembly. Depending on the materials available in the workshop, the materials that some components were fabricated out were not always exactly as specified in the drawings, i.e. the thickness of the plywood used for the powered base was 18mm rather than 15mm, but checks were performed in all cases to ensure that the substitute materials would meet the required safety criteria.

The section of the backrest intended to be in contact with the user was covered in foam padding. For safety reasons, a loose web made of bandages was created between the gap in the support so that the user could not fall through. The web was kept loose to ensure that the majority of the support was provided by the pipework.

Figure 4.27 – Prototype of novel adaptive seating system

4.3.7 Estimated costing for novel system

Although not yet at a stage where it could be sold commercially, by using an adapted version of the 1-3-9 rule (Rondeau, 1975) a rough estimate of the costs of goods (C_G) and retail price (P_r) of the system that includes parts, labour, overheads, and the various costs related to the wholesale and retail can be obtained. The costs incurred

during the fabrication of the prototype as a comparison for these calculations (the full bill of materials (BOM) has been included in appendix B). The following equations were used in the cost estimate-

Equation 1

$$C_G = 3\left[C_{MAT} + \left(\frac{C_{PART}}{2}\right)\right]$$

C_{MAT} = Material Cost. Calculated from mass (kg) x unit cost (£/kg) x scrap factor x tooling factor.

C_{PART} = Purchase cost of parts and components.

Equation 2

$$P_r = N_3 \times C_G$$

P_r = Retail selling price

N_3 = Includes costs incurred through packaging, insurance, shipping, commission; along with the profits of manufacturers, wholesalers, retailers etc. Rondeau estimated this to be 3.0.

In addition to this, the fact that this is a one off prototype must be taken into account. In general, the larger the quantity of an item to be made the lower the cost per item, an effect generally known as the "economies of scale" (Ullman, 1997). An approximation of this effect that is commonly used by designers is based around the assumption that costs will reduce by 10% if the quantity is doubled. This can be expressed as the following equation-

Equation 3

$$C_n = C_{n1}\left[\frac{N_1}{N}\right]^{0.152}$$

Where C_n is the estimated cost of making N items and C_{n1} is the cost of making N_1 items.

A number of other assumptions have been made. These include-

- Material overhead covering tooling and scrap costs was set at 20%
- Labour costs were set at £20/hour
- Labour overheads were set at 20%
- Where components have been donated to the project, the retail cost has been used, or, if it was not possible to find this, the retail cost of an equivalent component has been used
- Where components and assemblies were not actually fabricated for the prototype, labour cost has been estimated after consultation with a mechanical technician
- The sit-to-stand frame has been treated as a separate device in this instance, and as such it has been left out of these calculations

Table 4.1- Cost of prototype split into its constituent assemblies

Assembly	Cost (£)
Powered base	1293.09
Tilting mechanism	446.38
Seatbase	378.46
Armrest	381.57
Backrest	410.07
Footrest	311.89
Pelvic and lower lateral supports	184.91
Knee block	83.13
Fold out casters	256.60
Total Cost	3746.10

The cost of fabricating the system (C_G in equation 1) was estimated to be approximately £3900. From Table 4.1, the full cost of fabricating the prototype was

£3746, a value in line with the estimate suggesting that the assumptions made were within an acceptable margin of error.

Using equations 1-3 as well as the costs incurred during the construction of the prototype it can be estimated that the retail cost of this system, assuming a conservative manufacturing run of 100 units, will be around £5900. This is substantially more expensive than most current adaptive seating systems. However this value should be considered an upper estimate. The inclusion of a powered base is also a significant cost, with these units often costing over £2000 when bought separately (for example from uCan Health LLC, Issaquah, USA). As well as this, the novel features of this system, especially the backrest and the multi-planar tilting seatbase, all add to its overall value. Further iterations of the design would undoubtedly reduce these costs as well as improving the overall design. The use of more advanced manufacturing techniques, i.e. injection moulding and CNC pipe bending, than those available for the prototype's fabrication could also play a significant role in reducing the overall cost of the system, for example the majority of the seatbase assembly could be injection moulded as one unit. The use of these manufacturing techniques would necessitate a greater initial outlay for moulds, jigs etc, but would allow long term cost savings to be made.

4.3.8 Changes to the PDS

Due to a number of contributing factors, it was not possible to meet all of the criteria laid down by the original PDS. The changes that have been made are noted below with an explanation of why the original criterion was not met-

- It was originally intended that the system would be able to be fitted into a standard car boot but it was not possible to achieve this goal at the current stage of development. To achieve this requires some folding mechanism to be incorporated into the design. The system does still fit into the boots of larger cars but only by taking off the parcel shelves and putting down seats
- The aim to make the system as lightweight as possible (<5kg) was not possible, mainly due to the budgetary constraints on the project. The use of

high strength plastics and even carbon fibre components would reduce the overall weight substantially. However, it should still be possible for a single person to lift the system (without the power unit)

- Measuring such a subjective item as aesthetic appeal is always a difficult task, but for the prototype version of the system at least it would be fair to say that it was not overly attractive. The main reasons for this lay with the limited materials and manufacturing processes available at the time of fabrication, making it difficult to introduce smooth curved surfaces into the design
- As described in the previous section, it is estimated that the overall cost of the system will be higher than it would have been ideally, i.e. in line with retail price of current adaptive seating units, and the reasons for this have been covered

In addition, due to the nature of some of the criteria it was not possible to test how well the design achieved its aim (for example, with criteria relating to wear and tear and long term reliability).

4.4 Conclusion

This chapter has described the development of the novel adaptive seating system and the processes used. The system has been designed using standard design methodologies and with reference to criteria derived from the literature review and the parent/teaching staff survey. The design met the majority of the criteria set before concept generation began with some exceptions which have been noted and commented upon. A functional prototype based on the final design for the system and incorporating the majority of its assemblies was constructed.

5 Design Methods and Results – Active Dynamic Orthoses

5.1 Introduction

One of the most interesting ideas that came out of the design process for the novel adaptive seating system was that of active and dynamic support. Ideally the seating system would have been developed to feature a number of these dynamic support elements, allowing it to adapt to postural changes or spasms from the user while at the same time an active element, controlled in part by position and force feedback, would provide the necessary corrective forces to try and prevent deformities occurring. This would require a fairly complex control unit and software for monitoring and manipulating the support positions while at the same time allowing the user to perform functional tasks unhindered. Such a system is beyond the scope and financial limitations of this project but a smaller, simpler orthotic device that deals with only one joint would allow the technical feasibility of the idea to be tested.

Therefore, based on this idea, the objective of this part of the project was to design a novel type of dynamic orthosis that is able to mechanically mimic the stretching exercises carried out by physiotherapists, while at the same time receiving feedback from the patient's muscular responses. This device is considered to be an active, dynamic orthosis (ADO) and will be described as such for the remainder of this thesis. The orthosis was designed using the same methodologies described in chapter 4 for the design of the novel adaptive seating system. A functional prototype of the ADO was also constructed and tested to provide proof of concept.

5.2 Background

The benefits of applying a stretching force to a muscle, particularly spastic ones, in terms of maintaining the range of motion of a joint and preventing contractures occurring have been covered in chapter 2 of this thesis. Orthotic devices that try to

achieve this stretch by incorporating a dynamic aspect (Farmer et al., 2005; Finger & Willis, 2008; Lai et al., 2009) or devices that use a powered mechanism to apply a stretching force to the joint (Bressel & McNair, 2002; Yeh et al., 2005) have previously been reported in the literature, however powered devices tend not to be portable. To the author's knowledge no devices exist which provide both a dynamic and powered (active) element in one portable orthotic stretching device.

5.3 Design of Active Dynamic Orthosis

5.3.1 Design brief

"To design a novel orthotic device which incorporates dynamic elements and can mechanically mimic stretching exercises normally carried out by physiotherapists."

5.3.2 Product design specification outline

The PDS for this device is in many ways similar to that produced for the seating system. Therefore, only the key points that relate to this design are noted here.

There are a number of joints on the body that could potentially be benefited by this type of device but it was decided to target the wrist and, therefore the ADO had to be designed to provide a stretching force that would extend the wrist. This joint was chosen for a number of reasons, including: it is commonly affected in spastic patients, it is a relatively straightforward joint to stretch in a single axis of rotation; and it is easily accessible. Future work would include adapting the device for other joints, with the ankle and the elbow being potential targets.

The torque generated during wrist flexion by a typical subject varies significantly with position, with maximal forces being produced at close to full flexion (Morse et al., 2006) with the mean maximal torque for males found to be 9.6 ± 5.07Nm. Subjects with CP or other conditions affecting neuromuscular control are likely to vary from this value, however the literature is limited in terms of describing these

forces. Therefore, the orthosis has been designed to accommodate the forces found in normal subjects for the purposes of this work.

The device needs to be lightweight (<300g) and have safety features such that there is no risk of the user being injured by the device. It should not be bulky and must be comfortable for the user to wear.

5.3.3 Final design

A rendered CAD model (produced in Solid Edge V14 (Siemens PLM Software, Plano, Texas, USA)) of the final design concept is shown in Figure 5.1.

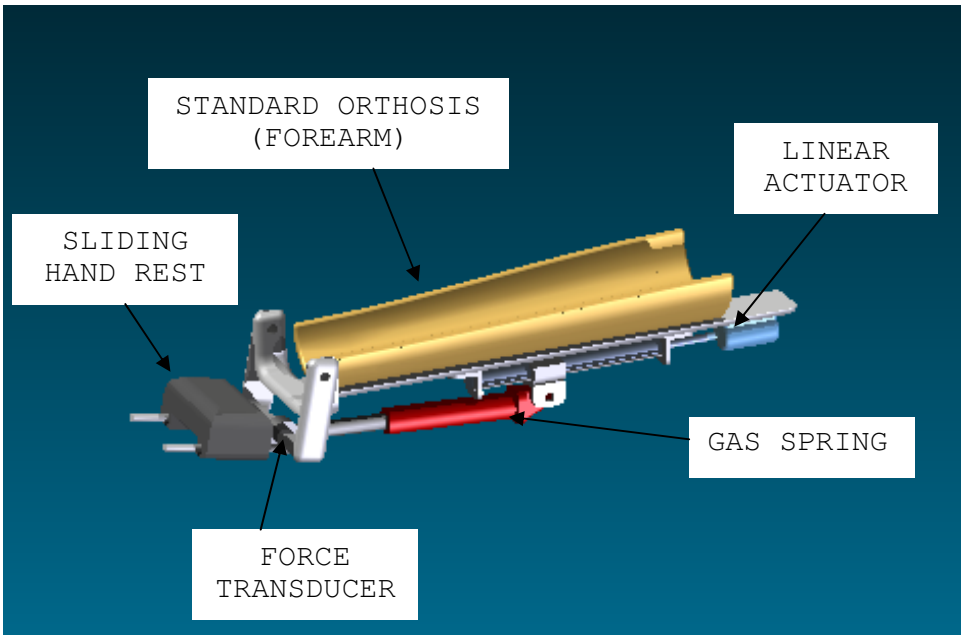


Figure 5.1 – CAD model of active dynamic orthosis for the wrist

The device features a standard, custom moulded orthosis of the forearm that is intended to be strapped on to the patient's wrist. A lightweight and low-power linear actuator mounted beneath this section is used to provide the active stretching force to the joint. The part of the device where the hand is placed (sliding hand rest) can rotate about an axis approximately in line with the wrist joint flexion/extension centre and the component in direct contact with the hand is also able to slide to

accommodate the change in position of the hand relative to the wrist resulting from the fact that when the wrist flexes it does not strictly rotate about a single axis.

The dynamic aspect of the device is achieved by the inclusion of a gas spring that connects the linear actuator to the hand section of the hinged orthosis. This type of spring was chosen because, rather than giving the rapid rise in resistance force that results from compressing a standard coil spring, the force output from the gas spring is relatively constant due to the large volume of compressed gas in the cylinder compared to that displaced by the plunger. This improves the user's safety when wearing the device by preventing any rapid increase in return force while the wrist is being flexed. By adjusting the pressure in the gas spring the basic stretching force being applied to the joint can be varied.

When compared to stretching exercises carried out by a physiotherapist or other experienced individual, the lack of ability to react to feedback from the patient in mechanical stretching devices is a major concern and poses a potential safety hazard. To overcome this, the ADO uses a transducer located at the point where the gas spring attaches to the actuator to measure the forces being applied by the user and feeds this information back to a control unit. The angular position of the orthosis hinge is also detected as is the linear position of the actuator. This means that, for example, if the user were to have a muscle spasm in their wrist, while the initial force was being absorbed by the gas spring, the control system would detect the increase in wrist torque and flexion and reduce the force being applied by reversing the actuator. After the spasm had passed the stretching force would be gradually reapplied until it returned to previous levels. The movement range of the actuator is also limited by microswitches mounted on the main body of the device.

The control unit is a simple microprocessor and interface unit that is attached to the device and can be programmed to change the position of the linear actuator, and apply the stretching force, depending on the instructions programmed in by clinicians and the information it receives from the feedback mechanisms previously mentioned.

The control unit and the feedback mechanisms can be set up in such a way to have the ADO to apply different stretching routines to the joint. There remains some doubt over whether applying a constant torque, moving the wrist to a set angle, or applying a cyclical-style loading is the most effective way of stretching a muscle and this device would perhaps make it possible to test which method best suits patients. In addition, the ability to measure and record the force and positional signals generated with a data logger while the device is being used gives the ADO a number of potential applications for research purposes and means that it may be useful to cater for individualised stretching programs for different patients. Other benefits from this feature could include the ability to objectively measure compliance to different stretching regimes.

5.4 Prototype

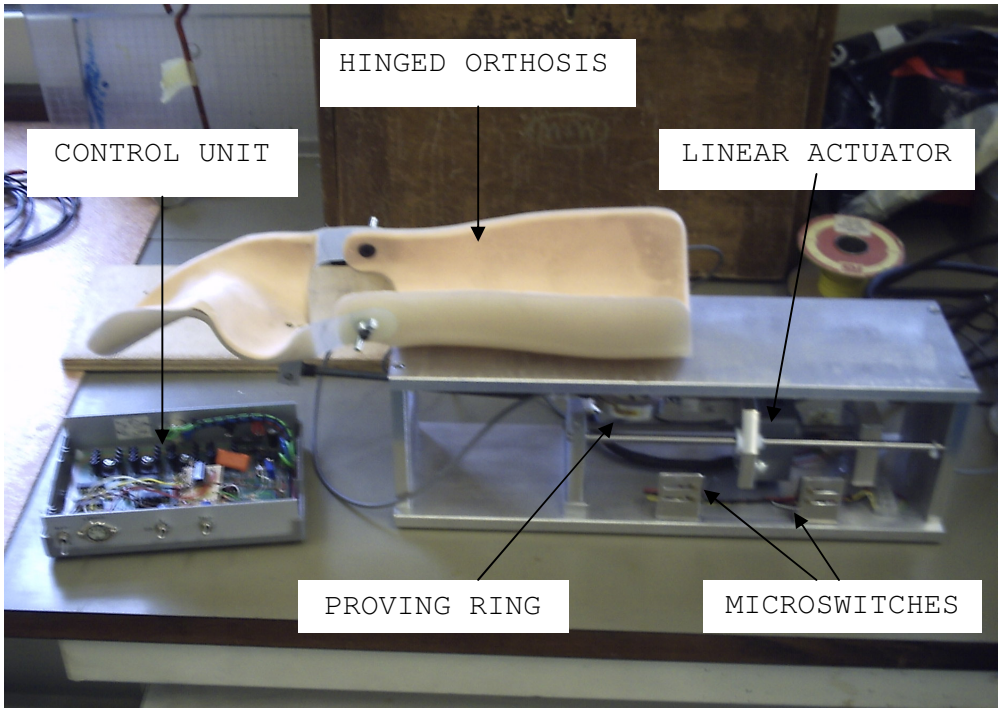


Figure 5.2 – Prototype active dynamic orthosis

The aims of producing this prototype were: a proof of concept that the setup of the device would work; and a working device that could be used for demonstration

purposes to orthotists and other clinicians. Again, time, cost and limited fabrication options meant that it was not possible to build a version of the prototype close to that conceived in the initial design, and a number of compromises had to be made.

The fabricated prototype is shown in Figure 5.2. It was not possible to purchase the small and lightweight actuators initially selected to provide the active element of the system, and instead a linear actuator that was available in the department was used. This was a fairly large and bulky motor (approximate dimensions 100x70x50mm, weight 0.3kg) and its use meant that the prototype could not be portable, one of the main requirements of the final design. A set of guide rods and the mounting brackets for the motor also had to be included. With the prototype now consigned to being a desk mounted model, a standard signal amplifier could be used rather than a smaller, customised circuit needing to be designed.

A simple electronic control unit was also designed and fabricated. This controlled the stepper motor and gave it the ability to be manually operated or put in automatic mode where the motor would simply travel back and forth between two preset points, defined by microswitches. A proving ring, located between the gas spring and the wrist part of the orthosis, was used to measure the forces applied.

A novel orthosis was fabricated. This was made from a mould of a large adult male arm and foam cushioning inserts were used to alter the shape so that it could be demonstrated on other individuals with smaller arms. The sliding part for the hand envisaged in the final design was not featured in this prototype because of the need to simplify the fabrication process and a simpler, but still functional, non-sliding hand section was used.

5.4.1 Materials used

- Gas spring: 160mm length, 60mm stroke, 6mm rod diameter (RS Components, Northants, UK)
- Type N linear stepping actuator (RS Components, Northants, UK)

- Polypropylene hinged orthosis (designed and fabricated by Mr William Spence and Mr Stephen Murray, Bioengineering Unit, University of Strathclyde)
- Aluminium (RS Components, Northants, UK)
- Proving ring (designed and fabricated by Mr Stephan Solomonidis at the Bioengineering Unit, University of Strathclyde)

5.5 Testing of prototype

5.5.1 Methods

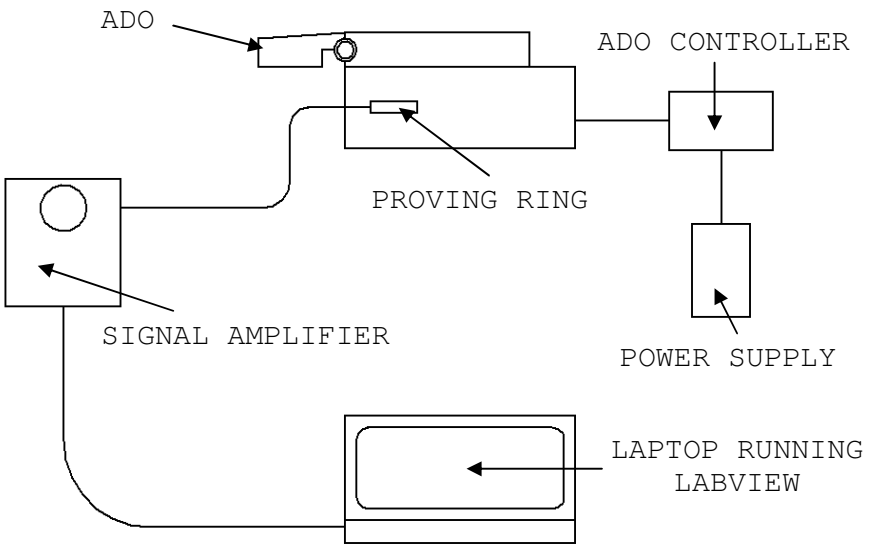


Figure 5.3 – Test setup for ADO prototype

The equipment set up used for this experiment is shown in Figure 5.3. The proving ring used to measure the forces at the gas spring was tested and calibrated using an Instron mechanical testing instrument (Instron, High Wycombe, UK) before being fitted to the ADO. The full prototype was then tested on one normal subject in several set ups. First, the hinge of the wrist orthosis was locked in one position and

the stepper made to do a reciprocating movement covering the full extent of its range (test 1). This was intended to test whether the force being applied was consistent as the gas spring was compressed. Secondly, the actuator was positioned approximately halfway along its range of travel and the subject flexed their wrist 10 times (test 2). The purpose of this test was to investigate the repeatability of the forces needed to begin compressing the gas spring. Finally, the wrist was flexed 10 times when linear actuator was moving to provide a stretching force (test 3) to test whether this affected the repeatability of the forces needed to compress the spring. All tests were repeated three times. The pressure of the gas spring was reduced from the factory level until the subject was able to compress it without difficulty.

The data acquisition program was written using LabView version 8.6. The output from the proving ring was acquired using a PCI-MIO-16E-4 data multifunction input/output data acquisition card (National Instruments, Austin, USA) at 20Hz and 12-bit resolution. The card was interfaced with LabView using the driver software NI-DAQ 6.5.1.

5.5.2 Results and discussion

The proving ring used was found to respond in a linear manner to forces applied (r^2=0.999) with the RMS error equal to 7.6N (0.4% of the range tested) based on the output of the Instron load cell.

Figure 5.4 shows the force profile measured by the proving ring when the wrist is held in a fixed position and the linear actuator moves first to compress the gas spring (0-40 seconds) and then to decompress it (40-80 seconds). After an initial peak to overcome the static resistance of the gas spring, the load is relatively constant at around 29N for the period 10-30 seconds before increasing slightly at the end of the actuator's travel. This increase at the end can be explained by a shortening of the lever arm as the wrist angle reaches the end of its range. The reduction in load when the linear actuator is reversing results in the detected load being significantly lower, varying between 10 and 20N. The fact that the force isn't completely constant over the full range of the actuators movement has implications for the measurement of

forces. However, it would be relatively simple to correct for this using a simple algorithm programmed into the control unit. The magnitude of the forces involved can be altered by adjusting the pressure in the gas spring.

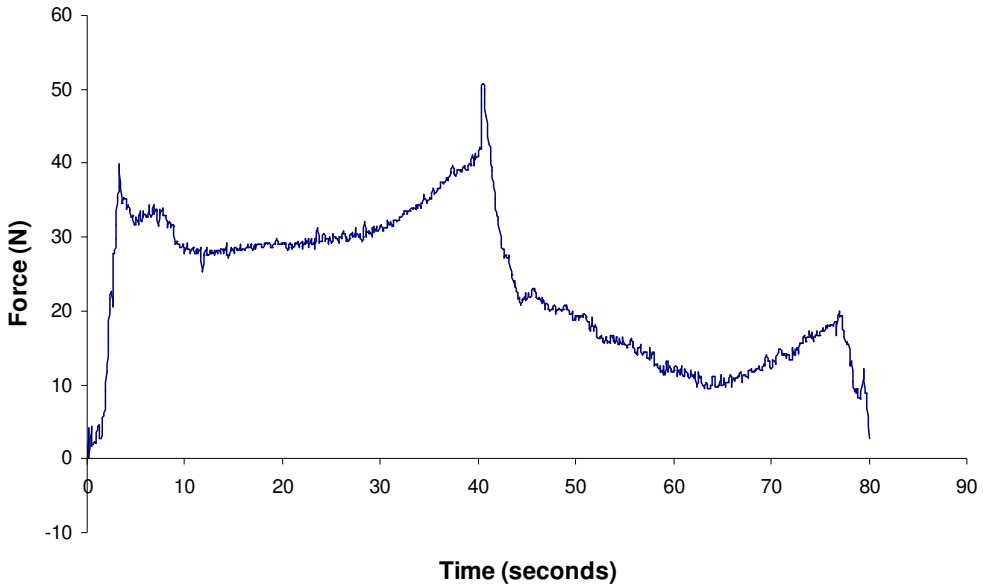


Figure 5.4 – Typical force profile from ADO (test 1). From 0 to 40 seconds linear actuator is moving to compress the gas spring; from 40 to 80 seconds the actuator is reversing and the cylinder is being decompressed

For test 2, when the linear actuator is not moving, the results for the force required to initially begin compressing the gas spring was found to be within an acceptable range of repeatability (mean 41.7N standard deviation 4.2N). This was conformed in test 3 (Figure 5.5), where results gave a mean value of 45.7N with a standard deviation of 3.67N. The slight increase in the mean value in test 3 can be explained as energy lost against the linear actuator. The fact that the force does not return to zero between flexes is assumed to be the result of friction in the hinged orthosis and other mechanisms, and this could be reduced significantly by introducing bearings in future prototypes. The forces required to initially compress the gas spring were found to larger than those registered during test 1 when the wrist angle was fixed, showing that there is a initial resistive, possibly inertial type force that need to be overcome to begin compressing the spring. This characteristic could perhaps be

useful as a signal to stop the actuator when the user wanted to halt a stretching program and carry out functional activities with the joint.

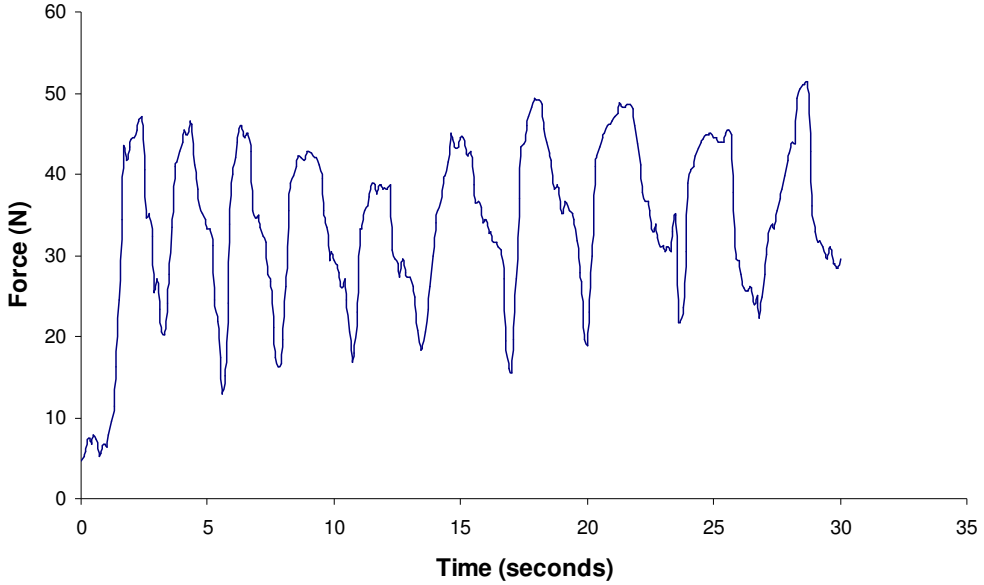


Figure 5.5 - Force profile from ADO as wrist flexes (x10) and stepper motor is on (test 3)

A proportion of the energy involved in these tests and therefore force measured is undoubtedly lost as heat in the gas spring and as friction in moving parts but it is assumed that these losses are negligible and that the results presented here give a good indication of the prototype's characteristics.

5.6 Future developments

The current prototype has a number of features that need to be changed before more thorough testing can be carried out. Not least of these is a reduction in weight and size to bring it more in line with the original concept (Figure 5.1). This should be relatively simple to achieve by the replacement of the stepper motor with a miniature linear actuator (Firgelli Technologies Inc., Surrey, Canada), a lightweight (<50g) and low power (5Vdc, 450mA) device that is currently used mainly in robotics. The linear actuator also has a built in potentiometer that gives positional feedback to the

control unit, a feature that makes it ideal for the ADO. Replacing the stepper motor with this device will allow the removal of the aluminium framework that was needed to guide and support the motor and make the ADO truly portable and relatively unobtrusive.

Another feature that will be introduced is the ability for the position of the applied stretching force to be altered. With the current design, the wrist can only be stretched out in one direction, around an axis of rotation running horizontally through the joint, parallel to the base of the moulded orthosis. For many patients the stretching of the joint they require to maintain a full ROM may not be so simple. By allowing the device to provide angled and lateral stretching forces this will help to increase its versatility.

5.7 Discussion and conclusion

A novel type of orthosis is intended to mechanically stretch the wrist joint has been designed. A desk mounted version of the design was fabricated and underwent a series of preliminary tests. It was shown that with the use of a gas spring to introduce dynamic support to the system, a relatively constant stretching force can be maintained, showing that a device such as this could, while allowing functional or muscular spasm-related movement to be accommodated, be of benefit to individuals who require the use of an orthosis to maintain or improve joint range of motion.

Incorporating this "active dynamic" approach could have a number of potentially therapeutic effects in the more complex setting of an adaptive seating system. As well as being able to provide an effective stretching force to muscles, for example the hip extensors in the case of an active dynamic backrest, simply being able to change the joint angle at set periods of time or at the user's discretion could have benefits for overall levels of comfort. The user could also use the chair to perform strengthening or propioception-type exercises against variable resistance forces provided by the chair in a safe and controlled manner.

Scaling up to the device to use the same approach on, for example, the backrest of the seating system may result in some technical considerations needing to be resolved. A more powerful motor would likely be required to provide an adequate stretching moment. One the other hand, the space and weight limitations related to ensuring the wrist device could be used during day to day activities are less constraining in the case of the seating system and it would be possible to incorporate more mechanisms. Modular devices intended to be mounted temporarily on the seating system could be designed to target joints such as the knee or elbow, and could be powered from the system's battery, allowing them to be made lightweight and adaptable.

Overall, active dynamic support could allow a number of innovative and potentially beneficial features to be incorporated into adaptive seating systems.

6 An investigation into the potential for actigraphy to be used as a objective indicator of seating discomfort

6.1 Background

During the course of this project a number of methods used to try and measure sitting discomfort were considered for use in testing the novel adaptive seating system. It became clear when looking into the literature for these approaches that there was not one set method that was entirely satisfactory (see section 2.4). Therefore, it was decided to investigate an alternative approach.

6.2 Introduction

There has been a shift in recent years towards using low powered and miniaturised sensors for certain areas of postural and clinical research (Wong et al., 2007). These devices have the advantage of being lightweight, portable and often have built in data loggers, resulting in potential for information relevant to outcome measures that previously only have been able to be assessed in the laboratory to be recorded in "real-life" situations. The activity monitor, or actigraph, is one such sensor. Developed initially as an instrument for measuring sleep activity (Brown et al., 1990), it uses body mounted accelerometers to provide a continuous measure of movement. Outside of sleep research, activity monitors have been used to measure the agitation of patients in critical care units (Grap et al., 2005), for gait analysis (Veltink & Franken, 1996), and for measuring upper limb movement (Van Someren, 1996). Actigraphs can also, depending on the type of accelerometer employed, be used to measure posture as well as movement (Foerster & Fahrenberg, 2000; Prill & Fahrenberg, 2006).

The aim of this study was to investigate a novel approach to measuring sitting movements: by the use of actigraphy. Furthermore, it was hypothesised that there

may be some relationship between discomfort related movements as measured by the actigraphy system and the subjective discomfort measurements given by subjects.

6.3 Methods and Materials

6.3.1 Subjects

Twelve subjects (nine males and three females) volunteered for this study. Demographic details are summarised in Table 6.1. Subjects were recruited from the student and staff bodies at the Bioengineering Unit, University of Strathclyde. All were reported to be in good health and to have no history of neuromuscular disorders or pain when sitting. All experimental work was approved prior to its commencement by the departmental ethics committee at the Bioengineering Unit and all subjects gave their written informed consent.

Table 6.1 – Summary of demographic data

Variable	Mean (SD) *
Gender (M/F)	9/3
Height (mm)	1753 (84)
Mass (Kg)	73.03 (15.4)
Age (years)	26.22 (1.56)

*Anderson Darling test used to assess normality of data

6.3.2 Materials

6.3.2.1 Actigraphy

The device used to measure the subjects' activity was the *Activ*PAL™ Trio (PAL Technologies, Glasgow, UK), a triaxial activity monitor that uses piezoelectric accelerometers. This device was chosen because of its compact size, light weight and the fact that it had a built in data logger of a capacity suitable for this study. The activity monitor was attached to the subjects using PAL*stickies*™ (PAL

Technologies, Glasgow, UK) hydrogel adhesive pads which are designed to stick the device directly to the skin. The monitor was affixed to the subject at the top of the sternum. This location was chosen as it would allow the monitor to detect all major changes in posture of the upper body whilst being unobtrusive. It has been previously suggested that upper body movement increases with perceived discomfort in driving tasks (Na et al., 2005). In subjects where chest hair was an issue sticky tape was used to reinforce the monitor's position. The location of the device was chosen as it would allow the monitor to detect all major changes in posture while being unobtrusive and not detecting task related movements. This location also served to minimise the amount of flesh between skin and bone.

For the main experiment, movements were recorded at 10Hz (without compression), the standard sampling frequency of the activity monitor, as previous work has shown that subjects can move at frequencies approaching 0.5Hz (Fenety, 1995). The data were downloaded from the monitor using ActivPAL™ Professional, Version 5.8.1.12 (PAL Technologies, Glasgow UK).

6.3.2.2 Chairs

Four chairs (Figure 6.1) were selected to provide distinctly varying comfort levels across the 100 minute sitting sessions. The chairs also had to be non-swivel as these movements may cloud the actigraph data. Chair A was a simple wooden framed chair with minimal cushioning (10mm) on the seat base and an almost vertical, uncushioned, mid-height backrest. Chair B had cushioning (20mm depth) on both the seat base and its mid-height backrest was at a more reclined angle than the previous chair. Chair C featured more cushioning on both the seat base (50mm depth) and the mid-height backrest and also armrests (uncushioned). Chair D was a standard well upholstered armchair (cushion depth 100mm) with cushioned armrests and a relatively high backrest.

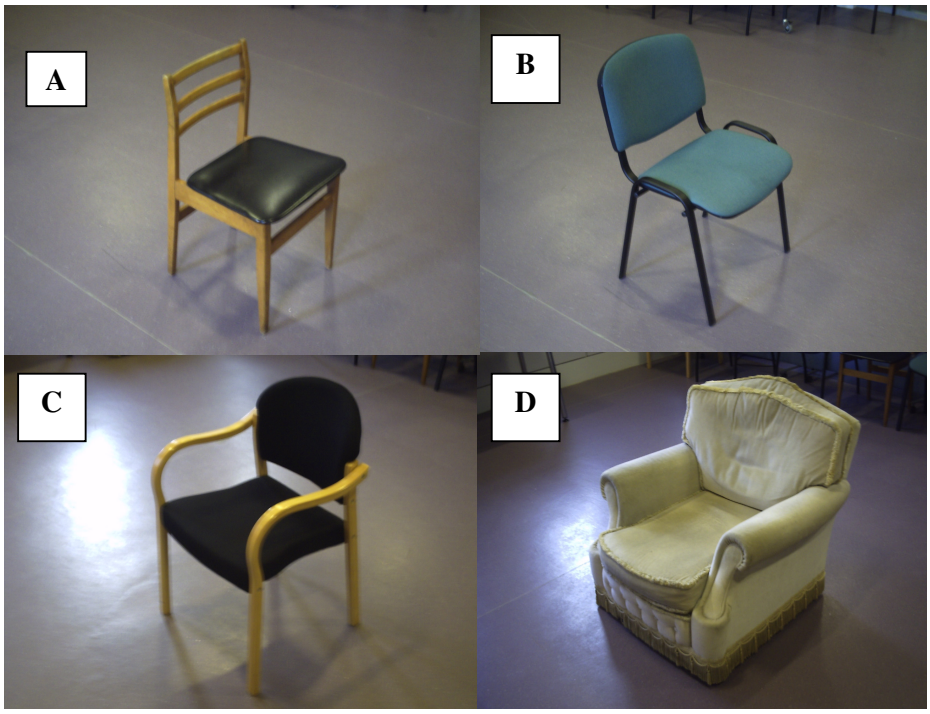


Figure 6.1 - Chairs used in test. Chair A: a simple wooden framed chair with minimal cushioning on the seat base and an almost vertical, uncushioned, mid-height backrest; Chair B: cushioning on both the seat base and its mid-height and a more reclined backrest than the previous chair; Chair C: more cushioning on both the seat base and the mid-height backrest and armrests (uncushioned); Chair D: a standard well upholstered armchair with cushioned armrests and a relatively high backrest.

6.3.2.3 Perceived discomfort

The Category Partitioning Scale (CP-50) was used to measure subjects' perceived feelings of discomfort. Originally developed as a scale for measuring pain intensity, the CP-50 has been tested thoroughly for reliability and absoluteness in scaling (Gobel et al., 1988). It is a vertical rating scale which requires the subject to firstly chose a category which describes their overall feeling of body discomfort, 0 = *no discomfort*, 1 = *slight discomfort,* 2 = *low discomfort,* 3 = *medium discomfort,* 4 = *high discomfort and* 5 = *severe discomfort*. Each of the categories is then further divided into 10 scale points with which the subjects are asked to refine their answer. Therefore the scale normally results in a number between 0 and 50 (points above 50 are provided to avoid the ceiling effect). The scale has previously been adapted and tested for measuring seated pressure discomfort and showed the highest reliability of

all the tools measured (Shen & Parsons, 1997). A copy of this scale is included as Appendix C.

6.3.2.4 Experimental design and analysis

For this experiment, sitting movement has been defined as a shift in position in the seat, for any reason, which alters the signals from the activity monitor. It was decided to analyse the results at this stage in two different ways. Firstly, this was done by simply summing the total magnitude of the signal changes in the activity monitor caused by the sitting subject. This process was carried out for both the Y and Z channels of the monitor (ΣYZ) and for all three channels (ΣXYZ) to find out if there was any benefit from measuring activity in a larger number of axes. Secondly, two types of movement, identified from the in the pre-testing data, were defined. These were-

- Distinct Postural Change (DPC): defined as a change in orientation of at least 10° (from calibration of actigraph: equivalent to a change of 10 PAL units) over all channels that is maintained for over 10 seconds (see points marked A in Figure 6.2). This definition was chosen after analysis of pre-testing trials for postural movements which could be visually observed and time required to re-establish a static sitting posture after movement. Changes of position made over time, i.e. if the subject was to gradually slump down in the chair over a period of a few minutes, were also considered to be DPC if they produced a change of 10 PAL units or more for at least 10 seconds.
- Transient Postural Change (TPC): defined as a perturbation in the signal greater than 10 PAL units over all channels which returns to baseline levels within 10 seconds (see point B in Figure 6.2).

When the actigraph is attached to the subject, its X axis is orientated vertically, the Y orientated along the mediolateral axis and the Z axis orientated along the anterioposterior axis.

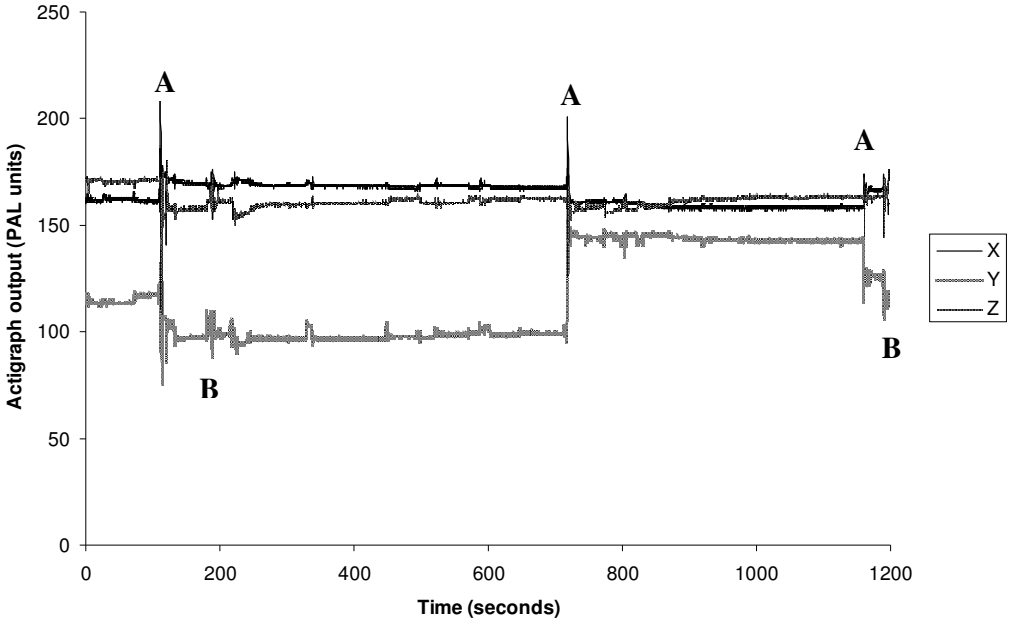


Figure 6.2 – Example of data output from test session with distinct postural changes (marked A) and transient postural changes (marked B) indicated. X represents changes in the sagittal plane, Y coronal plane and Z tranverse plane. A change of one PAL unit is equivalent to a change in the inclination of the monitor of 1° in the relevant plane.

6.3.2.5 Task and environment

Tests were carried out in a quiet room where interruptions could be prevented. No desk was used in the experiment. For each test session subjects were asked to bring enough reading material to last the full 100 minutes of each session. Subjects were allowed to highlight parts of this material if they wished, but were asked not to carry out any actual writing tasks. Each subject was tested during the same time slot for each test session in order to minimise the influence of factors such as general fatigue levels on the results. Time slots began at 09.00, 11.00, 13.00 or 15.00hrs and lasted for approximately 1 hour 50 minutes including set up time. Three subjects were tested in each time slot and the slots were randomly allocated. The maximum time for each individual between completing the first and last test sessions was 28 days and the majority were completed in less than three weeks. Subjects were also asked to wear the same type of clothing for each test session in case the material used for

these may have had an effect on their comfort. The room was maintained at a steady temperature of 21^{o}C.

6.3.2.6 Test Procedure

6.3.2.6.1 Calibration of actigraph

In order to use the ActivPAL to measure posture it was necessary to test its ability to measure angular displacement. To achieve this, a test rig was fabricated to allow the ActivPAL's angular orientation to be altered in Around the Y and Z axes. The actigraph started in a position such that the X axis was parallel to the ground and the Y axis perpendicular to the ground. The actigraph's angular position around the Z axis was then altered by 10° at each stage until it had been moved a full 180°. It was held in each position for 20 seconds. In order to check for any hysteresis effect, after reaching the 180° point the actigraph was moved to retrace its path back to the 0° position, again at 10° intervals and being held in each position for 20 seconds. To calibrate the actigraph in around the Y axis, the experiment was repeated except with the actigraph starting such that the X axis was parallel to the ground and the Z axis perpendicular to the ground.

6.3.2.6.2 Sitting tests

In order to validate the assumption that changes in sitting posture would be shown up on the data recorded by the activity monitor, it was necessary to carry out tests comparing the recognisable ICM with the output from the activity monitor. This was achieved by videoing two 100 minute trial sitting sessions and playing them back looking for DPCs or TPCs, noting the time that these occurred and comparing them to those independently identified from the activity monitor.

Prior to the second part of the experiment commencing the order that the chairs would be tested was randomised for each subject. Subjects were not informed of the function of the activity monitor and the labelling on the device was obscured for the purposes of the trial (indeed, the gel like nature of the sticky pad led several subjects

to speculate when asked after the completion of the trial that it was a device for monitoring heart rate or muscle activity). Before their first test session commenced subjects were instructed on how to use the discomfort scale and reminded of this for each of their following sessions.

The timers in the activity monitor and the laptop used for data collection were synchronised at the start of each test session and a timer function on the laptop used to mark 20 minute intervals. The monitor was then adhered to the subject and its orientation checked by the researcher. After sitting down subjects were given a few seconds to familiarise themselves with the chair that they had been allocated for the session, then the timer was started and the first discomfort scale handed out and filled in by the participant. Scales were then filled in at intervals of 20 minutes for the duration of the 100 minute test, including at the end of the session.

6.3.2.7 Statistical Analysis

Statistical analyses were performed using Minitab 14 statistical software (Minitab Inc, State College, PA, USA). The comparison of the observed and measured postural changes was carried out by finding the Pearson correlation coefficient. Due to the non-parametric nature of much of the data, the Friedman test was used to determine if there were any significant effects on CP-50 and activity data from the chair used and time period. Since multiple comparisons were undertaken, Bonferonni correction was applied. Therefore, the level of significance was set at $P < 0.005$. Regression analysis was used to determine the extent to which subjects' sitting movements, as measured by actigraphy, could be used to predict perceived discomfort.

6.4 Results

6.4.1 Calibration of actigraph

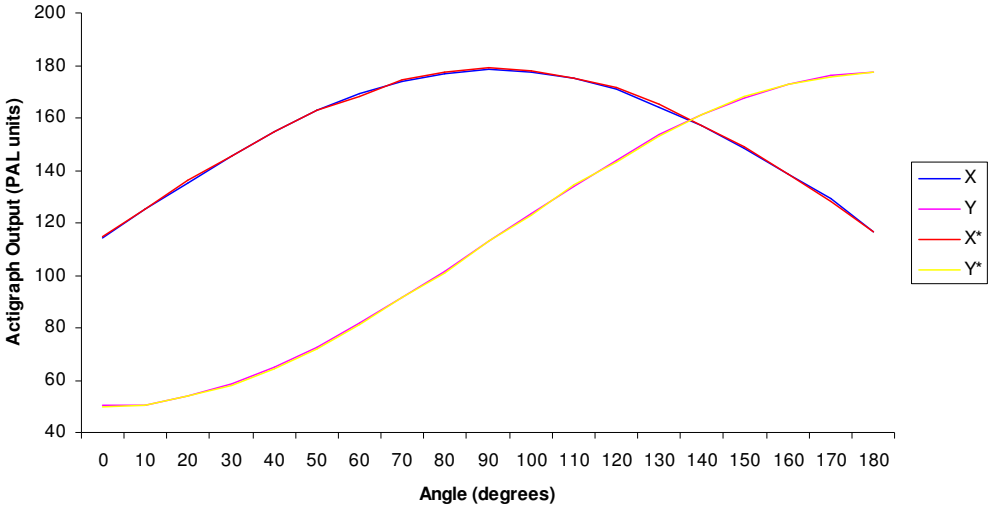


Figure 6.3 – Results from test 1: rotating actigraph around the Z axis. X: output from X channel from 0 - 180°; X*: output from X channel from 180 - 0°; Y: output from Y channel from 0 - 180°; Y*: output from Y channel from 180 – 0°. Data are means taken over three individual trials.

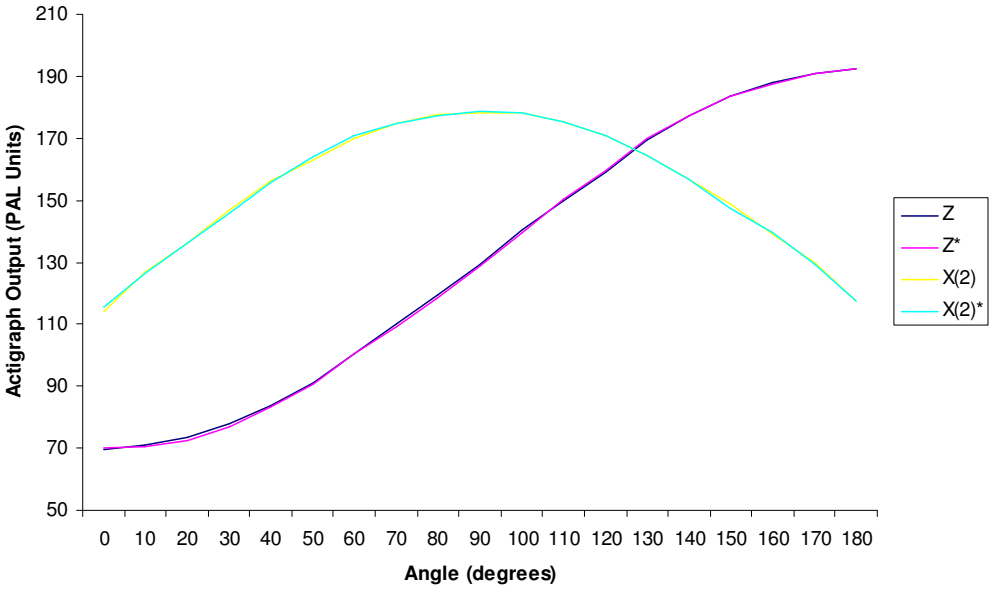


Figure 6.4 – Results from test 2: rotating actigraph around the Y axis. Z: output from Z channel from 0 - 180°; Z*: output from Z channel from 180 - 0°; X(2): output from X channel from 0 - 180°; X(2)*: output from X channel from 180 - 0°. Data are means taken across three individual trials.

From Figures 6.3 and 6.4 it can be seen that the response in the Y and Z channels of the actigraph output is linear (R^2>0.99) between 60 and 120 degrees (with vertical being defined as 90 degrees). From visual inspection of the preliminary sitting data, it is within this movement range that postural sitting changes almost exclusively fall. There was little evidence of drift or hysteresis (<0.1%) shown from these results. It can be confirmed from these results that a change of 1 PAL unit is approximately equivalent to a 1 degree shift in the angular position of the actigraph.

6.4.2 Verification of actigraph's ability to detect sitting movement

Correlation between the observed and detected movements was found to be high for DPCs and TPCs with Pearson coefficents found to be > 0.95 ($p < 0.005$) for both measures. Figures 6.5 and 6.6 show the scatterplots for both sets of data.

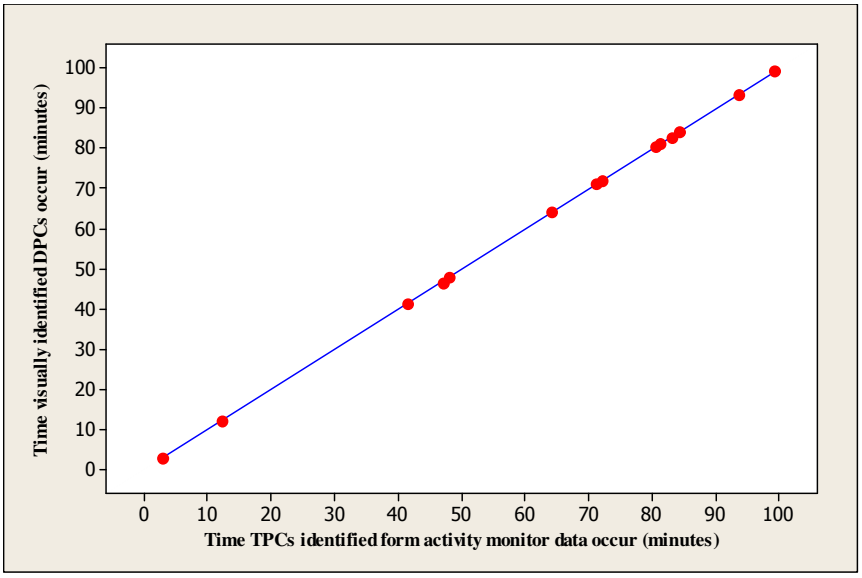


Figure 6.5- Scatterplot for distinct postural changes identified from the actigraph data vs those that were visually identified

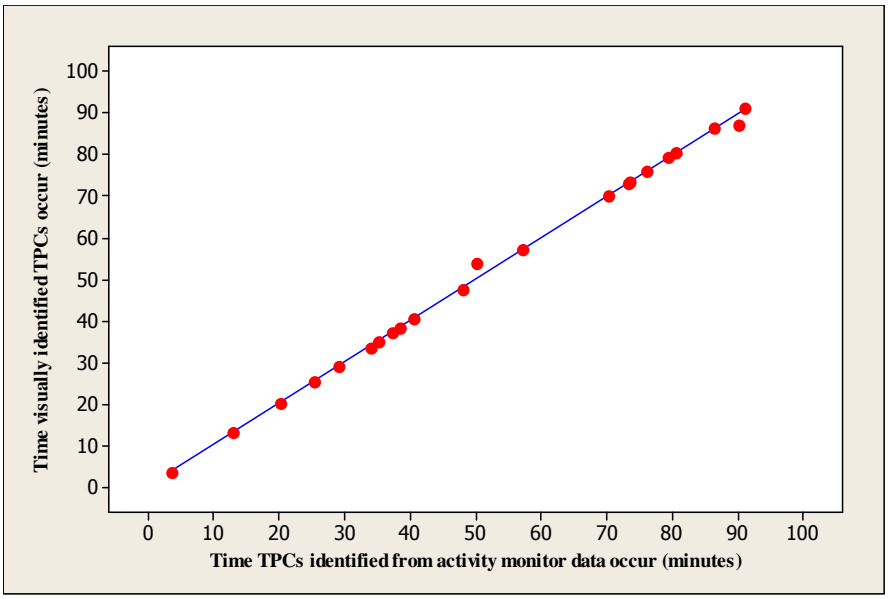


Figure 6.6 – Scatterplot for transient postural changes identified from the actigraph data vs those that were visually identified

6.4.3 Analysis of chair and time effects

Comparing different chairs for effects on both perceived discomfort (as measured by the CP-50 scale) and DPCs and TPCs, it was shown there were significant differences between the different chairs for each of the measures (Table 6.2). For the raw measures of detected movement, ΣYZ and ΣXYZ, different chairs were not found to have a significant effect. In terms of discomfort induced, chair A was perceived as the most uncomfortable, followed by chair B, chair C and chair D induced the least discomfort. Similarly, most DPCs were detected in chair A, followed by B, then C then D. For TPCs, the order from most movements induced to least was ABDC. A comparison of the effects due to the time the subject had been sitting showed similarly significant results for: CP-50 over all chairs; DPC in all chairs except chair D; and TPC in all chairs except chair B. These results have been summarised in Table 6.3. In general, perceived discomfort and the frequency of DPCs and TPCs tended to increase over the time course of each trial, although ΣYZ and ΣXYZ failed to reach statistical significance for this temporal increase under some experimental conditions.

Table 6.2 – Summary of Friedman test results for CP-50, DPC, TPC, ΣYZ, ΣXYZ, all versus chair blocked by subject

Variable	P-value (adjusted for ties)
CP-50	<0.001
DPC	0.001
TPC	0.002
ΣYZ	0.151
ΣXYZ	0.376

General trends for all of the measures over time and under the different experimental conditions have been presented as follows: CP-50: Figure 6.7; DPC: Figure 6.8; TPC: Figure 6.9; ΣYZ: Figure 6.10; ΣXYZ: Figure 6.11. From visual inspection, it can be seen that there are similarities between many of the graphs, with temporal increases displayed in all and the chairs being able to be separated, to some extent at least, in all cases.

Table 6.3 – Summary of Friedman test for CP-50, DPC and TPCs versus time and blocked by subject for each chair

Variable	Chair A	Chair B	Chair C	Chair D
CP-50	<0.001	<0.001	<0.001	0.001
DPC	0.001	<0.001	<0.001	0.029
TPC	0.001	<0.001	<0.001	0.029
ΣYZ	0.113	0.006	<0.001	0.036
ΣXYZ	0.02	0.004	<0.001	0.008

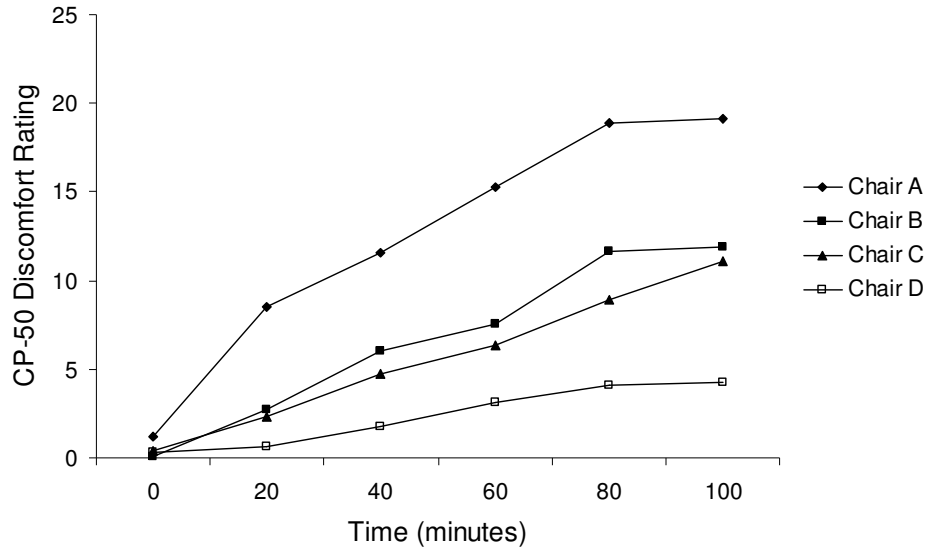


Figure 6.7 – Perceived discomfort as measured by the CP-50. Data shown are estimated medians for all subjects

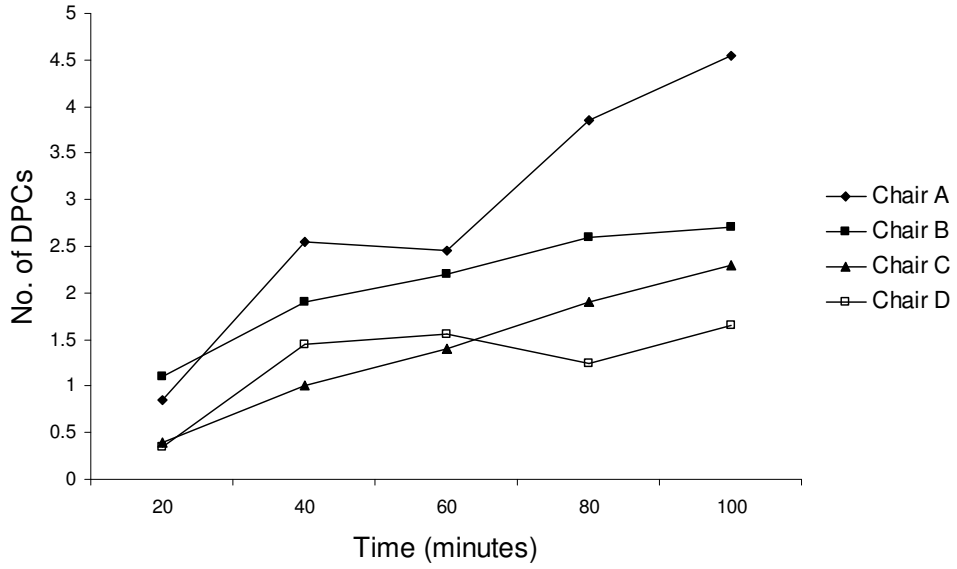


Figure 6.8 – Distinct postural changes as detected by the activity monitor. Data shown are estimated medians for all subjects.

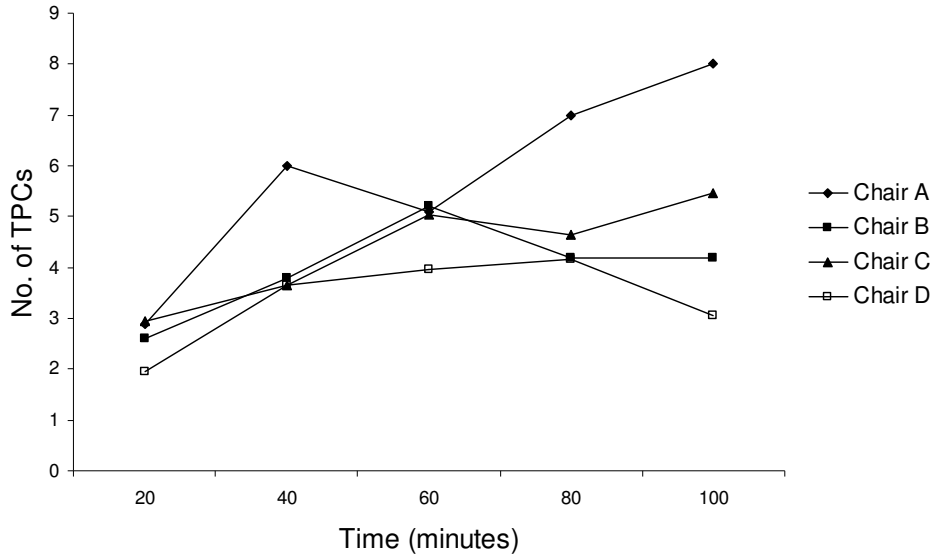


Figure 6.9 – Transient postural changes as detected by the activity monitor. Data shown are estimated medians for all subjects.

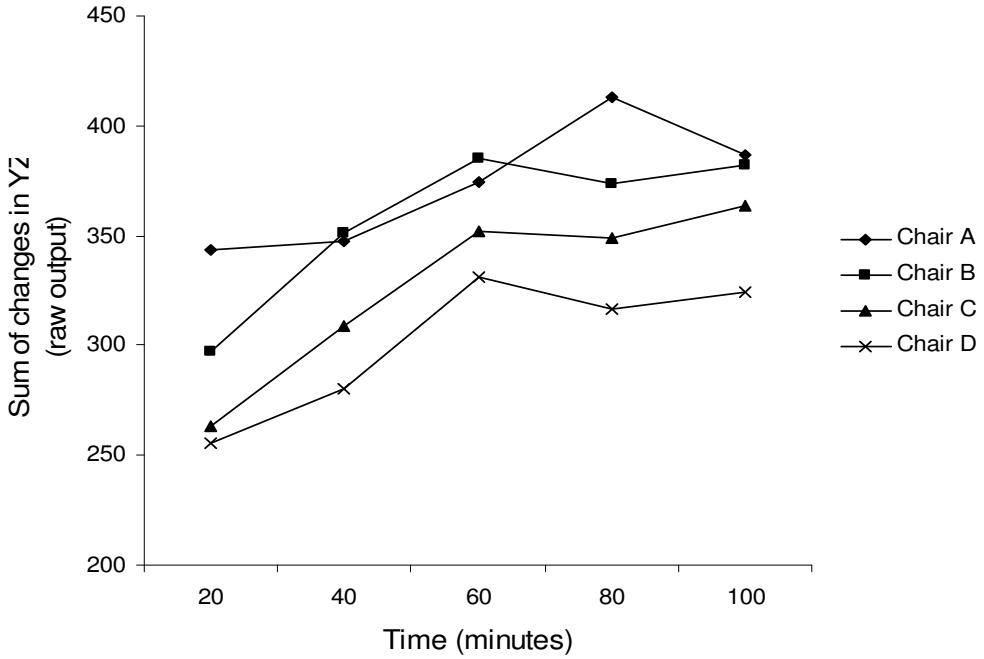


Figure 6.10 – Summation of outputs from Y and Z channels of activity monitor. Data shown are means for all conditions

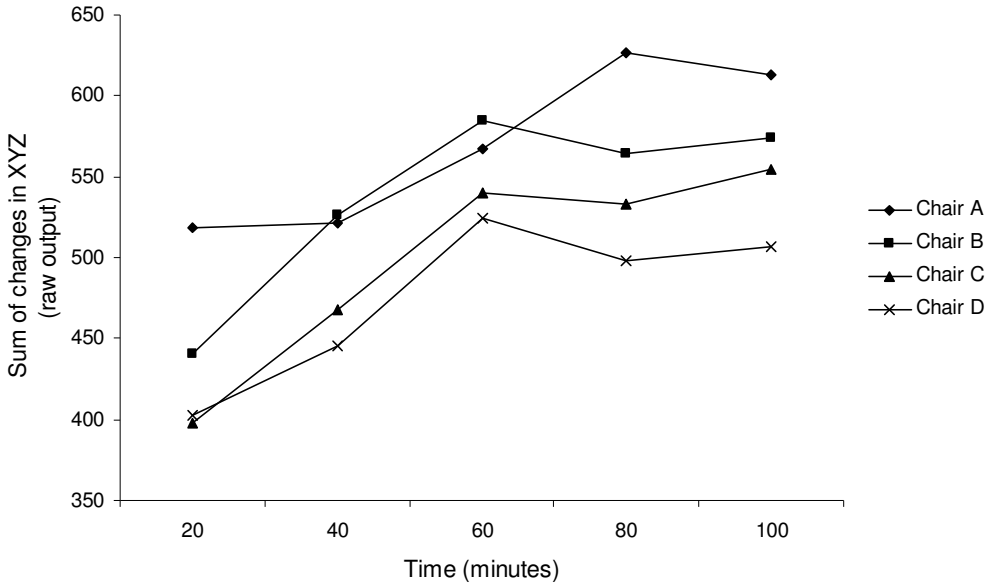


Figure 6.11 – Summation of outputs from X, Y and Z channels of the activity monitor. Data Shown are means for all conditions.

6.4.4 Prediction of discomfort

Table 6.4 summarises the multiple regression model. Of primary interest here was the relationship between perceived discomfort and subjects' sitting movement as measured by the actigraph, CP-50 was made the dependent variable. Using DPC and TPC as predictors, it was possible to account for 29.7% of the variance in the subjective discomfort data. The model as a whole was significant ($P < 0.001$).

Table 6.4 – Summary of discomfort measure variables and regression analysis

	Median (IQR)*	Regression analysis		
		B	β	*P*-value
DPC	2 (0, 4)	0.4852	0.2423	0.046
TPC	25.75 (25.43, 26.5)	0.5848	0.1801	0.001

B: unstandardised beta coefficient; β : standardised beta coefficient
* Anderson-Darling test used to test normality of data

6.5 Discussion

The aim of this study was to determine if actigraphy, the measurement of activity using body mounted accelerometers, has the potential to be used as- 1) a technique for detecting the discomfort related movement produced by a sitting subject, and 2) an objective indicator of seating discomfort. In order to achieve this, an experiment was devised which measured the amount, frequency and also type of subjects' movements along with their own perception of discomfort when sitting for a set period of time and in a range of different chairs. This rationale was based around the dynamic nature of sitting and the related theory that as an individual becomes more uncomfortable in a seat, for any reason, they will tend to move around and fidget more and that these movements may be able to be related - directly or indirectly - to sitting discomfort.

Results showed that changes in sitting posture could be reliably identified from the actigraph data. The chairs chosen for this study were shown to induce a wide range of perceived discomfort levels, and that these levels increased significantly over time. This meant that the hypotheses could be tested over a wide range of discomfort states. The sitting activities detected by the actigraph were split into 'distinct postural changes' and 'transient postural changes'. The frequency of these measures occurring was shown to increase significantly over time and, in general, the more uncomfortable a chair had been perceived to be by the subjects, the more DPCs and TPCs were presented in them. A less selective analysis where the changes in raw output data from the activity monitor were summed proved to be less effective as indicators in indicating different discomfort states, although they did show some potential. Measuring DPCs and TPCs may be more effective because they did not take smaller, task related movements into account. Regression analysis showed that there is a relationship between the defined sitting movements identified by the actigrapy and perceived discomfort, albeit a low one (this is likely to be due to the relatively small sample size with high variance used in this study and future work

should involve the investigation of a larger sample). The suggestion that the major changes in posture in the form of DPCs and TPCs that are detected by the sternum mounted activity monitor are related to sitting discomfort is reinforced by earlier studies finding that large changes in posture are good indicators of the presence of discomfort (Vergara & Page, 2000, 2002).

The advantage of actigraphy as a measurement technique lies in its portability and the ease of interpreting the data it generates. The software exists such that an individual's different activities (i.e. walking lying or sitting) can be indentified from the data from the monitor, therefore sitting comfort tests could feasibly be carried out, without the need for supervision, in the subject's own workplace or home for extended periods of time. This is important as it is considered best practice to measure discomfort in the field. Motion sensitive cameras and force plates such as those used in gait laboratories may be able to provide a more accurate picture of the individual's exact movements, but it is not practical to follow the subject around with this equipment; and studying them in the lab hardly constitutes an accurate representation of their activities during a normal day. Another option is a pressure mat system that can be spread over a seat base and used to track a subject's centre of gravity, but these are often quite expensive and may not be suitable for every type of seat. Thus, it is believed that despite the reduction in the accuracy of the precise amount of movement measured, for longer and larger studies especially, the advantages presented by using actigraphy are important to take into consideration. Future work should involve the comparison of actigraphy to gold standard discomfort measurement techniques such as dynamic pressure distribution.

There are a number of factors that can influence sitting discomfort and our reaction to it. These include fatigue, boredom, general wellbeing and the task being performed. A study which used surface electromyography to investigate the effects of fatigue during sitting did not find any significant effects on the signals from cervical erector spinae and external oblique muscles after a 150 minute trial (El Falou et al., 2003), suggesting that fatigue may not have played a significant role in this 100 minute study. This is reinforced by findings from the current study that

even in the chair considered to be the most uncomfortable, perceived comfort levels tended to peak below 20 on the 50 point CP-50 scale, with 20 being considered to represent *low discomfort*. Another influence on discomfort which is not dealt with directly in this experiment and must be noted is boredom. ICM has been used as a measure of boredom (Bull, 1987) but due to the relatively short period of these trials and the fact the subjects had reading material it is believed that the effect of this would be minimal. There are also flaws with using questionnaires at set intervals to determine discomfort levels, especially due to the fact that continuously raising the issue of discomfort may make the subject more conscious of sensations that could be related to discomfort (Kolsch et al., 2003). Differences in some aspects of sitting behaviour between males and females have been noted (Dunk & Callaghan, 2005), and this is another area that, although beyond the scope of this general study, is worth investigation in the future. It could be argued that some of the seats used and the fact that there was no desk to lean on in this experiment meant that reading was not an entirely suitable task. However, it was intended to test if the technique would be robust enough to determine changes in discomfort levels while subjects were carrying out a simple, everyday task and it is believed that any specifically task related discomfort felt by the subjects would be registered on both the subjective rating scales and the activity monitoring data. Previous research has suggested that subjects carrying out reading tasks may present more upper body movements (van Dieen et al., 2001) than those carrying out word processing or computer aided design, however there were no differences in the amount of these task related movements in different chair types. The lack of true office chair in the selection tested here is a limitation to the general applicability of this study, and presents a further opportunity for future research.

There were some unforeseen events, including coughing and sneezing, that occurred during the test sessions that could be recognised in the results as TPCs. As these were involuntary actions not related to discomfort it is possible that they could skew the results for the TPC data as there were significant effects from the chair used and time period. Task related movements, such as turning pages or opening and closing books may also have shown up as TPCs and contaminated the results. This would

tend to lead authors to believe that, despite failing to reach statistical significance in the regression analysis, with further investigation DPCs may be shown to be a more robust indicator of sitting discomfort.

It is sensible therefore to note that these results should be interpreted with some level of caution. Predicting human sitting behaviour is far from a precise science and a number of other factors must be considered. Indeed, the lack of a clear and precise biomechanical definition of discomfort in itself presents a major problem for seating research. However, it is believed that the results presented here and the advantages inherent with the use of activity monitors of the type used in this study do suggest that actigraphy may be able to play a useful role in future sitting discomfort research and related fields.

7 Investigation of the novel adaptive seating system

7.1 Introduction

The nature of this project required that the majority of time was spent on activities relating to the design and fabrication of the novel adaptive seating system, and this meant that it was not possible to carry out the kind of longitudinal study (ideally lasting several months or longer) that could attempt to fully investigate the long term and lasting effects of the novel design. In light of this, it was decided that the most effective use of the final experimental component of the project would be to focus on an investigation of the short term effects of one feature of the system: the stimulus reducing backrest.

7.2 Background and aims

As described in the literature review, adaptive seating has been reputed to have a wide range of effects on the user. Measuring all of these effects is a difficult task requiring a great deal of time and equipment. Therefore, for this study it was decided to concentrate on a smaller and more manageable number of factors, specifically those that have been identified as most important from the parent/teachers investigation and from the literature review. The hypotheses for this study are that when compared to an adaptive seating user's current system, the novel system will result in a change in their-

- posture
- functional ability
- pressure distribution under the ischeal tuberosities
- sitting activity patterns

The reasons for measuring postural and functional changes are self explanatory. Through the measurement of pressure distributions and sitting activity patterns it was hoped to gain some indication of sitting discomfort levels.

7.3 Methods and materials

7.3.1 Experimental design

The wide ranging difficulties that arise when attempting to objectively evaluate the efficacy of adaptive seating based interventions have been discussed at length in the literature review. With these in mind, it was decided to use a repeated measures study design to evaluate the effects of using the novel seating system when compared to the seating system that the subjects normally used. Repeated measures-type study designs have been used previously to examine AT type devices empirically using small and often heterogeneous samples (Koontz et al., 2005; Levy et al., 2004). Various outcome measures, both qualitative and quantitative in nature, are used to evaluate the hypothesis that the novel adaptive seating system will results in improvements in the areas of posture, functionality, or reducing discomfort. The order that the subjects were tested as well as the order they sat in the seating systems was randomised before the test day.

7.3.2 Subjects

7.3.2.1 Recruitment

It was initially intended to recruit subjects directly through the NHS (specifically through the West of Scotland Mobility and Rehabilitation Centre (WESTMARC)). However, when the time came to begin identifying suitable subjects, circumstances were such that it was not possible to follow this route, and an alternative recruitment strategy had to be implemented. This new approach involved the charity Capability Scotland (registration number SC011330), an organisation whose aims relate to the promotion of equality for disabled individuals. Through this charity's links, contact

was made with Stanmore House School (Lanark, Lanarkshire, UK), a special needs school attended by a large number of pupils who use adaptive seating. The school consented to being involved in this project, and staff in the school's physiotherapy department kindly lent their time and expertise and agreed to help with the testing sessions.

The physiotherapy staff members were also invaluable in helping to identify suitable students to take part in the study (inclusion/exclusion criteria are given in the following section). Once these potential subjects had been identified, two sets of participant information sheets and consent forms - one designed for the children who would be the subjects in the study, and one for their parents - were sent out as a pack to parents along with a letter describing the general purpose of the research. If the child was unable to give written consent (as was the case for all but one of the subjects) verbal or indicated consent, if confirmed by parent or carer, was accepted. During the course of their test session, subjects were asked at specified points if they were happy to continue taking part and were required to give their verbal or indicated consent before continuing.

A number of visits were made to Stanmore House School prior to the testing session. These visits allowed aspects of the protocol to be discussed with the physiotherapy staff members who would be present during testing, and for information about the subjects to be gathered. On the day of testing, all equipment was transferred to the school that morning and set up in the physiotherapy department, an area of the school that all of the subjects were familiar with.

7.3.2.2 Inclusion and exclusion criteria

To be eligible for inclusion in this study, subjects had to be-

- *diagnosed with CP*: the inclusion of subjects with other neuromuscular disorders was ruled out in order to try and maintain some level of conformity across the sample
- *GMFCS level IV or V*

- *an experienced adaptive seating user*: subjects had to use their chair for six hours or more per day
- *a user of a seating system that had undergone a recent (within approximately three months) revision at a seating clinic*: a considerable amount of time will be spent setting up the test rig so that it provides optimum positioning for the subject. Therefore, in order to gain a valid comparison with the novel system the subject's current system must provide a high level of positioning and support, as defined by a specialist seating bioengineer. In addition, due to the non-linear growth patterns of the subjects, physiotherapy staff were asked to confirm whether they were happy with the seating system at that point in time.
- *able to understand simple verbal instructions*: these instructions were part of the functional testing

Exclusion criteria were that the subjects must not have any -

- *major skeletal deformities that could not be accommodated by the novel system*: i.e. subjects who used custom moulded seating systems
- *skin complaints*: this criterion was required due to the initial intention for this study to involve the measurement of surface EMG signals, as dermatological conditions could have been exacerbated by the preparation process for and application of the electrodes. This component of the experiment had to be removed from the final protocol at a late stage due to problems with the recording software.

7.3.2.3 Subject characteristics

General demographic data for the subjects involved in this study are given in Table 7.1. Staff at the school were not able to provide exact dates for the most recent seating assessment for each subject, therefore some of the figures stated here are approximate values. Weight measurements were those most recently available.

Table 7.1 – Characteristics of the subjects

Variable	Mean (range)
Male/Female	4/1
Age	14.8 years (13-18)
Weight	25.6 kg (23-32)
Time since last seating assessment	3 months (1-4)

7.3.3 Ethics

As this work was originally intended to take place within the framework of the NHS, ethical approval was applied for and obtained through the National Research Ethics Service (NRES, formerly COREC, now IRAS). Additionally, for insurance purposes, ethical approval was required from the University Ethics Committee (UEC) at the University of Strathclyde and this was applied for using the same set of documentation as that submitted to the NRES. Both approvals were granted by January 2008. The reference number for these applications is 07/S0703/99.

7.3.4 Materials

7.3.4.1 Seating systems

The seating system to be tested was the prototype of the novel design that was described in chapter 4. The system was tested for safety and checked for reliability before the study commenced. The seating currently used by the subjects were two CAPS II, two Zitzi Delfi systems and one contoured advanced seat (Leckey). Subjects were tested without their knee blocks in place to avoid any additional confounding effects resulting from the use of two different types of orthotic support.

7.3.4.2 Pressure distribution measurement system

7.3.4.2.1 System selection

There are a number of pressure distribution measurement systems on market, each based around different technologies, resulting in different advantages and limitations. Attempts to secure funding to allow the purchase of the preferred system for this study (the Pliance-x from Novel, Munich, Germany) were unsuccessful or had not completed the review process before the study was due to begin. Thus, in order to be able to collect at least some interface pressure data, a Tekscan system (Tekscan Inc, MA, USA) was borrowed from the National Centre for Prosthetics and Orthotics at the University of Strathclyde. Sincere thanks go out to Dr Arjan Buis from the Centre for his time and advice regarding the use of this system.

The Tekscan system, although generally considered to be less reliable than many of other systems on the market, has been shown to be very popular among clinicians (Ferguson-Pell & Cardi, 1992). This is most likely to be due to a number of user friendly features in the software, including-

- An accessible software interface with several options for viewing the data (2D, 3D and contour plots) in both real time and for pre-recorded tests.
- Variable sampling frequency and time frame
- Graphing options for data
- Straightforward calibration of transducers
- Raw data are easily exported in ASCII format for further analysis

7.3.4.2.2 Transducer characteristics

The transducers used by this system are based around force sensing resistor (FSR) technology and are fabricated from two layers of bi-axially orientated polyethelene terephthalate (boPET) polyester film printed metal circuits separated by a layer of conductive ink. When a force is applied to the sensor, the resistive properties of the ink layer alter, hence changing the output from the circuit. BoPET is a viscoelastic material, meaning that time dependent characteristics, especially drift and hysteresis, must be taken into account when analysing the data produced.

Behaviour claims for the transducer were as follows (taken from the system manual if source not referenced)-

- Drift: occurs up to 5% in initial 5 seconds, thereafter the time factor increases by a factor of 10.
- Temperature sensitivity: data output alters by 1% per degree Celsius.
- Repeatability: A number of previous studies have identified issues with repeatability associated with Tekscan transducers (Brown et al., 1996; Buis & Convery, 1997; Woodburn & Helliwell, 1996). Tekscan suggest that transducers should undergo a preconditioning period of 10 loading cycles before use, and this has been independently shown to significantly improve the repeatability of the data generated (Buis & Convery, 1997).

An additional feature of FSR sensing technology that must be noted if it is to be used on a contoured surface is response to curvature. It becomes quickly apparent from initial familiarisation with the system that when the transducer is bent, a noticeable change is registered on the output readings. This has previously been reported in the literature when FSR technology was being used to measure in-shoe pressure measurements, where places where curvature is noted, especially around the metatarsal head and heel areas (Rose et al., 1992). Indeed, even without the effect of curvature Tekscan transducers are known to have an inter-cell variability of ±25%. However, the equilibration and calibration features of the software mean that the inaccuracies that occur due to inter-sensor variations and curvature can be reduced dramatically if the sensors are calibrated in situ, as was the case in this study.

The manufacturers have claimed that developments in later versions of the software used to collect the data have improved some of these characteristics, and part of this project aims to evaluate these changes. The version of the software used for this study and its preparatory work was F-Scan 5.8.1.

7.3.4.2.3 Transducer selection

Two pressure measurement transducers compatible with this pressure measurement system were available for this study. (It should be noted that a wide range of other transducers, including mats designed specifically for seating purposes, are available

but the way these are interfaced with the system varies, thus limiting the options available for this study.) These were-

- The 9810 Tekscan sensor, a rectangular sensor matrix of 96 individual sensors arranged in an array of 6 columns of 16 sensors, giving a total sensing area of 15,500mm^2. This sensor is intended for use in prosthetic sockets. Each sensor has an area of 40mm^2 (giving a resolution of 0.6 sensors per cm^2), an overall thickness of 0.017mm, and is intended for pressures up to 25kPa (750mmHg)
- The 3000 Tekscan sensor, designed for in-shoe applications but is able to be trimmed to a variety of required shapes. Sensor thickness is again 0.017mm and it has a resolution of 3.9 sensors per cm^2. This transducer is intended to measure pressures up to 75kPa (2250mmHg)

Initial attempts to use the 3000 sensor in order to achieve the maximum resolution from the system were aborted as the sensor proved to lack sensitivity at the relatively low pressures that are found in seating research (peaking at approximately 200 mmhg (Apatsidis et al., 2002)). Therefore, the 9810 sensor was chosen due to its more suitable range of intended operating pressures.

7.3.4.2.4 Equipment for calibration and testing of transducers

To calibrate the transducers and test their initial static response, a pressure chamber rig, previously developed in the Bioengineering Unit, was used. This rig consists of two aluminium plates of dimensions 370 x 185 x 18mm. The upper plate has a central chamber milled out (320 x 135 x 1mm, positioned centrally) that is covered and sealed with a 0.2mm thick Mylar membrane. Twelve 5mm inlet holes are directly connected with the central chamber and these are connected to an external air compressor, via a variable pressure valve and a pressure gauge. Inlet holes are evenly distributed around the chamber at approximately 50mm spacing, centre to centre. There is an additional 3mm hole in the top plate that allows the pressure chamber to be connected to an external pressure measurement device. The lower plate is perforated with 1mm diameter holes, spaced 10mm centre to centre (parallel

to the edges of the plate) and these are intended to eliminate the assumed affect of air pressure build up between the membrane and the bottom plate.

During calibration and characteristic testing the transducer was placed in the central chamber and the upper and lower plates bolted together. A paper sheet was placed between the transducer and the bottom plate to prevent any protrusion of the transducer through the perforated holes in the lower plate. The pressure rig has previously been tested to ensure that it functions effectively and provides an equal pressure across the full area of the central chamber.

Pressure was measured using the gauge on the control valve, and using a mercury column connected to the chamber. The reading taken from the mercury column was taken as the overriding measurement due to its greater accuracy. The full testing set up is shown in Figure 7.1.

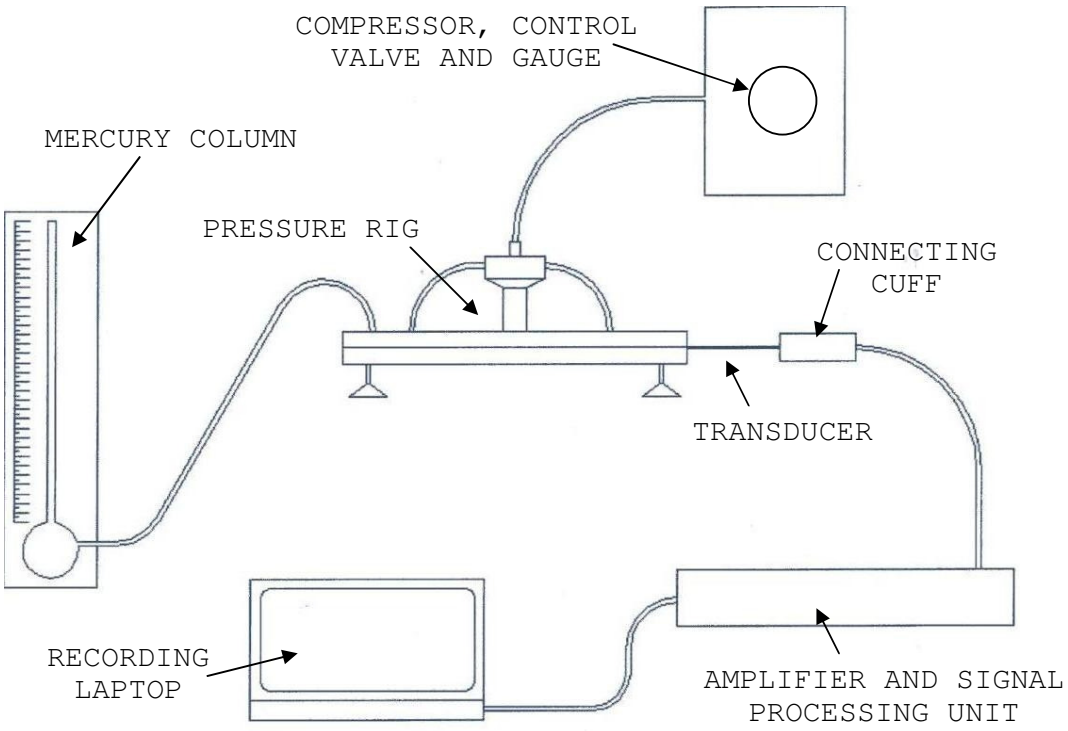


Figure 7.1 – Calibration and testing set up

7.3.4.3 Seated postural control measure

In order to measure changes in posture and functionality, a clinical evaluation tool has been used. The Seated Postural Control Measure (SPCM) (Roxborough et al., 1994) was developed to try to objectively measure static postural alignment and functional movement in adaptive seating system users. The measure is divided into two distinct sections covering each of these objectives. The first section attempts to measures static postural alignment. Predefined neutral or symmetrical position for various parts of the body are defined, and by measuring how far the subject deviates from these positions the efficacy of the system can be determined. The second section comprises a mix of distinct and combined tasks related to 12 measured items. The subjects are asked to complete whilst seated and are assessed on their ability to carry out the tasks. Activities range in difficulty allowing an objective measure of seated function to be obtained. This measure has the advantage of not requiring any complicated or difficult to obtain equipment for the tasks.

The SPCM is described by its developers as a "criterion-referenced outcome measure" with posture and functional task items being graded on a scale of 1 to 4, with 4 representing close to optimum posture/functional ability and 1 representing very poor posture/functional ability. The reliability of the evaluation tool has previously been established with inter-day variability of >5% (McDonald, 2005). The full test is designed to be administered in less than 30 minutes, and this was the case when it was used in this experiment. Due to concerns about the low sensitivity of the criterion based evaluation where each postural item is defined using a choice of four categories, each postural item was also measured manually in absolute degrees using a goniometer during the test session.

In this study three items were taken out of the functional assessment. Items 11 ("Moves his/her wheelchair forward 45 feet in less than 20 seconds") and 12 ("Moves his/her wheelchair forward 19 feet along an 8 feet wide corridor, turns right or left 90 degrees and passes through 33 inch doorway") were removed because of concerns relating to the variety of different controls used to control powered seating systems that might not be able to be accommodated on the novel system. As it

turned out, four of the five children did not use a powered chair. Item 8 ("Picks up raisin (or cheerio), places into mouth with preferred hand") was removed after discussion with the therapists who identified risks involved with the subject choking. In addition, three of the subjects had visual impairments which mean that they may be unable to carry out a number of the items in the assessment. As a result of this, the subjects with visual impairments were only asked to perform items 1, 2 and 5 of the assessment. Subject performances were scored during the test.

7.3.4.4 Activity monitor

As with the work described in chapter 6, the ActivPAL triaxial activity monitor was used to measure sitting activity in this study. The protocol previously developed for its use was repeated, i.e. the monitor was located at the top of the subject's sternum, a sampling frequency of 10Hz was chosen with no compression. The monitor was not removed from the subject after testing in each chair, rather, the key time points (i.e. when the subject were transferred between seating systems, when functional tasks were carried out, etc) were noted and used to extract the required sections from the raw data. Sections of the test where functional tasks were being carried out were not included in the analysis.

7.3.5 Methods

Before commencing pressure measurements, functional tests, or postural measurements, subjects were given a few minutes to get used to the seating system they were using.

7.3.5.1 Testing of pressure measurement transducers

Using the pressure chamber rig, the transducer was preconditioned by loading it to a level of 400mmHg, reducing the load to zero, and repeating this process for a period of 10 cycles. This was repeated for all of the transducers used. Calibration was carried out using a constant pressure of 300mmHg.

Once this preconditioning was completed the software was set up to sample the output from the transducer at a rate of 2Hz. The pressure in the chamber was increased in increments of 50mmHg from 0mmHg up to 400mmHg. Pressure was then decreased in the same increments until it reached 0mmHg. Transducer output was recorded for 120 seconds at each pressure level, including 0mmHg.

7.3.5.1.1 Sitting pressure measurements

In order to measure the pressure distributions under the ischeal tuberosities, four 9810 transducers were used. Prior to testing these transducers were equilibrated, calibrated and pre-conditioned using the same pressure rig and procedures described earlier. Transducers were then cut longitudinally between the columns to reduce the effects of curvature on the transducers and adhered to a sheet of plain paper using Spray Mount™ (Maplewood, Minnesota, USA) in the layout shown in Figure 7.2. This was to hold the transducers in the same position when they were transferred between seating systems. Data were recorded in five minute blocks before and after the functional tasks and in both seating systems.

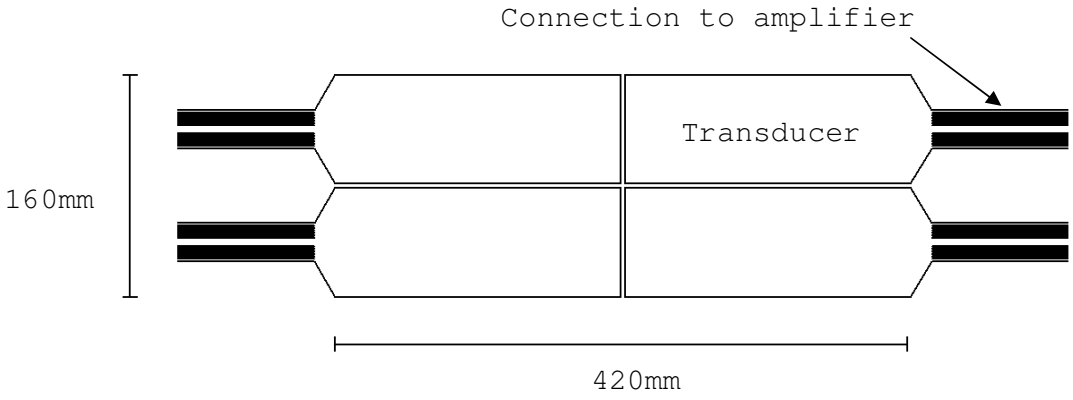


Figure 7.2 – Pressure transducer set up for seating tests

7.3.5.1.2 Anthropometric measurements

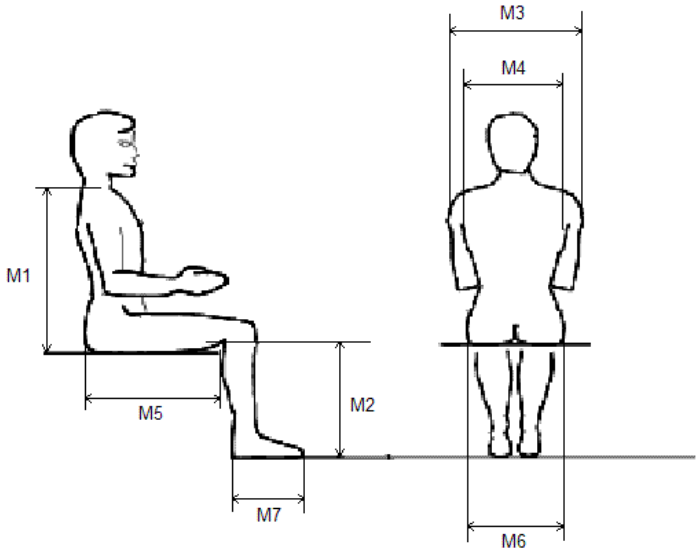


Figure 7.3 – Anthropometric measurements

A number of measurements (illustrated in Figure 7.3) were taken by a researcher prior to transfer into the novel system so that it could be set up in a manner that would attempt to ensure optimal positioning. The measurements of interest were-

- Sitting height (M1): the vertical distance from the horizontal sitting plane to the highest point of the shoulders
- Lower leg length (M2): the vertical distance from the lower surface of the foot the lower surface of the thigh when the knee is bent at 90°
- Shoulder breadth (M3): the maximum width of the shoulders in the coronal plane
- Chest breadth (M4): breadth of torso taken at the level of the axillae
- Buttock to popliteal (M5): the maximum horizontal distance from the posterior of the buttock to the popliteal (the area at the back of the knee)
- Hip breadth (M6): breadth of body across the widest portion of hips
- Foot length (shod) (M7): maximum distance form heel to toe of shoe

Due to the materials available, individual measurements were generally rounded to the nearest centimetre. Further adjustments were made, if necessary, once the

subject was sitting in the novel system and every attempt was made to ensure they were comfortable and relaxed in the seat (Figure 7.4).

Figure 7.4 – Subject prior to testing in their own (left) and the novel (right) seating system

7.3.5.1.3 Postural and functional measurements

For the testing, each subject was assigned a SPCM scoring form (this has been included as Appendix D). This form was completed for the subjects as they sat in each of the seating systems during the test session. For the functional tasks, each subject was asked three times to perform the task and their best attempt was the score recorded. Including the time taken to transfer the subject between seating systems, each test session was completed in less than one hour.

7.3.5.2 Statistical analysis

In all relevant cases, prior to analysis the Anderson Darling test was used to check the normality of the data and a suitable statistical test chosen depending on the result. No correction for multiple comparisons has been made in this analysis due to the small sample size and exploratory nature of the study.

The characteristics of the Tekscan system have been presented in descriptive format with the most relevant measure of error reported in each case. For the pressure distribution measurements from the sitting tests, descriptive results have been presented for peak and average values (mean, SD), and comparisons between the readings taken on the novel system and the user's own seating system made using a paired t-test. Temporal effects in the data taken before and after the functional tasks were performed were also tested for using the same analysis.

Findings from the SPCM have been presented in descriptive form for both postural and functional measures. For the categorical measurements, Wilcoxon Signed Ranks test has been used to compare the results from the novel and original systems because of the non-parametric nature of this data. In addition, the postural measurements in absolute degrees were compared between the novel and the subject's own system using a paired t-test.

As with the protocol presented in chapter 6, DPC and TPC-type movements were identified from the actigraphy data. Due to the short timeframe of each test session and the nature of the seating system, the general activity data, measured from the Y and Z channels in the activity monitor and defined as degrees movement per minute, was also analysed in case this gave insight into the subjects' discomfort levels. Temporal effects in the data recorded before and after the functional tasks were also tested for.

7.4 Results

7.4.1 Characteristics of the Tekscan system

7.4.1.1 Linearity

Analysis of linearity, the variation in the constant of proportionality between an input physical quantity and output signal, found that the transducer showed R^2 values of 0.998 and 0.988, for the loading and unloading data respectively, when compared to the best fitting straight line. As expected at this level of loading, there was no sign of output saturation (the manufacturer suggests saturation does not occur in these transducers until loading reaches pressures of greater than 25kPa (425mmHg)).

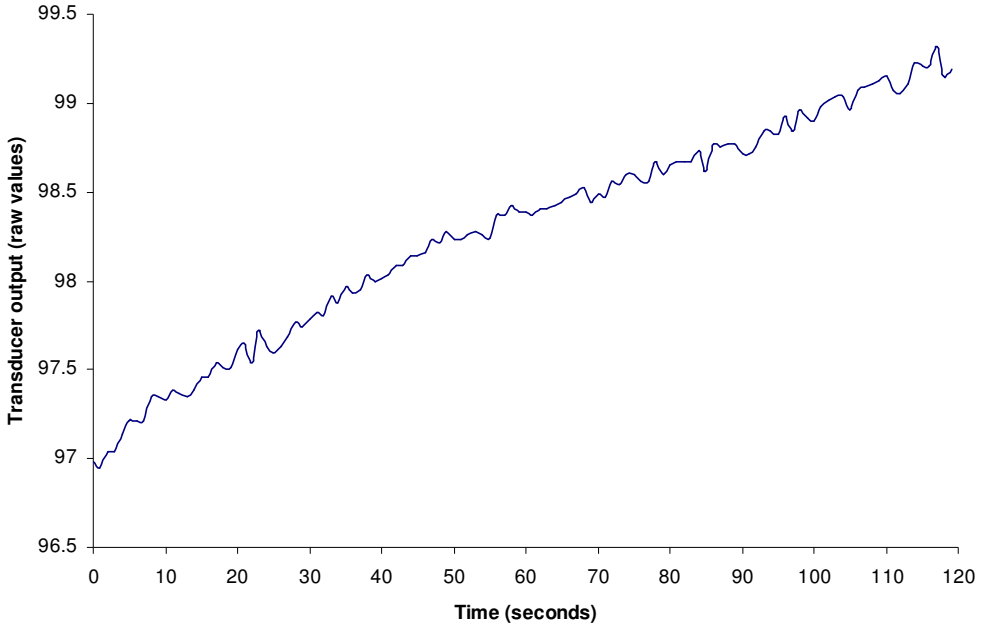


Figure 7.5 – Output from transducer loaded with a constant pressure of 350mmHg

7.4.1.2 Drift

Drift (also known as output stability) is the variation in output signal under constant conditions. Findings show that the raw output signal from the transducer increases by on average 2.5 units over the 120 seconds of measurement for each pressure interval in the increasing loading cycle, with little variation shown for each loading value. During unloading, the transducer displayed very little evidence of drift

occurring, with 0.3 units being the average change registered. The direction of the change did not appear to be consistent, with both increases and decreases in the signal being found depending on the whether the transducer was being loaded or unloaded. A randomly chosen output signal at constant load is displayed in Figure 7.5.

7.4.1.3 Noise

Some noise, the appearance of variations in the sensor output unrelated to the system input, can be clearly seen in Figure 7.5. However, it is at a level (under 0.2% of total signal) that can be discounted for these experiments. It was also noted during familiarisation with the system that the close proximity of electrical equipment could interfere with the output, and this fact was taken into account during testing of the adaptive seating systems.

7.4.1.4 Hysteresis

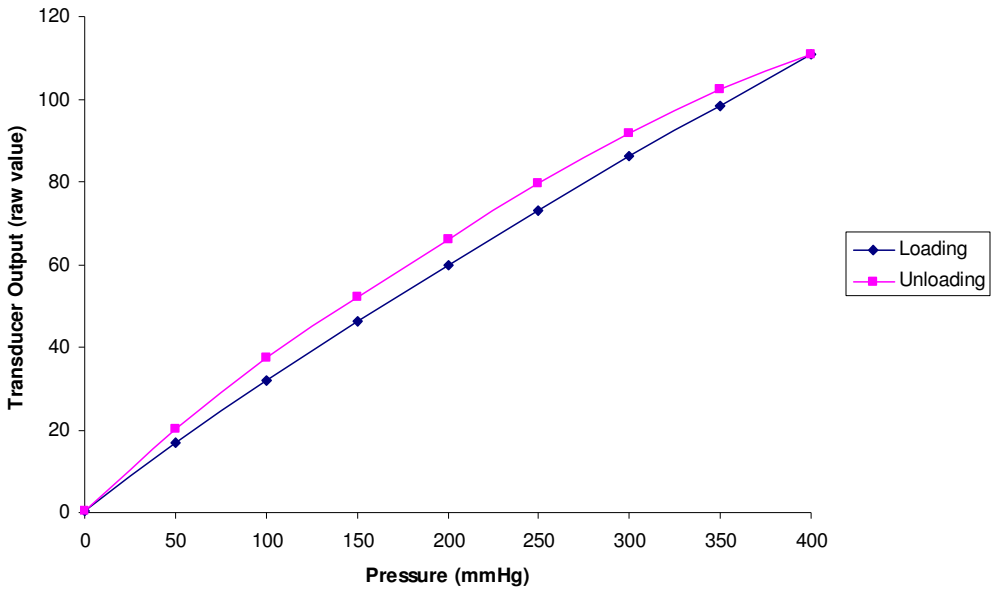


Figure 7.6 – Graph showing hysteresis effects on transducer output. Values are means taken across the constant load period and across all three tests.

Hysteresis is commonly defined as a phenomenon where two (or more) physical quantities bear a relationship which depends on their prior history. In this case it more specifically refers to the fact that the sensor output provides different values depending on whether the pressure load has been increasing or decreasing prior to the measurement being taken.

To test the effects of hysteresis, output values obtained during characteristic testing were averaged across each time period and across the three tests (see Figure 7.6). Following analysis, it was found that for measurements taken in the typical seating loading range, the maximum error as a direct result of the hysteresis effect was 6.24%, with this error being defined as the maximum difference between the ascending and descending output values described as a percentage of the maximum output value at said loading.

7.4.2 Testing of novel seating system

7.4.2.1 Anthropometric measurements

The measurements taken to allow the novel seating system to be set up to suit each subject are given in Table 7.2.

Table 7.2 – Anthropometric measurements

Measurement number	Name	Mean and range (mm)
M1	Sitting height	620 (530-780)
M2	Lower leg length	422 (390-520)
M3	Shoulder breadth	380 (370-400)
M4	Chest breadth	282 (230-310)
M5	Buttock to popliteal	450 (430-490)
M6	Hip breadth	290 (240-320)
M7	Foot length	200 (180-230)

It was found for one of the subjects that their legs were too long to fit correctly into the footrests on the novel system, and for this test the footrest assembly was removed for the duration of the trial. There did not appear to be any noticeable effect on the subject's overall posture resulting from this modification.

7.4.2.2 Pressure measurements

Table 7.3 – Pressure measurement results

	Normal System (SD) mmHg	Novel System (SD) mmHg	Paired t-test (p-value)
Average pressure	91.5 (12.7)	67.5 (31.24)	0.777
Peak pressure	169.4 (76.7)	141.8 (82.4)	0.663

No temporal effects were found in the pressure distribution data, therefore findings have been presented as means for the whole test period (Table 7.3). Although average and peak pressures were generally found to be lower in the novel system with mean reductions of 24 and 27.6mmHg respectively, statistical significance was not achieved for either measure.

7.4.2.3 Postural measurements

None of the differences in the measured postural items was found to be statistically significant when the subject's own chair was compared with the novel system (Table 7.4). A large but non-significant improvement in the rotational positioning of the head was found, but this was countered by an increase in the lateral shift of the trunk. Overall, the findings showed a mix of relatively small changes between the systems, both improvements and deteriorations in posture.

7.4.2.4 Functional task results

As with the postural results, no significant changes in functional ability were detected (Table 7.5). Notably, there were slight improvements in the head positioning items in the novel system, and this was thought to be related to the

improvements in the rotational positioning of the head described in the previous section.

Table 7.4 – Postural measurements. Category statistics are p-values from Wilcoxon Signed Ranks test; degree statistics are p-values from paired t-tests

Body Segement	Plane	Angular Position (SPCM rating (degrees from neutral))		Category Statistics	Degree Statistics
		Own System	Novel System		
Head	Lateral tilt	3 (11.4)	3 (11.2)	0.564	0.932
	AP tilt	4 (15.4)	4 (13.8)	0.414	0.744
	Rotation	2 (25.2)	3 (11.6)	0.257	0.166
Shoulder	Height	3 (4.6)	3 (7.4)	0.564	0.371
Trunk	Rotation	3 (6.2)	3 (7.4)	1.00	0.477
	Lateral shift	4 (2.4)	3 (9.2)	0.083	0.116
	Inclination	4 (4.4)	4 (3)	0.317	0.28
	Lumbar curve	4 (-)	4 (-)	1.000	N/A
	Thoracic curve	4 (-)	4 (-)	0.317	N/A
Pelvis	Obliquity	4 (0)	4 (0)	1.000	0.944
	Tilt	3 (8.4)	3 (9.4)	1.000	0.593
	Rotation	4 (0)	4 (0.8)	1.000	0.658
Right hip	Flexion/extension	4 (7)	4 (7.2)	1.000	0.374
	Rotation	3 (3.4)	3 (3.2)	0.564	0.944
	Ab/adduction	4 (1.4)	4 (5)	0.564	0.942
Left hip	Flexion/extension	4 (7.2)	4 (6.8)	1.000	0.365
	Rotation	3 (3.4)	3 (5)	0.564	0.884
	Ab/adduction	4 (4.2)	4 (6)	1.000	0.706
Knee	Flextion/extension	4 (0.6)	4 (2.4)	1.000	0.634
Ankle	Dorsal/plantar flexion	4 (0)	4 (0)	1.000	0.529

Table 7.5 – Functional task results. Differences between performance in own and novel seating system compared with Wilcoxon Signed Ranks test. Performance ratings are median values for both systems.

Task	Performance ratings		Statistics
	Own system	Novel system	
1. Lifts head upright and maintains for 5 seconds	3	4	1.000
2. Lifts head upright, in midline, and maintains for 10 seconds	2	3	0.317
3. Leans forward, touches toy with preferred wrist or hand, re-rects	4	3.5	0.317
4. Leans forward and to right or left, touches toy with opposite hand, re-erects	4	3.5	0.317
5. Lifts both upper limbs free of support	4	4	1.000
6. Reaches forward, grasps and toy with preferred hand	2	2	1.000
7. Removes and replaces lid of screw-type jar	2	2	1.000
8. Picks up pen and makes mark on paper	3	3	1.000
9. Places dice in jar, one at a time with preferred hand, in 30 secs	2.5	3	0.317

7.4.2.5 Actigraphy measurements

No temporal effects in the actigraphy data were observed during the time course of the experiment. Therefore, data has been presented as means for the full quiet sitting test in each chair (Table 7.6 and 7.7). Despite an overall increase in the movements detected in the novel system, the difference was not found to be significant for any of the analyses carried out (TPC p=0.343, DPC p=0.477).

Table 7.6 – Actigraphy data presented as transient postural changes (TPC) and distinct postural changes (DPC)

Subject	Normal System		Novel System	
	TPC	DPC	TPC	DPC
1	5	0	5	0
2	8	0	19	2
3	4	0	9	1
4	10	1	8	0
5	5	0	4	0
Mean	6.4 (2.2)	0.2 (0.4)	9 (5.3)	0.6 (0.8)

Table 7.7 – General actigraphy data. Values stated are degrees of movement per minute

Subject	Normal system (SD)	Novel system (SD)	T-test p-value
1	91.1	71.4	
2	148.9	367.6	
3	74.1	146.4	
4	179.9	131.6	
5	97.9	59.1	
Mean	118.4 (44.3)	155.2 (124.5)	0.504

There was found to be a large amount of variation in the subjects' activity patterns in the novel system. When first put into the novel system, one subject (subject 2) did appear quite agitated at the beginning of the trial and this was reflected in the

actigraphy data for this period, with detected movements being over two times greater for general actigraphy movement and TPCs in the novel chair.

7.5 Discussion

This study was focused mainly on the investigation of the short term effects of one aspect of the novel adaptive seating system (described in Chapter 4): the stimulus reducing backrest. To do this, a repeated measures type study design was used which allowed subjects' posture, functional ability and sitting activity, along with their sitting pressure distributions, to be tested in both their own seating system and a prototype of the novel system. The hypothesis was that a measurable change in these variables could be detected between the current and novel systems.

Investigation of the Tekscan pressure measurement system properties indicated that the latest version of the software did produce some improvements in terms of lower drift and hysteresis errors when compared to figures previously reported in the literature (Ferguson-Pell & Cardi, 1992). The effect of hysteresis, with a maximum variation found here to be 6.25%, remains something of a concern but was deemed to be within acceptable limits for the seating test elements of this study. Regarding the drift characteristics of the transducer, it would normally be expected that there would be a distinct signal drift directly after the loading had been changed, the influence of which would then decrease exponentially over time. This was not particularly noticeable in the results presented here, but this may be able to be accounted for by the transient rather than instant nature of the loading changes used. To alter the pressure in the test rig, a screw based mechanism on the control valve had to be turned several times and this meant that it took a few seconds to increase or reduce the pressure to the required level. Measurements were only recorded once the target pressure had been achieved. One characteristic of the Tekscan transducers that was not addressed here was their response to curvature. However, by cutting the transducers between the columns of load cells it was hoped to minimise the effects of this during the sitting trials. Overall, these results suggested that it would be acceptable to use the Tekscan system, and in particular the 9810 transducer, for the

adaptive seating trials. This was reinforced by the fact that the results from the seating trials themselves were in line with those previously found in previous work (Spijkerman et al., 1995).

The measurements taken to assist in setting up the novel system were found to be in line with those already available in the literature (Hobson & Molenbroek, 1990), suggesting that the small sample tested here was representative, in terms of anthropometric sizes, of the greater population of children with CP.

From the results of the seating trials, no temporal effects were noted in any of the measures tested. This is most likely due to the relatively short time span of each of the sitting tests and is perhaps influenced by the fact that the subjects were accustomed to sitting for extended and uninterrupted periods of time.

There would appear to be no improvements in posture or functional ability resulting from the use of the novel seating system. The SPCM detected small and non-statistically significant improvements and deteriorations in posture but no conclusive changes. However, when using the SPCM, it was found that even when using visual aids as suggested in the manual, i.e. the flexible curve that was used to join the iliac crests, there was still a level of measurement error inherent in the postural position measurements that needs to be noted. This error was estimated to be 2-5° but may vary depending on the postural angle being measured. A possible improvement to this method would be to attach flexible electronic goniometers to the subjects in order to measure the postural angles. The number of different postural angles may make this course of action difficult, and using a single device that was moved between locations would require validation in terms of repeatability. During the course of using the SPCM to measure posture, it was noted that movements made by the subjects on occasion could make it difficult to decide what the subject's resting posture was and this is a limitation of this kind of measure. In cases where this was an issue the data represents the posture which was held for the longest period of time. Again the short time frame of the experiment may have influenced this as the subjects may have favoured a different sitting posture after a longer period. The

findings from this study add to those from McDonald et al (2007) suggesting that the categorical measurements used by the SPCM may be too insensitive for many seating research applications.

The results for the measures that were intended to indicate discomfort were found to contradict each other. Despite lower peak and average pressures, overall sitting activity was higher in the novel system. The increase in activity may in part be down to the subject being in an unfamiliar system, especially in respect to the stimulus reducing backrest which, by nature, is providing a different type of support when compared to their own systems. A longer trial, where the subject used the system for a period of days may reduce the influence of this. The wide variations in detected movement suggest that individuals may have very different reactions to the novel system, with large changes in both directions being seen (one subject showing a 150% increase in activity while another showed a 40% decrease). The values for the pressure measurements were found to be in the same range as those published in previous research (Michael et al., 2008). Other tools do exist for measuring seating discomfort in individuals who use a wheelchair, however these tend to be based on subjects' responses to interview questions (i.e. the Wheelchair Seating Discomfort Assessment Tool (WcS-DAT) Crane et al, 2004)), an approach which was not appropriate for this subject group; or would have required longer periods of sitting and observation than were available for this study (i.e. the Non-Communicating Children's Pain Checklist (Breau et al., 2002)).

As the backrest was hypothesised to bring about benefits through a reduction in stimulus pressure to the user's trunk, the use of EMG measurements may have helped with this, although again the acute nature of the study may have limited the value of these results.

There are a number of limitations with this work. The time constraints imposed on this project meant that testing could only be carried out for the acute effects of the novel system. This is unsatisfactory for a number of reasons, mainly relating to the inability to test any functional or postural changes that may only become evident

through medium or long term use. The relatively low number of subjects who participated in and completed the study reflects in part the difficulties, noted in a number of studies (Springle, 2007), involved with recruiting and carrying out research on children with severe and complex disabilities. As a result of this, the statistical analyses that were carried out may not have had the necessary statistical power to achieve statistical significance for differences in some of the variables (type II error). A number of the other possible effects of the seating system were not tested for, including eating, drinking and pulmonary.

It was not possible to match exactly the cushions the children were using in their seating systems, therefore the pressure measurements taken have to be considered to have limited value. As the cushion used in the novel system was relatively new and unused this may also have had an affect on the results. An additional problem with the test set up was that with the tilting mechanism not being used in the prototype of the novel system, it was not always possible to match the angle of posterior tilt that the subject's own system was used at. Some adjustments were able to be made by adjusting the position of the backrest and the hip adjusters in the seatbase assembly, but in general the novel system was at around a 5° shallower tilt angle than the subject's own system. This could have potentially affected both the subject's posture - as it has been shown that angle of tilt can affect muscle tone (Nwaobi, 1986) - and the pressure distribution measurements (Burns & Betz, 1999). However, it is worth noting that peak and average pressures were consistently found to be lower in the novel system despite the often shallower tilt angle, when previous investigations have shown that posterior tilt tends to reduce sitting pressures (Michael et al., 2008).

Three children (those with visual impairments) out of the five tested were asked to perform a reduced number of items from the modified functional assessment. This had a further limiting effect on the studies ability to detect any significant functional changes resulting from the use of the novel system. However, it is the author's opinion that the functional assessment may not have the required level of sensitivity to detect the sometimes subtle changes in functional ability brought about by changing the set up of an adaptive seating system, and that an additional or adapted

measure, perhaps analogous to the absolute degree measurements that are used alongside the categorical ones in the postural assessment, may be required. The form of this additional assessment, whether based on timing, range of motion or other, requires further investigation.

Although this study was primarily focused on investigating the short term effects of the novel backrest shape, there were a number of other points found relating to the overall design of the system. Specific shortcomings that were found included-

- Footrests did not extend sufficiently to accommodate all of the children tested. This was the result of a mistake when designing the assembly that was not detected prior to the production of the engineering drawings or the seating tests proper. In addition, the footrest assemblies were found to be less stable than was intended and time consuming to adjust.
- Two of the subjects had difficulty maintaining a fully upright position with the support provided by the novel backrest, shown in the SPCM as a deterioration in postural quality of the trunk. This may be in part due to the shallower angle that the novel system was inclined at but it was also noted that in these cases the lower parts of the backrest which provide most of the lateral support to the user did not contact the subject satisfactorily.

With the exception of the footrests, the system displayed a good level of adjustability and was found to be quick and simple to adjust when setting up. Staff present during the trials appeared happy with the novel system's performance although they did comment on its lack of aesthetic appeal.

As a result of the findings from this study, the design of the footrest and backrest assemblies were modified to try and improve on the problems that had been identified. The left and right footrests, rather than being separately mounted on the system were altered so they both now come off a single, centrally mounted column which should provide more stability.

7.6 Conclusion

No significant differences were found between the novel seating system and the users' own in terms of posture, function, pressure distributions and activity. Using a Tekscan 9810 pressure transducer was found to be an acceptable method of measuring pressure distributions for the purposes of this experiment.

8 Conclusion

The research presented in this thesis provides a number of findings relating to the design of adaptive seating systems and their assessment, as well as suggestions for future developments of seating and related technologies, and the techniques used to assess them.

It has been shown that there are several areas relating to adaptive seating technology and provision where the parents of and teaching staff members that live and work with the children who use these systems feel improvements could be made. In particular, these areas related to how the systems cope with growth patterns of the children, the time taken for repairs or replacements, and the time it takes to transfer children to and from the systems. The functions of adaptive seating were also rated by perceived importance and it was found that postural support, providing comfort, positioning for eating and preventing the development of deformities were considered to be most important by both groups.

These results were used, in combination with a review of the relevant literature and a previously constructed prototype seating system, as a basis for the development of a novel adaptive seating system. Standard design methodologies were followed to produce the novel design and a prototype was fabricated for testing purposes. The novel design has a number of innovative features including a backrest that is intended to minimise stimulus to the posterior surface of the trunk and a seatbase that tilts in both the coronal and sagittal planes. In addition, a dynamic wrist orthosis featuring an active control and feedback mechanism was designed and fabricated, an idea that arose from the development of the seating system. The device could potentially be used to stretch and maintain ROM of the joint and the prototype successfully demonstrated the technical feasibility of the idea.

A prototype of the novel seating system - featuring the stimulus reducing backrest - was tested on a small sample group of adaptive seating users with a repeated

measures type study design. No significant differences were found in terms of posture, functional ability, pressure distributions or sitting activity when compared to the users' own systems. The study did allow problems in the design to be identified and for improvements to be made.

The technique of actigraphy was shown to potentially have a number of applications in many areas of seating research as indicator of discomfort. In a variety of sitting conditions it was possible to detect subjects' postural reactions to a range of discomfort states. Subsequently it was found that the detected movements could be used as an indication of the subjects' perceived sitting related discomfort.

These findings may be of some interest and benefit to clinicians, researchers and designers working in the field of adaptive seating and assistive technology in general.

9 Future Work

This project provides the foundations for a number of areas - both closely and indirectly related to adaptive seating - that could be investigated in the future. There is a great deal of scope for both the devices and the assessment techniques that have been described in this thesis to be researched further.

The opportunity remains for using the same items investigated in chapter 3 in a study of adult adaptive seating users and their carers, as well as comparing these results further with the views of clinicians in order to determine fully the extent to which their perceptions vary.

Further research is required into the effects, especially in the long term, of adaptive seating systems, both of the novel system described in this thesis and, indeed, in more general terms. Initial results suggested that the stimulus reducing backrest may be of limited efficacy, but several other aspects of the novel system, including the multi-planar tilting seatbase and the floating dynamic backrest, remain open for investigation and indeed, the benefits and disadvantages of dynamic supports in general have yet to be comprehensively defined.

Current trends in healthcare are moving further towards a much stricter evidence based criteria for medical interventions (DOH, 1996), meaning that the provision of adaptive seating may be under deeper scrutiny in future. Long term evaluation of seating based interventions for the prevention or slowing of progression of deformities and for the facilitation of function would also greatly assist clinicians by providing an evidence base for the prescription of these devices. The use of randomised, controlled trials (RCT) to investigate seating design and prescription is an u

nderused tool in this area for reasons already discussed (see chapter 2), but there are specific aspects which would benefit from this rigorous testing (for example, a number different methods are used to fabricate custom contoured seats for

individuals with deformities but to the author's knowledge no definitive trials comparing the quality of the final casts exist in the literature).

The Active Dynamic Orthosis and the principles it is based upon is another area believed to be worth further investigation. Such work could be multifaceted and involve, for example, patients' tolerance to the device, the testing of different stretching programs and the influence of dynamic support on abnormal muscle tone. If successful it may provide a basis for extrapolating the technology for use on other joints and, ultimately, adaptive seating systems.

The use of actigraphy as an indicator of sitting discomfort requires further validation. Carrying out a study on a larger sample with equal sized gender and age groups would be the start of this process. If the technique was validated, testing on equipment such as office chairs and car seats would be of "real world" benefit and could attract industrial interest due its low cost and portability advantages over current sitting discomfort measurement technologies. A further progression that could potentially link the actigraphy technique to adaptive seating is to use the movements detected by the activity monitor to control adjustment of the seating system. Hypothetically, if movements were detected which suggested the user was in discomfort related to their posture, a signal could be sent to a central processing system that would, in turn, initiate a controlled change in the orientation of the supports. The adjustment could be of the multi-planar tilting seat base that is described in chapter 4 or some other adjustment that would alter the user's sitting position.

10 Publications and Events

A number of publications and events relating to the work described in this thesis have occurred, the most notable of which are described below.

10.1 Journal publications

A paper titled "The development of a novel adaptive seating system for individuals with neuromuscular disorders" which is based on the work described in chapter 4 was published in the Journal of Medical Devices in June 2009-
Telfer, S., Solomonidis, S.E., & Spence, W.D. (2009). The development of a novel adaptive seating system for children with neuromuscular disorders. J Med Devices, 3(2), 027538.

A paper titled "An investigation of teaching staff members' and parents' views on the current state of adaptive seating technology and provision" which is based on the research presented in chapter 3 was published in January 2010 by the journal Disability and Rehabilitation: Assistive Technology-
Telfer, S., Solomonidis, S.E., & Spence, W.D. (2009). An investigation of teaching staff members' and parents' views on the current state of adaptive seating technology and provision. Disabil Rehabil: Assit Tech, 5(1), 14.24.

A paper titled "An investigation of the potential for actigraphy to be used as an indicator of sitting discomfort" which is based on the work described in chapter 6 was published in October 2009 in Human Factors: The Journal of Human Factors and Ergonomics Society.
Telfer, S., Solomonidis, S.E., & Spence, W.D. (2009). An investigation of the potential for actigraphy to be used as an indicator of sitting discomfort. Hum Factors, 51, 694-704.

10.2 Conference presentations

A poster titled "The design of a novel adaptive seating system for children with neuromuscular disorders" was presented at the Design of Medical Devices conference in Minneapolis, April 2009.

An oral presentation titled "An investigation of the potential for actigraphy to be used as a measure of sitting discomfort: preliminary results" was given at the XXII Congress of the International Society of Biomechanics in Cape Town, July 2009 and published in the proceedings.

A poster titled "The design of a novel adaptive system for individuals for individuals with neuromuscular disorders" was presented at the XXII Congress of the International Society of Biomechanics in Cape Town, July 2009 and published in the proceedings (Telfer, Solomonidis, & Spence, 2009a). This poster was also presented at the 2009 HealthQwest Graduate School Research Student Conference where it won the prize for Best Poster.

An oral presentation entitled "Testing of a novel adaptive seating system for children with neuromuscular disorders" was given at the 13th International Society of Prosthetics and Orthotics in Leipzig, May 2010.

10.3 Other

The Active Dynamic Orthosis system was shortlisted for and highly commended in the Strathclyde Supernovas "Most Dazzling New Product" competition run by the Research and Innovation Department at Strathclyde University, November 2007.

References

Ade-Hall, R., & Moore, A. (2000). Botulinum toxin type A in the treatment of lower limb spasticity in cerebral palsy. *Cochrane Database Syst Rev, 2*, CD001408.

Al-Turaiki, H.S. (1996). seating orthotics for young cerebral palsy patients: a report on practice in Saudia Arabia. *Disabil Rehabil, 18*(7), 335-340.

Andreoni, G., Santambrogio, G.C., Rabuffetti, M., & Pedotti, A. (2002). Method for the analysis of posture and interface pressure of car drivers. *Appl Ergon, 33*(6), 511-522.

Anthony, D., Barnes, J., & Unsworth, J. (1998). An evaluation of current risk assessment scales for decubitus ulcer in general inpatients and wheelchair users. *Clin Rehabil, 12*, 136-142.

Apatsidis, D.P., Solomonidis, S.E., & Michael, S.M. (2002). Pressure distribution at the seating interface of custom-molded wheelchair seats: Effect of various materials. *Arch Phys Med Rehabil, 83*(8), 1151-1156.

Asbjornslett, M., & Hemmingsson, H. (2008). Participation at school as experienced by teenagers with physical disabilities. *Scand J Occup Ther, 15*, 153-161.

Assaiante, C., Mallau, S., Viel, S., Jover, M., & Schmitz, C. (2005). Development of postural control in healthy children: a functional approach. *Neural Plast, 12*(2-3), 109-118.

Babski-Reeves, K., Stanfield, J., & Hughes, L. (2005). Assessment of video display workstation set up on risk factors associated with the development of low back and neck discomfort. *Int J Ind Ergon, 35*(7), 593-604.

Bennett, D., Gillis, D., Portney, L., Romanow, M., & Sanchez, A. (1989). Comparison of integrated electromyographic activity and lumbar curvature during standing and during sitting in three chairs. *Phys Ther, 69*(11), 902-913.

Bertocci, G., Hobson, D., & Digges, K. (1996). Development of transportable wheelchair design criteria using computer crash simulation. *IEE Trans Rehabil Eng, 4*(3), 171-181.

Bertocci, G.E., Ha, D., Deemer, E., & Karg, P. (2001). Evaluation of wheelchair seating system crashworthiness: "drop hook"-type seat attachment hardware. *Arch Phys Med Rehabil, 82*(4), 534-540.

Bjornson, K.F., & McLaughlin, J.F. (2001). The measurment of health related quality of life (HRQL) in children with cerebral palsy. *Eur J Neurol, 8*(5), 183-193.

Black, J.M., & National Pressure Ulcer Advisory Panel. (2005). Moving toward consensus on deep tissue injury and pressure ulcer staging. *Adv Skin Wound Care, 18*, 415-416, 418, 420-421.

Blair, E., Ballantyne, J., Horsman, S., & Chauvel, P. (1995). A study of a dynamic proximal stability splint in the management of children with cerebral palsy. *Dev Med & Child Neurol, 37*, 544-554.

Bobath, B. (1979). The application of physiological principles to stroke rehabilitation. *Practitioner, 223*(1338), 793.

Bouten, C., Oomens, C., Baaijens, F., & Bader, D. (2003). The etiology of pressure ulcers: Skin deep or muscle bound? *Arch Phys Med Rehabil, 84*(4), 616-619.

Boyd, R., & Graham, H. (1997). Botulinum toxin A in the management of children with cerebral palsy. *Eur J Neurol, 4*, S15-22.

Branton, P. (1969). Behaviour, body mechanics and discomfort. *Ergonomics, 33*, 316-327.

Breau, L., McGrath, P., Camfield, C., & Finley, A. (2002). Psychometric properties of the Non-Communicating Children's Pain Checklist – revised. *Pain, 99,* 349-57.

Bressel, E., & McNair, J. (2002). The effect of prolonged static and cyclic stretching on ankle joint stiffness, torque relaxation, and gait in people with stroke. *Phys Ther, 82*, 880-887.

Brienza, D.M., Lin, C-T., & Karg, P.E. (1999). A method for custom-contoured cushion design using interface pressure measurements. *IEEE T Rehabil Eng, 7*(1), 99-108.

Brogren, E., Hadders-Algra, M., & Forssberg, H. (1998). Postural Control in Sitting Children with Cerebral Palsy. *Neurosci Biobehav Rev, 22*(4), 591-596.

Brouwer, B., Wheeldon, R.K., Stradiotto-Parker, N., & Allum, J. (1998). Reflex excitability and isometric force production in CP: The effect of serial casting. *Dev Med & Child Neurol, 40*, 168-175.

Brown, A., Smolensky, M., D'Alonzo, G., Redmond, D., Conrad, E., & His, B. (1990). Circadian rhythm in human in human activity objectively quantified by actigraphy. *Prog Clin Biol Res, 341A*, 77-83.

Brown, M., Rudicel, S., & Esquenazi, A. (1996). Measurement of dynamic pressures at the shoe-foot interface during normal walking with various foot orthoses using the F-scan system. *Foot Ankle Int, 17*(3), 152-156.

Buis, A.W.P., & Convery, P. (1997). Calibration problems encountered while monitoring stump/socket interface pressures with force sensing resistors: techniques adopted to minimise inaccuracies. *Prosthet Orthot Int, 21*(3), 179-182.

Bull, E.P. (1987). Posture and Gesture. New York: Pergamon.

Burgoyne, W., & Fairbank, J. (2001). The management of scoliosis. *Curr Paediatr, 11*(5), 323-331.

Burns, S., & Betz, K. (1999). Seating pressures with conventional and dynamic wheelchair cushions in tetraplegia. *Arch Phys Med Rehabil, 80*, 566-571.

Butler, P. (1998). A preliminary report on the effectiveness of trunk targeting in achieving independent sitting balance in children with cerebral palsy. *Clin Rehabil, 12*, 281-293.

Carcone, S.M., & Keir, P.J. (2007). Effects of backrest design on biomechanics and comfort during seated work. *Appl Ergon, 36*(6), 755-764.

Carr, J.H., Shepard, R.B., & Ada, L. (1995). Spasticity: Research findings and implications for intervention. *Physiotherapy, 81*(8), 421-429.

Charlton, P., Ferguson, D., Peacock, C., & Stallard, J. (1999). Preliminary clinical experience of a contracture correction device. *Prosthet Orthot Int, 23*, 163-168.

Chung, J., Evans, J., Lee, C., Lee, J., Rabbani, Y., Roxborough, L., Harris, S.R. (2008). Effectiveness of adaptive seating on sitting posture and postural control in children with cerebral palsy. *Pediatr Phys Ther, 20*(4), 303-317.

Clark, J., Morrow, M., & Michael, S.M. (2004). Wheelchair postural support for young people with progressive neuromuscular disorders. *Int J Ther Rehabil, 11*(8), 365-373.

Clever, K., Smith, G., Bowser, C., & Monroe, K. (2002). Evaluating the efficacy of a uniquely delivered skin protectant and its effect on the formation of sacral/buttock pressure ulcers. *Ostomy/Wound Management, 48*(12), 60-67.

Cobb J.R. (1948). The American Academy of Orthopedic Surgeons Instructional Course Lectures. Vol. 5. Ann Arbor, MI: Edwards.

Coggrave, M.J., & Rose, L.S. (2003). A specialist seating assesment clinic: changing pressure relief practice. *Spinal Cord, 41*, 692-695.

Cottalorda, J., Gautheron, V., & Metton, G. (2000). Toe-walking in children younger than 6 years with CP: the contribution of serial corrective casts. *J Bone Joint Surg, 82*(B), 541-544.

Coutinho, E.L., Gomes, A.R., Franca, C.N., Oishi, J., & Salvini, T.F. (2004). Effect of passive stretching on the immobilized soleus muscle fibre morphology. *Braz L Med Biol Res, 37*(12), 1853-1861.

Cowan, R., Nash, M., Collinger, J., Koontz, A., & Boninger, M. (2009). Impact of surface type, wheelchair weight, and axle position on wheelchair propulsion by novice older adults. *Arch Phys Med Rehabil, 90*(7), 1073-1075.

Cox, D. (2003). Wheelchair needs for children and young people: a review. *Brit J Occup Ther, 66*, 219-223.

Crane, B., Holm, M., Hobson, D., Cooper, R., Reed, M., & Stadelmeier, S. (2004). Development of a consumer-driven Wheelchair Seating Discomfort Assessment Tool (WcS-DAT). *Int J Rehabil Res 27*(1), 85-90.

Cross, N. (1989). Engineering Design Methods. Chichester: Wiley.

Crouchman, M. (2000). Principles of management of cerebral palsy. *Curr Pediatr, 10*, 167-171.

Currey, J., & Butler, G. (1975). The mechanical properties of bone tissue in children. *J Bone Joint Surg Am, 57*, 810-814.

Czaja, R., & Blair, J. (2005). Designing Surveys: A Guide to Decisions and Procedures. Thousand Oaks, CA: Pine Forge Press.

Darrah, J., Hodge, M., Magill-Evans, J., & Kembhavi, G. (2003). Stability of serial assessments of motor and communication abilities in typically developing infants--implications for screening. *Early Human Development, 72*(2), 97-110.

de Looze, M.P., Kuijt-Evers, L.F., & JH, Van Dieen, D. (2003). Sitting comfort and discomfort and the relationships with objective measures. *Ergonomics, 46*, 985-997.

DeLuca, P. (1996). The musculoskeletal management of children with cerebral palsy. *Pediatr Clin North Am, 43*(5), 1135-1150.

Deway, A., Rice-Oxley, M., & Dean, T. (2004). A qualitative study comparing the experiences of tilt-in-space wheelchair use and conventional wheelchair use by clients severely disabled with multiple sclerosis. *Br J Occup Ther, 67*, 65-74.

Dicianno, B., Margaria, E., Arva, J., Lieberman, J., Schmeler, M., Souza, A., et al. (2008). RESNA position on the application of tilt, recline, and elevating legrests for wheelchairs. *Rehabilitation Engineering & Assistive Technology Society of North America*.

Ding, D., Cooper, R.A., & Cooper, R. (2007). Monitoring seat feature usage among wheelchair users. *Proceedings: 29th Annual International Conference of the IEEE EMBS*, 4364-4367.

DOH. (1996). Towards an evidence based health service. *London: HMSO*

Dunk, N., & Callaghan, J. (2005). Gender-based differences in postural responses to seated exposures. *Clin Biomech, 20*, 1101-1110.

Egilson, S., & Traustadottir, R. (2009). Participation of students with physical disabilities in the school environment. *Am J Occup Ther, 63*(3), 264-272.

El Falou, W., Duchene, J., Grabisch, M., Hewson, D., Langeron, Y., & Lino, F. (2003). Evaluation of driver discomfort during long-duration car driving. *Appl Ergon, 34*(3), 249-255.

Emery DFG, & Wedge JH. (2003). Orthopaedic management of chidren with total body involvement cerebral palsy. *Curr Ortho, 17*, 81-87.

Emery, E. (2003). Intrathecal baclofen. Literature review of the results and complications. *Neurochirurgie, 49*(2-3 Pt 2), 276-288.

Eriksson, L. (2005). The relationship between school environment and participation for students with disabilities. *Pediatr Rehabil, 8*(2), 130-139.

Evans, P., Elliott, M., Alberman, E., & S, E. (1985). Prevalence and disabilities in 4 to 8 year olds with cerebral palsy. *Arch Dis Child, 60*, 940-945.

Evans, P.M., Evans, S.J.W., & Alberman, E. (1990). Cerebral palsy: why we must plan for survival. *Arch Dis Child, 65*, 1329-1333.

Eyman, R.K., Grossman, H.J., Chaney, R.H., & Call, T.L. (1990). The life expectancy of profoundly handicapped people with mental retardation. *New Engl J Med, 323*, 584-589.

Farmer, S., Woollam, P., Patrick, J., Roberts, A., & Bromwich, W. (2005). Dynamic orthoses in the management of joint contracture. *J Bone Joint Surg Br, 87B*(3), 291-295.

Fenety, P. (1995). Factors influencing sitting comfort and in-chair movement in the office environment. *Doctoral Thesis, Dalhouse University, CAN*.

Fenety, P., Putnam, C., & Walker, J.M. (2000). In-chair movement: validity, reliablity and implications for measuring sitting discomfort. *Appl Ergon, 31*, 383-393.

Ferguson-Pell, M., & Cardi, M. (1992). Pressure mapping systems. *TeamRehab Report, October*, 28-32.

Fermin, K., & Wellard, M. (2002). When seated in a wheelchair, how many degrees of tilt is needed to improve postural stability for function in children with a neurological disorder? *Occup Ther: Critically Appraised Topics*, 1-10.

Finestone, H., Levine, S., Carlson, G., Chizinsky, K., & Kett, R. (1991). Erthema and skin temperature following continuous sitting in spinal cord injured individuals. *J Rehabil Res Dev, 28*, 27-32.

Finger, E., & Willis, F. (2008). Dynamic splinting for knee flexion contracture following total knee arthroplasty: a case report. *Cases J, 1*(1), 421.

Flett, P. (2003). Rehabilitation of spasticity and related problems in childhood cerebral palsy *J Paediatr Child Health, 39*, 6-14.

Foerster, F., & Fahrenberg, J. (2000). Motion and posture: correctly assessed by calibrated accelerometers. *Behav Res Methods Instrum Comput, 32*, 450-457.

Fowler, F.J. (2002). Survey Research Methods: Third Edition. Thousand Oaks, CA: Pine Forge Press.

French, M. (1992). Form, structure and mechanism. London: Macmillan Education Ltd.

Gobel, H., Heller, O., Nowak, T., & Westphal, W. (1988). Zur Korrespondenz von Schmerzreiz und Schmerzerleben. *Der Schmerz, 2*, 205-211.

Goosens, R.H.M., Snijders, C.J., Holscher, T.G., Heerens, W.C., & Holman, AE. (1997). Shear stress measured on beds and wheelchairs. *Scand J Rehab Med, 29*, 131-136.

Gordon, A., Charles, J., & Wolf, S. (2006). Efficacy of constraint-induced movement therapy on involved upper-extremity use in children with hemiplegic cerebral palsy is not age dependent. *Pediatrics, 117*(3), 363-373.

Gormley, M. (2001). Treatment of neuromuscular and musculoskeletal problems in cerebral palsy. *Pediatr Rehabil, 4*, 5-16.

Gracies, J-M. (2001). Pathophysiology of impairment in patients with spasticity and use of stretch as a treatment of spastic hypertonia *Phys Med Rehabil Clin N Am, 12*(4), 747-792.

Gracies, J., Marosszeky, J., Renton, R., Sandanam, J., Gandevia, S., & Burke, D. (2000). Short-term effects of dynamic Lycra splints on upper limb in hemiplegic patients. *Arch Phys Med Rehabil, 81*(12), 1547-1555.

Gracies, J.M., Fitzpatrick, R., Wilson, L., Burke, D., & Gandevia, S.C. (1997). Lycra garments designed for patients with upper limb spasticity: Mechanical effects in normal subjects. *Arch Phys Med Rehabil, 78*(10), 1066-1071.

Graf, M., Guggenbuhl, U., & Krueger, H. (1995). An assessment of seated activity and postures at five workplaces. *Int J Ind Ergon, 15*, 81-90.

Graham, H.K., & Fixsen, J.A. (1988). Lengthening of the calcaneal tendon in spastic hemiplegia by White slide technique. *J Bone Joint Surg, 70B*(B), 472-475.

Grap, M.J., Borchers, C.T., Munro, C.L., Elswick, R.K., & Sessler, C.N. (2005). Actigraphy in the critically ill: Correlation with activity, agitiation, and sedation. *Am J Crit Care, 14*(1).

Gyi, D.E., & Porter, J.M. (1999). Interface pressure and the prediction of car seat discomfort. *Appl Ergon, 30*(2), 99-107.

Ham, R., Aldersea, P., & Porter, D. (1998). Wheelchair users and postural seating. A clinical approach. New York: Churchill Livingstone.

Harms, M. (1990). Effect of wheelchair design on posture and comfort of users. *Physiotherapy, 76*(5), 266-271.

Health and safety matters for special educational needs: moving and handling. (2006). Caerphilly, UK: Health and Safety Executive.

Healy, A., Ramsay, C., & Sexsmith, E. (1997). Postural support systems: their fabrication and functional use. *Dev Med & Child Neurol, 39*, 706-710.

Henderson, R.C., Lark, R.K., Gurka, M.J., Worley, G., Fung, E.B., Conaway, M., Stallings, V.A., & Stevenson, R.D. (2002). Bone density and metabolism in children and adolescents with moderate to severe cerebral palsy. *Pediatrics, 110*(1), 1-10.

Hobson, D., & Molenbroek, J. (1990). Anthropometry and design for the disabled: experiences with seating design for the cerebral palsy population. *Appl Ergon, 21*(1), 43-54.

Hoenig, H., Giacobbi, P., & Levy, C. (2007). Methodological challenges confronting researchers of wheeled mobility aids and other assistive technologies. *Disabil Rehabil: Assist Technol, 2*(3), 159-168.

Holmes, K.J., Michael, S.M., Thorpe, S.L., & Solomonidis, S.E. (2003). Management of scoliosis with special seating for the non-ambulant spastic cerebral palsy population--a biomechanical study. *Clin Biomech, 18*, 480-487.

Hulme, J.B., Shaver, J., Archer, S., Mullette, L., & Eggert, C. (1987). Effects of adaptive seating devices on the eating and drinking of children with multiple handicaps. *Am J Occup Ther, 41*, 81-89.

Kang, W., & Pilkey, W. (1998). Crash simulations of wheelchair-occupant systems in transport *J Rehabil Res Dev, 35*(1), 73-84.

Karg, P., & Springle, S. (1996). Development of test methodologies for determining the safety of wheelchair headrest systems during vehicle transport. *J Rehabil Res Dev, 33*(3), 290-304.

Kauzlarich, J., & Thacker, J. (1989). Wheelchair tire rolling resistance and fatigue. *J Rehabil Res Dev, 22*(3), 25-41.

Keeping, P., & Major, R. (1999). Use of a gas spring contracture correction orthosis for the management of a fixed flexion contracture of the elbow. *Prosthet Orthot Int, 23*, 82-84.

Kinali, M., Messina, S., Mercuri, E., Lehovsky, J., Edge, G., Manzur, A.Y., & Muntoni, F. (2006). Management of scoliosis in Duchenne muscular dystrophy: a large 10-year retrospective study. *Dev Med & Child Neurol, 48*(6), 513-518.

Kolich, M. (2003). Automobile seat comfort: occupant preferences vs. anthropometric accommodation. *Appl Ergon, 34*(2), 177-184.

Kolich, M. (2008). A conceptual framework proposed to formalize the scientific investigation of automobile seat comfort. *Appl Ergon, 39*(1), 15-27.

Kolsch, M., Beall, A., & Turk, M. (2003). An Objective Measure for Postural Comfort. *Proceedings: Human Factors and Ergonomics Society Annual Meeting, 47*, 725-728.

Koman, L.A., Smith, B.P., & Shilt, J.S. (2004). Cerebral palsy. *Lancet, 363*(9421), 1619-1631.

Konno, S., Kikuchi, S., & Nagaosa, Y. (1994). The relationship between intramuscular pressure of the paraspinal muscles and low back pain. *Spine, 19*(19), 2186-2189.

Koontz, A., Cooper, R., Boninger, M., Yang, Y., & Impink, B. (2005). A kinetic analysis of manual wheelchair propulsion during start up on select indoor and outdoor surfaces. *J Rehabil Res Dev, 42*(4), 447-458.

Krick, J., Murphy-Miller, P., Zeger, S., & Wright, E. (1996). Pattern of growth in children with cerebral palsy. *J Am Diet Assoc, 96*(7), 680-685.

Kubo, K., Kaneshisa, H., Kawakami, Y., & Fukanaga, T. (2001). Growth changes in the elastic properties of human tendon structures. *Int J Sports Med, 22*(2), 138-143.

Lacoste, M., Weiss-Lambrou, R., Allard, M., & Dansereau, J. (2003). Powered tilt/recline systems: why and how are they used. *Assist Technol, 15*, 58-68.

Lai, J., Francisco, G., & Willis, F. (2009). Dynamic splinting after treatment with botulinum toxin type-A: A randomized controlled pilot study. *Adv Ther, 26*(2), 241-248.

Lance, J. (1980). Symposium synopsis. In: Feldman RG, Young RR, Koella WP. (Eds), Spasticity: Disordered Motor Control. *Year Book Medical Publishers, Chicago*, 485-494.

Leivseth, G., & Drerup, B. (1997). Spinal shrinkage during work in a sitting posture compared to work in a standing posture. *Clin Biomech, 12*(7-8), 409-418.

Levy, C., Chow, J., Tillman, M., Hanson, C., & Donohue, T. (2004). Variable ratio power assist wheelchair eases wheeling over a variety of terrains for elders. *Arch Phys Med Rehabil, 85*(104-12).

Lin, F., Parthasarathy, S., Taylor, S.J., Pucci, D., Hendrix, R.W., & Makhsous, M. (2006). Effect of Different Sitting Postures on Lung Capacity, Expiratory Flow, and Lumbar Lordosis. *Arch Phys Med Rehabil, 87*(4), 504-509.

Linder-Ganz, E., Shabshin, N., Itzchak, Y., & Gefen, A. (2007). Assessment of mechanical conditions in sub-dermal tissues during sitting: A combined experimental-MRI and finite element approach. *J Biomech, 40*(7), 1443-1454.

Lonstein, J., & Akbarnia, A. (1983). Operative treatment of spinal deformities in patients with cerebral palsy or mental retardation. An analysis of one hundered and seven cases. *J Bone Joint Surg, 65A*, 43-55.

Lou, E., Chan, C., Raso, V.J., Hill, D.L., Moreau, M.J., Mahood, J.K., & Donauer, A. (2005). A smart orthosis for the treatment of scoliosis. *Proceedings: 2005 IEEE Engineering in Medicine and Biology 27th Annual Conference*, 1008-1011.

Lukban, M., Rosales, R., & Dressler, D. (2009). Effectiveness of botulinum toxin A for upper and lower limb spasticity in children with cerebral palsy: a summary of evidence. *J Neural Transm, 116*(3), 319-331.

Makhsous, M., Lin, F., Hendrix, R., Hepler, M., & Zhang, L. (2003). Sitting with adjustable ischial and back supports: biomechanical changes. *Spine, 28*(11), 1113-1121.

Mao, H., Huang, S-L., Lu, T-W., Lin, Y-S., Liu, H-M., Wang, Y-H., & Wang, T-M. (2006). Effects of Lateral Trunk Support on Scoliotic Spinal Alignment in Persons With Spinal Cord Injury: A Radiographic Study. *Arch Phys Med Rehabil, 87*(6), 764-771.

Matthews, M., & Crawford, R. (2006). The use of dynamic Lycra orthosis in the treatment of scoliosis: a case study. *Prosthet Orthot Int, 30*(2), 174-181.

McDonald, R. (2005). Seating systems for children with cerebral palsy: a study of acceptability and effectiveness. PhD Thesis, Monash University.

McDonald, R., & Surtees, R. (2007). Changes in postural alignment when using kneeblocks for children with severe motor disorders. *Disabil Rehabil: Assist Technol, 2*(5), 287-291.

McDonald, R., Surtees, R., & Wirz, S. (2003). A comparison between parents' and therapists' views of their child's individual seating systems *Int J Rehabil Res, 26*, 235-243.

McDonald, R., Surtees, R., & Wirz, S. (2004). The international classification of functioning, disability and health provides a model for adaptive seating interventions for children with cerebral palsy. *Br J Occup Ther, 67*(7), 293-302.

McDonald, R., & Surtees, R. (2007). Longitudinal study evaluating a seating system using a sacral pad and kneeblock for children with cerebral palsy. *Disabil Rehabil, 29*(13), 1041-1047.

McGill, S., Van Wijk, M., Axler, C., & Gletsu, M. (1996). Studies of spinal shrinkage to evaluate low-back loading in the workplace. *Ergonomics, 39*(1), 92-102.

McInnes, E., Bell-Syer, S., Dumville, J., Legood, R., & Cullum, N. (2008). Support surfaces for pressure ulcer prevention. *Cochrane Database Syst Rev, 4*.

McLaughlin, E.M. (1981). Rapid atrophy of mouse soleus muscles after tentomy depends on an intact innervation. *Neurosci Lett, 25*, 269.

McNamara, L., & Casey, J. (2007). Seat inclinations affect the function of children with cerebral palsy: a review of the effect of different seat inclines. *Disabil Rehabil: Assist Technol, 2*(6), 309-318.

McPherson, J.J., Becker, A.H., & Franszczak, N. (1985). Dynamic splint to reduce the passive component of hypertonicity. *Arch Phys Med Rehabil, 66*(4), 249.

Mehta, C.R., & Tewari, V.K. (2000). Seating discomfort for tractor operators - a critical review. *Int J Ind Ergonom, 25*(6), 661-674.

Michael, S., Porter, D., & Pountney, T. (2007). Tilted seat position for non-ambulant individuals with neurological and neuromuscular impariment: a systematic review *Clin Rehabil, 21*, 1063-1074.

Miedaner, J.A., & Finuf, L. (1993). Effects of adaptive positioning on psycological test scores for pre-school children with cerebral palsy. *Pediatr Phys Ther, 5*, 177-182.

Miller, A., Temple, T., & Miller, F. (1996). Impact of orthoses on the rate of scoliosis progression in children with cerebral palsy. *J Pediatr Orthot, 16*, 332-335.

Moreau, M., Mahood, J., Moreau, K., Berg, D., Hill, D., & Raso, J. (2002). Assessing the impact of pelvic obliquity in post-operative neuromuscular scoliosis *Stud Health Technol Inform, 91*, 481-485.

Morrell, D., Pearson, J., & Sauser, D. (2002). Progressive bone and joint abnormalities of the spine and lower extremities in cerebral palsy. *Radiographics, 22*(2), 257-268.

Morse, J.L., Jung, M-C., Bashford, G.R., & Hallbeck, M.S. (2006). Maximal dynamic grip force and wrist torque: The effects of gender, exertion direction, angular velocity, and wrist angle. *Appl Ergon, 37*(6), 737-742.

Moving Forward: Review of NHS Wheelchair and Seating Sevices in Scotland. (March 2006). Edinburgh: The Scottish Government.

Na, S., Lin, S., Choi, H-S., & Chung, M.K. (2005). Evaluation of driver's discomfort and postural change using dynamic body pressure distribution. *Int J Ind Ergon, 35*, 1085-1096.

National Horizon Scanning Centre. (2002). Lycra garments for cererbal palsy and movement disorders. Birmingham: National Horizon Scanning Centre.

Nicholson, J., Morton, R., Attfield, S., & Rennie, D. (2001). Assessment of upper-limb function and movement in children with cerebral palsy wearing lycra garments. *Dev Med & Child Neurol, 43*, 384-391.

Nordmark, E., Josenby, A. L., Lagergren, J., Andersson, G., Stromblad, L. G., & Westbom, L. (2008). Long-term outcomes five years after selective dorsal rhizotomy. *BMC Pediatr, 8*, 54.

Nuismer, B., Ekes, A., & Holm, M. (1997). The use of low-load prolonged stretch devices in rehabilitation programs in the pacific northwest. *Am J Occup Ther, 51*(7), 538-543.

Nwaobi, O. (1986). Effects of body orientation in space on tonic muscle activity of patients with cerebral palsy *Dev Med & Child Neurol, 28*, 41-44.

Nwaobi, O., & Smith, P. (1986). Effect of adaptive seating on pulmonary function of children with cerebral palsy. *Dev Med & Child Neurol, 28*, 351-354.

Oomens, C.W.J., Bressers, O.F.J.T., Bosboom, E.M.H., Bouten, C.V.C., & Bader, D.L. (2003). Can loaded interface characteristics influence strain distributions in muscle adjacent to bony prominences? *Comput Meth Biomech Biomed Eng, 3*, 171-180.

Pahl, G., & Beitz, W. (1984). Engineering Design. London: Design Council Books.

Palisano, R., Tieman, B., Walter, S., Barlett, D., Rosenbaum, P., Russell, D., et al. (2003). Effect of environmental setting on mobility methods of children with cerebral palsy. *Dev Med & Child Neurol, 45*, 113-120.

Palisano, R.J., Rosenbaum, P., Walter, S., Russell, D., Wood, E., & Galuppi, B. (1997). Development and reliability of a system to classify gross motor function in children with cerebral palsy. *Dev Med & Child Neurol, 39*, 214-223.

Palisano, R.J., Snider, L.M., & Orlin, M.N. (2004). Recent advances in physical and occupational therapy for children with cerebral palsy. *Semin Pediatr Neuro, 11*(1), 66-77.

Pennington, L., Goldbart, J., & Marshall, J. (2004). Speech and language therapy to improve the ommunication skills of children with cerebral palsy. *Cochrane Database Syst Rev, CD003466*(2).

Picciolini, O., Albisetti, W., Cozzaglio, M., Spreafico, F., Mosca, F., & Gasparroni, V. (2009). "Postural Management" to prevent hip dislocation in children with cerebral palsy. *Hip Int, 19*(6), 56-62.

Pin, T., Dyke, P., & Chan, M. (2006). The effectiveness of passive stretching in children with cerebral palsy. *Dev Med & Child Neurol, 48*(10), 855-862.

Pirila, S., Van der Meer, J., Pentikainen, T., Ruusu-Niemi, P., Korpela, R., Kilpinen, J., & Nieminen, P. (2006). Language and motor speech skills in children with cerebral palsy. *J Commun Disord, 40*(2), 116-28.

Porter, J.M., Gyi, D.E., & Tait, H.A. (2003). Interface pressure data and the prediction of driver discomfort in road trials. *Appl Ergon, 34*, 207-214.

Pountney, T., Mulcahy, C., Clarke, S., & Green, E. (2000). *The Chailey approach to postural managment: An explaniation of the theoretical aspects of posture management and their practical application through treatment and equipment*. Birmingham: Active Design Ltd.

Pountney, T.E., Mandy, A., Green, E.M., & Gard, P. (2001). Management of hip dislocation with postural management. *Child Care Health Dev, 28*(2), 179-185.

Prill, T., & Fahrenberg, J. (2006). Simultaneous assessment of posture and limb movements (e.g., periodic leg movements with calibrated multiple accelerometry. *Physiol Meas, 27*, 47-53.

Pritchett, J.W. (1990). Treated and untreated unstable hips in severe cerebral palsy. *Dev Med & Child Neurol, 32*, 3-6.

Pugh, S. (1991). Total Design. Workingham: Addison-Wesley.

Quintavalle, P.R., Lyder, C.H., Mertz, P.J., Phillips-Jones, C., & Dyson, M. (2006). Use of high-resolution, high-frequency diagnostic ultrasound to investigate the pathogenesis of pressure ulcer development. *Adv Skin Wound Care, 19*(9), 498-505.

Ragan, R., Kernozek, T. W., Bidar, M., & Matheson, J. W. (2002). Seat-interface pressures on various thicknesses of foam wheelchair cushions: A finite modeling approach. *Arch Phys Med Rehabil, 83*(6), 872-875.

Rennie, D. J., Attfield, S. F., Morton, R. E., Polak, F. J., & Nicholson, J. H. (2000). A nevaluation of lycra garments in the lower limb using 3-D gait analysis and functional assessment (PEDI). *Gait Posture, 12*(1), 1-6.

Rondeau, H. (1975). The 1 (materials)-3 (cost of goods)-9 (selling price) rule for product cost estimation. *Mach Des, 47*, 50-53.

Rose K.J., Raymond J., Refshauge K.N., North K.N., Burns J. (2010) Serial night casting increases ankle dorsiflexion range in children and young adults with Charcot-Marie-Tooth disease: a randomised trial. *J Physiother, 56,* 113-9.

Rose, N.E., Feiwell, L.A., & Cracchiolo, A. (1992). A method for measuring foot pressures using a high resolution computerised insole sensor: the effect of heel wedges on plantar pressure distribution and centre of force *Foot Ankle, 13*(5), 263-270.

Rosenthal, M., Felton, R., Nastasi, A., Naliboff, B., Harker, J., & Navach, J. (2003). Healing of advanced pressure ulcers by a generic total contact seat: 2 randomized comparisons with low air loss bed treatments. *Arch Phys Med Rehabil, 84*(12), 1733-1742.

Rosenthal, M.J., Felton, R.M., Hileman, D.L., Lee, M., Friedman, M., & Navach, J.H. (1996). A wheelchair cushion designed to redistribute sites of sitting pressure. *Arch Phys Med Rehabil, 77*(3), 278-282.

Rowe, D.E., Bernstein, S.M., Riddick, M.F., Alder, F., Emans, J.B., & Gardner-Bonneau, D. (1997). A meta-analysis of the efficacy of non-operative treatments for idiopathic scoliosis *J Bone Joint Surg, 79A*(5), 664-674.

Roxborough, L., Fife, S., Story, M., & Armstrong, R. (1994). Seated Postural Control Measure Manual: Research Version. *Vancouver, British Columbia, Canada,: Sunny Hill Health Centre for Children*.

Ryan, S. E., Campbell, K. A., Rigby, P. J., Fishbein-Germon, B., Hubley, D., & Chan, B. (2009). The Impact of Adaptive Seating Devices on the Lives of Young Children With Cerebral Palsy and Their Families. *Archives of Physical Medicine and Rehabilitation, 90*(1), 27-33.

Saito, N., Ebara, S., Ohotsuka, K., Kumeta, H., & Takaoka, K. (1998). Natural history of scoliosis in spastic cerebral palsy. *Lancet, 351*, 1687-1692.

Salcido, R., & Popescu, A. (2009) Pressure ulcers and wound care. *The Medscape Journal of Medicine.* Retrieved June 12, 2010, from http://emedicine.medscape.com/article/319284-overview.

Sarwahi, V., Sarwark, J., Schafer, M., Michael, F., Backer, C., Lee, M., et al. (2001). Standards in anterior spine surgery in pediatric patients with neuromuscular scoliosis. *J Pediatr Orthop, 21*(6), 756-760.

Scheker, L.R., Chesher, S.P., & Ramirez, S. (1999). Neuromuscular electrical stimulation and dynamic bracing as a treatment for upper-extremity spacticity in children with cerebral palsy *J Hand Surgery, 24B*(2), 226-232.

Seeger, B.R., Caudrey, D.J., & O'Mara, N.A. (1984). Hand function in cerebral palsy: the effect of hip-flexion angle. *Dev Med & Child Neurol, 26*(5), 601-606.

Shackel, B., Chidsey, K.D., & Shipley, P. (1969). The assessment of chair comfort. *Ergonomics, 12*, 269-306.

Shapcott, N., & Levy, B. (1999). By the numbers. *TeamRehab Report January*, 16-20.

Shea, JD. (1975). Pressure sores: classification and management. *Clin Ortho, 112*, 89-100.

Shen, W., & Parsons, K.C. (1997). Validity and reliability of rating scales for selected pressure discomfort. *Int J Ind Ergon, 20*, 441-461.

Sheridan, M.D. (1997). From birth to five years: children's developmental progress. London: Routledge.

Shikako, T., Majnemer, A., Law, M., & Lach, L. (2008). Determinants of participation in leisure activities in children and youths with cerebral palsy: systematic review. *Phys Occup Ther Pediatr, 28*(2), 155-169.

Spijkerman, D., Terburg, M., Goosens, R., & Stijnen, T. (1995). Effects of inflation pressure and posture on the body-seat interface pressure of spinal cord injured patients on an air-filled wheelchair cushion. *J Rehabil Sci, 8*, 8-12.

Springle, S. (2007). State of the science on wheeled mobility and seating measuring the health, activity and participation of wheelchair users. *Disabil Rehabil: Assist Technol, 2*(3), 133-135.

Stavness, C. (2006). The effect of positioning for children with cerebral palsy on upper-extremity function: a review of the evidence. *Phys Occup Ther Pediatr, 26*(3), 39-53.

Steinbok, P. (2007). Selective dorsal rhizotomy for spastic cerebral palsy: a review. *Childs Nerv Syst, 23*(9), 981-990.

Stevenson, R., Roberts, C., & Vogtle, L. (1995). The effects of non-nutritional factors on growth in cerebral palsy. *Dev Med & Child Neurol, 37*, 124-130.

Stinson, M.D., Porter-Armstrong, A., & Eakin, P. (2003). Seat-interface pressure: A pilot study of the relationship to gender, body mass index, and seating position. *Arch Phys Med Rehabil, 84*(3), 405-409.

Stinson, M.D., Porter-Armstrong, A.P., & Eakin, P.A. (2002). Pressure mapping systems: reliability of pressure map interpretation. *Clin Rehabil, 17*, 504-511.

Stokes, I.A.F. (1997). Analysis of symmetry of vertical body loading consequent to lateral spinal curvature *Spine, 22*, 2495-2503.

Strauss, D., Brooks, J., Rosenbloom, L., & Shavelle, R. (2008). Life expectancy in cerebral palsy: an update. *Dev Med & Child Neurol, 50*(7), 487-493.

Tafti, M., Cramer, S., & Gupta, R. (2008). Orthopaedic management of the upper extremity of stroke patients. *J AM Acad Orthop Surg, 16*(8), 462-470.

Tardieu, D., Lespargot, A., Tabary, C., & Bret, M.D. (1988). For how long must the soleus muscle be stretched each day to prevent contracture? *Dev Med & Child Neurol, 30*, 3-10.

Taylor, E., Hanna, J., & Belcher, H. (2003). Splinting of the hand and wrist. *Curr Ortho, 17*(6), 465-474.

Terjesen, T., Lange, J.E., & Steen, H. (2000). Treatment of scoliosis with spinal bracing in quadriplegic cerebral palsy *Dev Med & Child Neurol, 42*, 448-454.

Thelen, E., Fisher, D.M., & Ridley-Johnson, R. (1984). The relationship between physical growth and a newborn reflex. *Infant Behav Dev, 7*, 479-493.

Thom, A. (1994). The effectiveness of the neurophysiological ankle foot orthosis. MSc thesis: University of Strathclyde

Thomson, J.D., & Banta, J.V. (2001). Scoliosis in cerebral palsy: an overview and recent results *J Pediatr Orthot B, 10*, 6-9

Trembley, F., Malouin, F., Richards, C., & Dumas, F. (1990). Effects of prolonged muscle stretch on reflex and voluntary muscle activations in children with spastic cerebral palsy. *Scand J Rehab Med, 22*, 177-180.

Tsirikos, A.I., & Spielmann, P. (2007). Spinal deformity in paediatric patients with cerebral palsy. *Curr Orthopaed, 21*(2), 122-134.

Ullman, D. (1997). The Mechanical Design Process. New York: McGraw-Hill.

van Dieen, J., & Toussaint, H. (1993). Spinal shrinkage as a parameter of functional load. *Spine, 18*(11), 1504-1514.

van Dieen, J.H., de Looze, M.P., & Hermans, V. (2001). Effects of dynamic office chairs on trunk kinematics, trunk extensor EMG and spinal shrinkage. *Ergonomics, 44*, 739-750.

Van Someren, E.J.W. (1996). Actigraphic monitoring of movement and rest-activity rhythms in aging, Alzheimer's disease and Parkinson's disease *In: 18th Annual Conference of the IEEE Engineering in Medicine and Biology Society*, 69-70.

VanRoosmalen, L., Bertocci, G., Ha, D., & Karg, P. (2001). Wheelchair integrated occupant restraints: feasibility in frontal impact. *Med Eng Phys, 23*(10), 687-698.

Vekerdy, Z. (2007). Management of seating posture of children with cerebral palsy by using thoracic-lumbar-sacral orthosis with non-rigid SIDO frame. *Disabil Rehabil, 29*(18), 1434-1441.

Veltink, P.H., & Franken, H.M. (1996). Detection of Knee unlock during stance using accelerometry. *IEE Trans Rehab Eng, 4*(395-402).

Vergara, M., & Page, A. (2000). System to measure the use of the backrest in sitting posture office tasks. *Appl Ergon, 31*, 247-254.

Vergara, M., & Page, A. (2002). Relationship between comfort and back posture and mobility in sitting posture. *Appl Ergon, 33*, 1-8.

Viano, D.C., & Andrzejak, D.V. (1992). Research issues on the biomechanics of seating discomfort: an overview with focus on issues of the elderly and low-back pain. *Society of Automotive Engineers, Technical Paper Series 920130*.

Vohra, R., & McCollum, C. (1994). Fortnightly Review: Pressure sores. *Brit Med J, 309*, 853-857.

Washington, K., Deitz, J., White, O., & Schwartz, J. (2002). The effects of a contured foam seat on postural alignment and upper-extremity function in infants with neuromotor impairments *Phys Ther, 82*(11), 1064-1076.

Wasiak, J., Hoare, B., & Wallen, M. (2004). Botulinum toxin A as an adjunct to treatment in the management of the upper limb in children with spastic cerebral palsy. *Cochrane Database Syst Rev, 4*(CD003469).

Waterlow, J. (1985). Pressure sores: a risk assessment card. *Nurs Times, 81*(48), 49-55.

Watier, E., Chevrier, S., Georgieu, N., A Pardo, A., Schück, S., & J P Pailheret. (2000). Our experience with ischial pressure sores in a series of 34 patients *European Journal of Plastic Surgery, 23*(1), 32-35.

Watson, M. J., Crosby, P., & Matthews, M. (2007). An evaluation of the effects of a dynamic lycra orthosis on arm function in a late stage patient with aquired brain injury. *Brain Inj, 21*(7), 753-761.

Watson, N., & Woods, B. (2005). The origins and early development of special/adaptive wheelchair seating. *Soc Hist Med, 18*(3), 459-474.

Webster, C. (1996). The health services since the war: volume II. Government and healthcare the National Health Service 1958-1979. *London*.

Weinstein, S.L. (1994). Editorial. Advances in the diagnosis and management of adolescent idiopathic scoliosis. *J Pediatr Orthop, 14*, 561-563.

WHO. (2001). International classification of functioning, disability and health. Geneva: World Health Organisation.

Wilder, D.G., & Pope, M.H. (1996). Epidemiological and aetiological of lower back pain in vibration enviroments-an update. *Clin Biomech, 11*, 61-73.

Wong, W.Y., Wong, M.S., & Lo, K.H. (2007). Clinical applications of sensors for human posture and movement analysis: A review. *Prosthet Orthot Int, 31*(1), 62-75.

Woo, R. (2001). Spasticity: orthopedic perspective. *J Child Neurol, 16*(1), 47-53.

Woodburn, J., & Helliwell, P.S. (1996). Observations on the F-scan in-shoe pressure measuring system. *Clin Biomech, 11*(5), 301-304.

Yeh, C-Y., Tsai, K-H., & Chen, J-J. (2005). Effects of prolonged muscle stretching with constant torque or constant angle on hypertonic calf muscles. *Archives of Physical Medicine and Rehabilitation, 86*(2), 235-241.

Zhang, L., Helander, M.G., & Drury, C.G. (1996). Identifying factors of comfort and discomfort in sitting. *Hum Factors, 38*, 377-389.

Zhang, M. (1994). The reaction of skin and soft tissue to shear forces applied externally to the skin surface. *Proc. Institute of Mechanical Engineers*(208), 217-222.

Zhoa, J.H., & Tang, L. (1994). An evaluation of comfort of a bus seat. *Appl Ergon, 25*, 386-392.

11 Appendix A

This appendix contains the version of the questionnaire that was sent out to the parents of children who use adaptive seating systems. The modifications that were made for the version sent to the teaching staff members that work with these children at special needs schools have also been noted.

Questionnaire

This questionnaire is designed to find out more about the use of adaptive seating systems and wheelchairs. Please take a few moments to fill it in and return it to the required address.

1. Could you rate the importance of the following functions of adaptive seating in the classroom?

Tick appropriate box for each function: 1 – Of No Importance; 2 - Of Very Little Importance; 3- Somewhat Important; 4- Very Important 5- Extremely Important

	1	2	3	4	5
Child interacting with teachers and other pupils					
Preventing deformities developing					
Mobility (indoors)					
Mobility (outdoors)					
Child's well being and self esteem					
Child being accepted by other pupils					
Postural Support					
Positioning child for eating					
Positioning child for cleaning/hygiene tasks					
Providing comfort					

2. How long on average would you estimate you spend during the course of a day transferring children to and from seating systems?

HOURS ☐ MINUTES ☐

3. How satisfied are you with the way seating systems cope with the growth pattern of pupils?

Tick appropriate box: 1 – Not At All Satisfied; 2 - Quite Satisfied; 3- Somewhat Satisfied; 4-Very Satisfied; 5 – Extremely Satisfied)

1	2	3	4	5

4a. Have you ever been involved with or seen an accident that involved a seating system?

YES ☐

NO ☐

4b. If YES could you briefly describe the incident?

…….

…….

…….

…….

……..…..

…….

5a. Have you ever needed to perform a repair on a seating system?

YES ☐

NO ☐

5b. If YES could you briefly describe what you had to do?

……

……

……

……

……

……

……

……

6. How satisfied are you with the provision of seating systems for pupils in terms of new or replacement models being issued?

Tick appropriate box: 1 – Not At All Satisfied; 2- Somewhat Satisfied; 3- Quite Satisfied; 4- Very Satisfied; 5 – Extremely Satisfied

	1	2	3	4	5
YES					
NO					

7. If you have experienced any other problems with or have any further comments about adaptive seating systems or wheelchairs which you feel are relevant please add them here-

……

……

……

……

……

……

……

Teaching Staff Version-

Finally, could you give us a few pieces of information about yourself so that your other replies can be put in a greater context.

8. What is your job title?

……..

9. Which type of school do you work at?

NURSERY ☐

PRIMARY ☐

SECONDARY ☐

10. How long have you worked with children with special needs?

YEARS ☐ MONTHS ☐

Thank you for taking the time to complete this questionnaire. Please return it in the stamped addressed envelope provided.

Parent Version -

Finally, could you give us a few pieces of information about your child so that your other replies can be put into a greater context.

8. Which type of school does your child go to?

Please Tick-

NURSERY ☐

PRIMARY ☐

SECONDARY ☐

9. For how long have they regularly used an adaptive seating system?

YEARS ☐ MONTHS ☐

10. What is the make and model of the seating system they use?

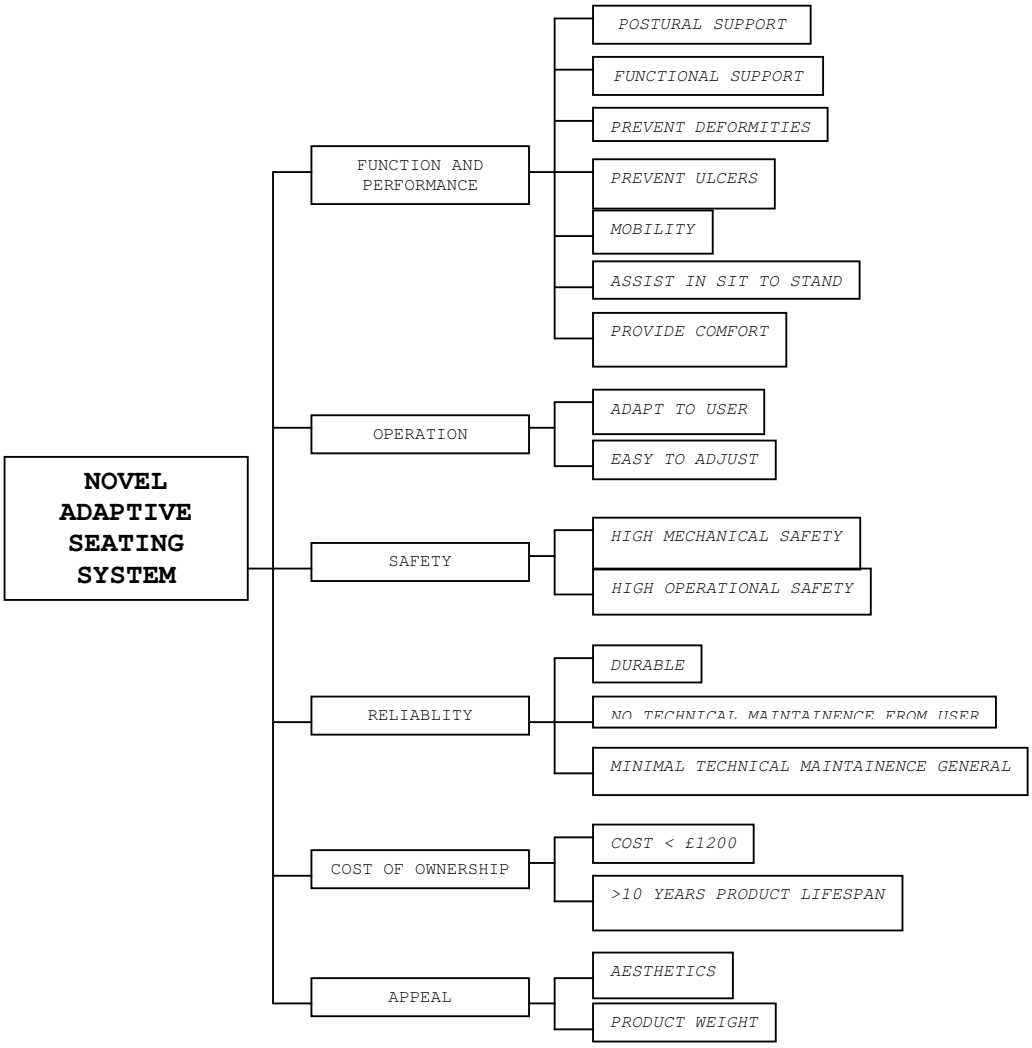
……..

Thank you for taking the time to complete this questionnaire. Please return it in the stamped addressed envelope provided.

12 Appendix B

This appendix contains information related to the development of the novel adaptive seating system as an example of the documentation produced during the design process. Included here are: the objectives tree that was the basis of the PDS; the full BOM used to record the materials and parts used and their costs; and the full set of engineering drawings for the tilting mechanism assembly (both assembly and component drawings).

12.1 Objectives Tree



12.2 Bill of Materials

12.2.1 Powered base assembly

Component	No. off	Bought or Fabricated	Material	Unit	Amount Used	Unit Cost	Labour Cost	Overhead	Total Component Cost (£)
Rear Casters	2	B			1	21.75	1		45.5
Front Wheels	2	B			1	34.95	1		71.9
Caster Forks	2	B			1	30.5	1		63
22mm T	6	B			1	2.44	1		20.64
60 degree bends	2	F	22mm S/S Pipe	m	0.5	33	5	8.6	51.6
60 Degree Right	1	F	Aluminium	m^3	0.000175	37833	5	2.32	13.94
60 Degree Left	1	F	Aluminium	m^3	0.000175	37833	5	2.32	13.94
M12 Insert	2	F	Aluminium	m^3	0.00001	37833	2	0.95	5.70
M12 Bearing	2	B			1	3.35	1		8.7
Battery Plate	1	F	8mm Ply	m^2	0.125	16.667	2	0.81	4.90
Half Connect	2	F	Aluminium	m^3	0.000054	37833	10	4.81	28.90
Half Connect (threaded)	2	F	Aluminium	m^3	0.000054	37833	10	4.81	28.90
177x22	2	F	22mm S/S Pipe	m	0.18	33	1	2.77	16.65
120x22	1	F	22mm S/S Pipe	m	0.12	33	1	0.99	5.952
308x22	2	F	22mm S/S Pipe	m	0.31	33	1	4.49	26.95
Cross Bend	4	F	22mm S/S Pipe	m	0.3	33	5	11.92	71.52
90 Bend	2	F	22mm S/S Pipe	m	0.2	33	5	4.64	27.84
Top	4	F	Aluminium	m^3	0.00003125	37833	5	4.94	29.67
Bottom	4	F	Aluminium	m^3	0.00003125	37833	5	4.94	29.67
22x15x22 T	1	B			1	6.75	1		7.75

Attachment	2	F	Aluminium	m^3	0.000054	37833	10	4.81	28.90
Attachment 2	2	F	Aluminium	m^3	0.000054	37833	10	4.81	28.90
Lower Inside	2	F	Aluminium	m^3	0.00004	37833	10	4.60	27.63
Lower Outside	2	F	Aluminium	m^3	0.00004	37833	10	4.60	27.63
180x15	2	F	15mm S/S Pipe	m	0.18	33	1	2.77	16.65
30x15	1	F	15mm S/S Pipe	m	0.03	33	1	0.39	2.38
15T	1	B			1	2.01	1		3.01
Wheelplate	2	F	Aluminium Plate	m^3	0.00012	37833	5	3.81	22.89
Powered Base Plate	1	F	8mm Ply	m^2	0.24	16.667	5	1.80	10.80
M15 Attach	2	F	Aluminium	m^3	0.00001	37833	5	2.15	12.90
Guide 1	4	F	8mm Ply	m^2	0.012	16.667	5	4.16	24.96
Guide 2	4	F	8mm Ply	m^2	0.003	16.667	5	4.04	24.24
Electric Motor	2	B			1	172	1		346
Controller	1	B			1	97.5	1		98.5
12V Battery	2	B			1	18	1		36
M5 and M6 Bolts	1	B			1	5	1		6
								Total Cost	1293.09

12.2.2 Tilting mechanism assembly

Component	No. off	Bought or Fabricated	Material	Unit	Amount Used	Unit Cost	Labour Cost	Overhead	Total Component Cost (£)
Tiltable bit 1	2	F	Aluminium	m^3	0.000192	37833	10	6.90	41.43
Tiltable bit 2	2	F	Aluminium	m^3	0.000192	37833	10	6.90	41.43
Tiltable bit 3	4	F	Aluminium	m^3	0.000192	37833	5	9.81	58.86
Tiltable bit 4	2	F	Aluminium	m^3	0.000096	37833	5	3.45	20.71
Tilt Support Bracket	1	F	Aluminium	m^3	0.000059	37833	5	1.44	8.67

Pivot bar	1	F	22 S/S	m^2	0.4	33	2	3.04	18.24
22x22 Perpendicular	2	F	Aluminium	m^3	0.000172	37833	10	6.60	39.61
U Bend	1	F	22mm S/S	m^2	0.6	33	5	4.96	29.76
Half Clamp	2	F	Aluminium	m^3	0.000172	37833	7.5	5.60	33.61
Half clamp (threaded)	2	F	Aluminium	m^3	0.000172	37833	7.5	5.60	33.61
Another Rubbish Clevis Joint	4	F	Aluminium	m^3	0.000024	37833	5	4.72	28.35
Clevis Joint for Pneu Cylinder	4	B			1	1	0		4
Pneumatic cylinder	4	B			1	22.01	0		88.04
								Total Cost	446.37

12.2.3 Seatbase assembly

Component	No. Off	Bought or Fabricated	Material	Unit	Amount Used	Unit Cost	Labour Cost	Overhead	Total Component Cost (£)
Seatbase 1	1	F	Ply	m^2	0.25	16.67	5	1.83	11.00
Seatbase 2	1	F	Ply	m^2	0.1	16.67	5	1.33	8.00
Seatbase Bracket	2	F	Aluminium	m^3	0.000005	37833	10	4.07	24.45
Seatbase Block	1	F	Ply	m^2	0.1	16.67	2	0.73	4.40
Pelvis Support bracket 25	2	F	Aluminium	m^3	0.000005	37833	5	2.07	12.45
Part 1	2	F	Aluminium	m^3	0.000005	37833	5	2.07	12.45
Seatbase Hip Adjuster R	1	F	Ply	m^2	0.05	16.67	7.5	1.66	10.00
Seatbase Hip Adjuster L	1	F	Ply	m^2	0.05	16.67	7.5	1.66	10.00
Hip Angle Adjustment Block	1	F	Aluminium	m^3	0.000005	37833	5	1.03	6.22
5x40	2	F	Aluminium	m^3	0.000005	37833	5	2.07	12.45

5x27	2	F	Aluminium	m^3	0.000005	37833	5	2.07	12.45
Seatbase Boss	2	F	Aluminium	m^3	0.000005	37833	5	2.07	12.45
Seatbase Threaded	2	F	Aluminium	m^3	0.000005	37833	5	2.07	12.45
Seatbase Plate	2	F	Aluminium	m^3	0.000005	37833	5	2.07	12.45
22mm Bearing	2	F	PTFE	m	0.05	55.9	7.5	4.11	24.70
Bracket 1	2	F	Aluminium	m^3	0.000005	37833	10	4.07	24.45
Another Rubbish Clevis Joint	2	F	Aluminium	m^3	0.000008	37833	5	2.12	12.72
Knee Block U Support	2	F	Aluminium	m^3	0.000003	37833	5	2.04	12.27
Knee Block Stopper	1	F	Aluminium	m^3	0.000003	37833	5	1.02	6.13
Footrest Attacher	2	F	Aluminium	m^3	0.000003	37833	5	2.04	12.27
Skirt Bracket	8	F	Aluminium	m^3	0.000002	37833	5	8.12	48.72
Thin Plastic	1	F	Acrlyic	m^2	0.03	65.7	5	1.39	8.36
Skirt A	1	F	Acrlyic	m^2	0.2	65.7	15	5.62	33.76
Skirt B	1	F	Acrlyic	m^2	0.2	65.7	15	5.62	33.76
								Total Cost	378.45

12.2.4 Armrest assembly

Component	No off	Bought or Fabricated	Material	Unit	Amount Used	Unit Cost	Labour Cost	Overhead	Total Component Cost (£)
Armrest 1	2	F	Aluminium	m^3	0.00009	37833	7.5	4.36	26.17
Armrest 2	2	F	Aluminium	m^3	0.00009	37833	7.5	4.36	26.17
Square Tighteners	4	F	Aluminium	m^3	0.000002	37833	5	4.06	24.36
Cushioning	2	F	Foam	m^3	0.00027	500	2	0.85	5.12
Upright Support 1	2	F	Aluminium	m^3	0.000054	37833	15	6.81	40.90
Armrest Pipework LHS	1	F	22mm chromium	m	0.15	7.76	7.5	1.73	10.39

Armrest Pipework RHS	1	F	coated copper pipe 22mm chromium coated copper pipe	m	0.15	7.76	7.5	1.73	10.39
Armrest Tilt	2	F	Aluminium	m^3	0.000032	37833	5	2.48	14.90
Back Bend (Halved)	2	F	22mm S/S Pipe	m	0.2	33	5	4.68	27.84
Bend	4	F	22mm S/S Pipe	m	0.2	33	5	9.28	55.68
Upright Support	4	F	Aluminium	m^3	0.000054	37833	15	13.63	81.80
New Backrest Block 1	2	F	Aluminium	m^3	0.000054	37833	10	4.81	28.90
New Backrest block 2	2	F	Aluminium	m^3	0.000054	37833	10	4.81	28.90
								Total Cost	381.56

12.2.5 Backrest assembly

Component	No off	Bought or Fabricated	Material	Unit	Material Volume	Unit Cost	Labour Cost	Overhead	Total Component Cost (£)
Backrest bearing 24mm	4	F	PTFE	m	0.06	59.7	2	4.46	26.79
Backrest Slider (threaded)	2	F	Aluminium	m^3	0.000072	37833	7.5	4.08	24.53
Backrest Slider (Non-threaded)	2	F	Aluminium	m^3	0.000072	37833	7.5	4.08	24.53
Backrest Slider 270x5	2	F	Aluminium	m^3	0.000021	37833	1	0.71	4.30
Sliding Backrest pivot	2	F	Aluminium	m^3	0.000027	37833	7.5	3.40	20.45
Sliding Backrest pivot (threaded)	2	F	Aluminium	m^3	0.000027	37833	7.5	3.40	20.45
Sliding Pivot Block	2	F	Aluminium	m^3	0.000027	37833	10	4.40	26.45
Spring Cross bar	1	F	22mm S/S	m	0.27	33	5	2.78	16.69
Spring Attachment bar	2	F	Aluminium	m^3	0.000036	37833	5	2.54	15.26

Spring Block	2	F	Aluminium	m^3	0.000003	37833	5	2.04	12.27
Split Backrest 90	2	F	22mm S/S	m	0.25	33	7.5	6.3	37.8
Split Backrest 10	2	F	22mm S/S	m	0.15	33	7.5	4.98	29.88
Split Backrest 25	2	F	22mm S/S	m	0.4	33	7.5	8.28	49.68
22mm Union	5	B			1	1.56	1		12.8
24mmx10 Bearing	4	F	PTFE	m	0.01	59.5	2	2.07	12.45
Sliding Backrest Stopper	2	F	Aluminium	m^3	0.000002	37833	2	0.83	4.98
Headrest 90	2	F	22mm Chrome Plated Copper	m	0.25	33	5	5.3	31.8
Headrest LHS	1	F	22mm Chrome Plated Copper	m	0.2	33	7.5	2.82	16.92
Headrest RHS	1	F	22mm Chrome Plated Copper	m	0.2	33	7.5	2.82	16.92
10x30	2	F	Aluminium	m^3	0.000003	37833	2	0.84	5.07
								Total Cost	410.07

12.2.6 Footrest assembly

Component	No off	Bought or fabricated	Made from	Unit	Material Volume	Unit Cost	Labour Cost	Overhead	Total Component Cost (£)
Upper Pipework	2	F	22mm S/S Pipe	m	0.25	33	7.5	4.65	36.15
Insert	2	F	Aluminium	m^3	0.00007065	37833	5	2.53	17.88
Insert for 22mm Pipe	2	F	Aluminium	m^3	0.00001256	37833	2	0.89	5.84
Lower Pipework	2	F	22mm S/S Pipe	m	0.35	33	7.5	5.31	43.41
30x30 Block	4	F	Aluminium	m^3	0.000045	37833	5	4.34	31.15
Footplate Left	1	F	Polyprop	m^2	0.025	65.7	10	2.32	13.97
Footplate Right	1	F	Polyprop	m^2	0.025	65.7	10	2.32	13.97

Adjuster	2	F	Aluminium	m^3	0.000024	37833	7.5	3.18	19.99
Heel Plate	2	F	Acrylic	m^2	0.02	65.7	5	2.26	14.89
Toe Plate	2	F	Acrylic	m^2	0.02	65.7	5	2.26	14.89
Square Tightener	2	F	Aluminium	m^3	0.000003	37833	5	2.02	12.24
Bottom Pipework	2	F	15 Copper Pipe	m	0.3	4.29	7.5	3.25	20.83
7.5 Spacer	4	F	Aluminium	m^3	0.000003	37833	5	4.02	24.47
Back attachment	2	F	Aluminium	m^3	0.000004	37833	2	0.83	5.13
Plate	2	F	Aluminium	m^3	0.0000125	37833	15	6.02	37.04
								Total Cost	311.88

12.2.7 Pelvic and lower lateral support assembly

Components	No Off	Bought or Fabricated	Material	Unit	Amount Used	Unit Cost	Labour Cost	Overheads	Total Component Cost (£)
Side Support	2	F	Foam	m^3	0.00048	500	2	0.89	5.37
Lateral Cushion	2	F	Foam	m^3	0.0006	500	2	0.92	5.52
Lateral Cushion Plate R	1	F	Ply	m^2	0.015	16.67	4	0.85	5.10
Lateral Cushion Plate L	1	F	Ply	m^2	0.015	16.67	4	0.85	5.10
Pelvis Cushion Plate R	1	F	Ply	m^2	0.012	16.67	4	0.84	5.04
Pelvis Cushion Plate L	1	F	Ply	m^2	0.012	16.67	4	0.84	5.04
Lateral Bend	2	F	15mm Chrome Plated copper	m	0.2	4.29	2	1.14	6.82
Lateral Bend Cushion Support	2	F	15mm Chrome Plated copper	m	0.4	4.29	2	1.48	8.91
Double Holder	2	F	Aluminium	m^3	0.00003	37833	5	2.45	14.72
Sliding Bracket L	1	F	Aluminium	m^3	0.000045	37833	5	1.34	8.04
Sliding Bracket R	1	F	Aluminium	m^3	0.000045	37833	5	1.34	8.04

Pelvis Support Angle R	1	F	Aluminium	m^3	0.000025	37833	5	1.18	7.13
Pelvis Support Angle L	1	F	Aluminium	m^3	0.000025	37833	5	1.18	7.13
Backplate	1	F	Aluminium	m^3	0.00038	37833	5	3.87	23.25
Pelvis Support Bracket 25	2	F	Aluminium	m^3	0.000016	37833	5	2.24	13.45
Back Cushion	1	F	Foam	m^3	0.016	500	2	2	12
Lateral support Guide (Big Slot)	2	F	Aluminium	m^3	0.000045	37833	7.5	3.68	22.08
Lateral Support Guide (Wee Slot)	2	F	Aluminium	m^3	0.000045	37833	7.5	3.68	22.08
								Total Cost	184.91

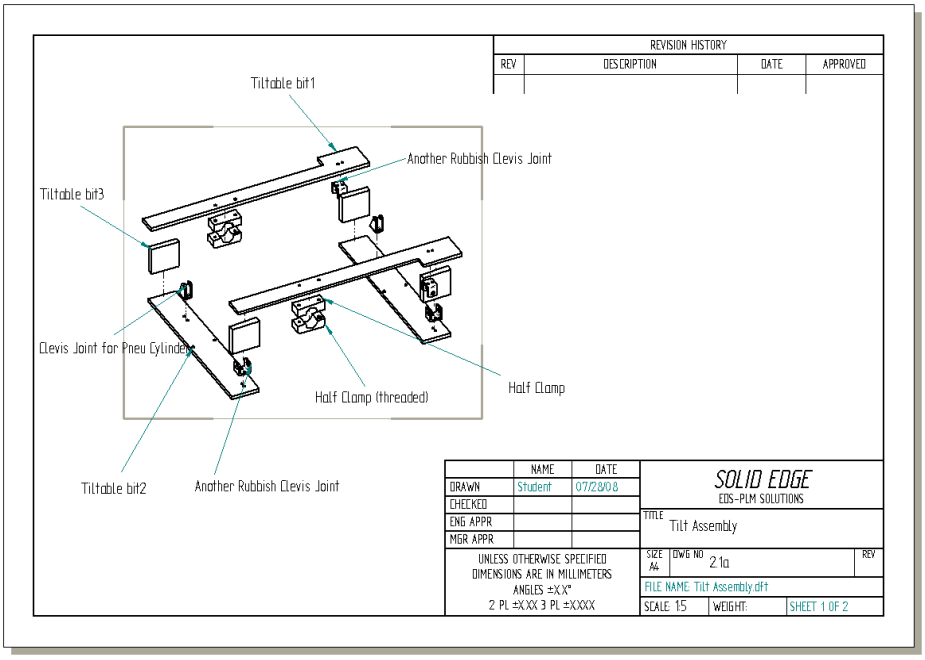
12.2.8 Knee block assembly

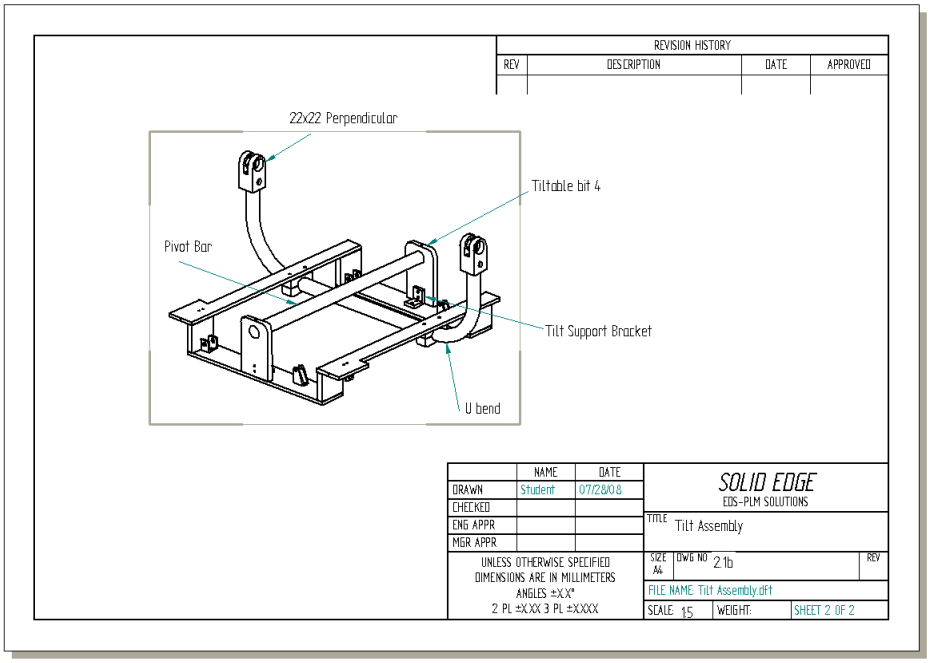
Component	No Off	Bought or Fabricated	Material	Unit	Amount Used	Unit Cost	Labour Cost	Overhead	Total Component Cost (£)
Offset Bar	1	F	Aluminium	m^3	0.00003	37833	7.5	1.72	10.36
Block 1	1	F	Aluminium	m^3	0.000003	37833	5	1.02	6.13
Block 2	1	F	Aluminium	m^3	0.000003	37833	5	1.02	6.13
Vertical Bar	1	F	Aluminium	m^3	0.00001	37833	2	0.47	2.85
Block 3	1	F	Aluminium	m^3	0.000003	37833	5	1.02	6.13
Horizontal Bar	2	F	Aluminium	m^3	0.0000157	37833	2	1.03	6.22
Pad Attachment	2	F	Aluminium	m^3	0.000004	37833	5	2.06	12.36
Pad	2	F	Plastic	m^2	0.02	65.7	10	4.52	27.15
Padding	2	F	Foam	m^3	0.0008	500	2	0.96	5.76
								Total Cost	83.12

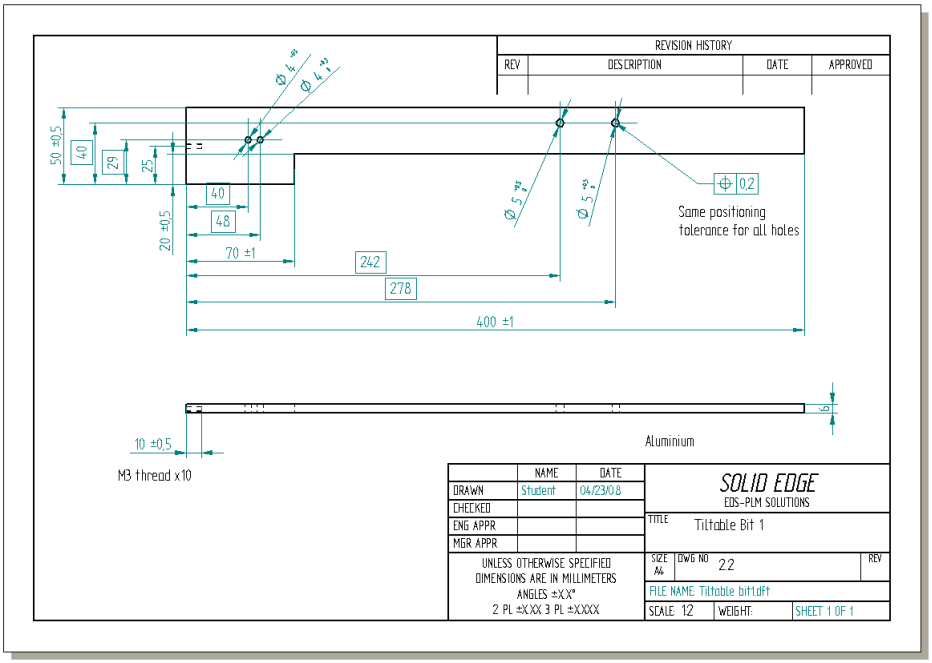
12.2.9 Fold out caster assembly

Component	No Off	Bought or Fabricated	Material	Unit	Amount Used	Unit Cost	Labour Cost	Overhead	Total Component Cost (£)
30 Degree Caster Adaptor	2	F	Aluminium	m^3	0.000045	37833	10	4.68	28.08
Caster Fork	2	B			1	30.5			61
Caster 100mm	2	B			1	21.75			43.5
Caster Rod	2	F	Aluminium	m^3	0.000005	37833	2	0.87	5.25
NFC Bend	2	F	22mm S/S	m	0.1	33	2	2.12	12.72
Fold Out Caster Bit 2	1	F	Aluminium	m^3	0.00006	37833	10	2.45	14.72
Caster Block	2	F	Aluminium	m^3	0.000054	37833	7.5	3.81	22.90
New Front Caster Block	4	F	Aluminium	m^3	0.000054	37833	7.5	7.63	45.80
Fold ut Caster bBit	1	F	Aluminium	m^3	0.00006	37833	10	2.45	14.72
619-0121 Bearing	2	B			1	1.45			2.9
M12 Insert	2	F	Aluminium	m^3	0.000002	37833	2	0.83	4.98
								Total Cost	256.59

12.3 Engineering drawings for tilting mechanism assembly






REVISION HISTORY
REV
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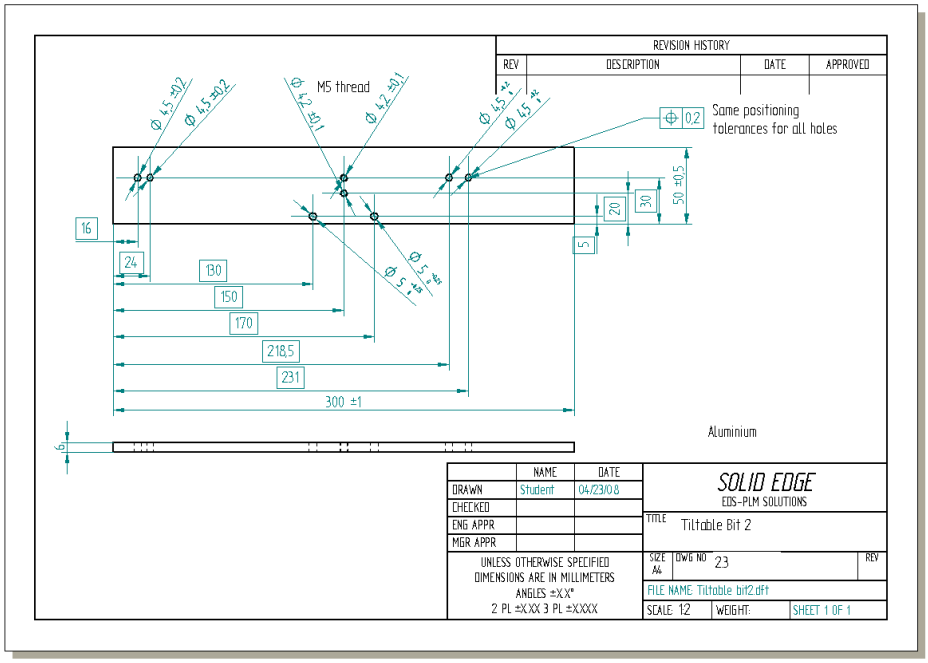
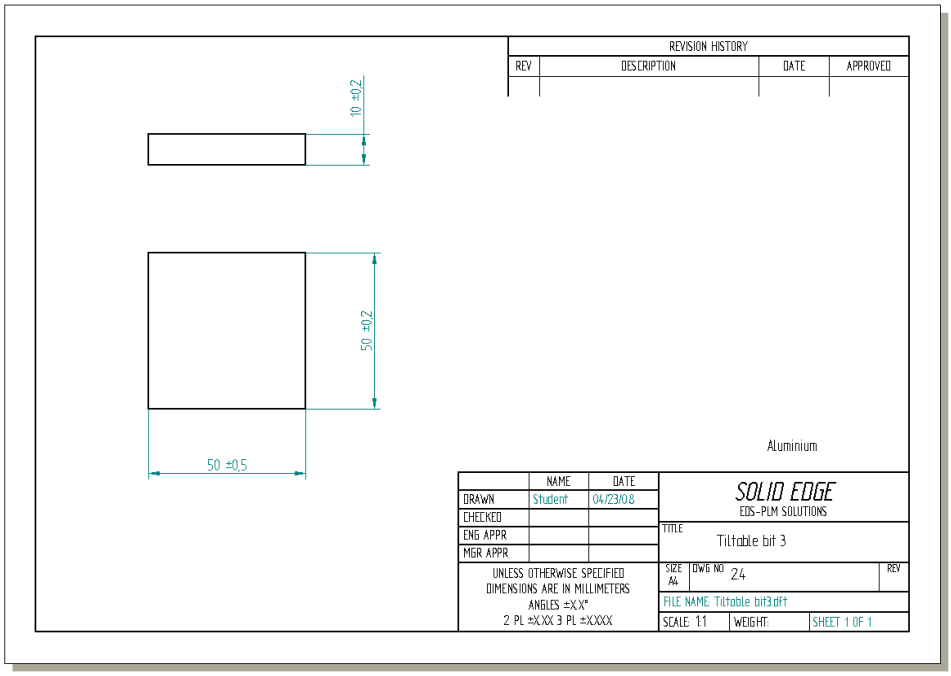
DATE
APPROVED
Same positioning tolerance for all holes
Aluminium
M3 thread x10
NAME
DATE
DRAWN
Student
04/23/08
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
ANGLES ±X.X°
2 PL ±X.XX 3 PL ±X.XXX
SOLID EDGE
EDS-PLM SOLUTIONS
TITLE
Tiltable Bit 1
SIZE
A4
DWG NO
2.2
REV
FILE NAME: Tiltable bit1.dft
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1


REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
M5 thread
Same positioning tolerances for all holes
Aluminium
NAME
DATE
DRAWN
Student
04/23/08
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
ANGLES ±X.X°
2 PL ±X.XX 3 PL ±X.XXX
SOLID EDGE
EDS-PLM SOLUTIONS
TITLE
Tiltable Bit 2
SIZE
A4
DWG NO
2.3
REV
FILE NAME: Tiltable bit2.dft
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1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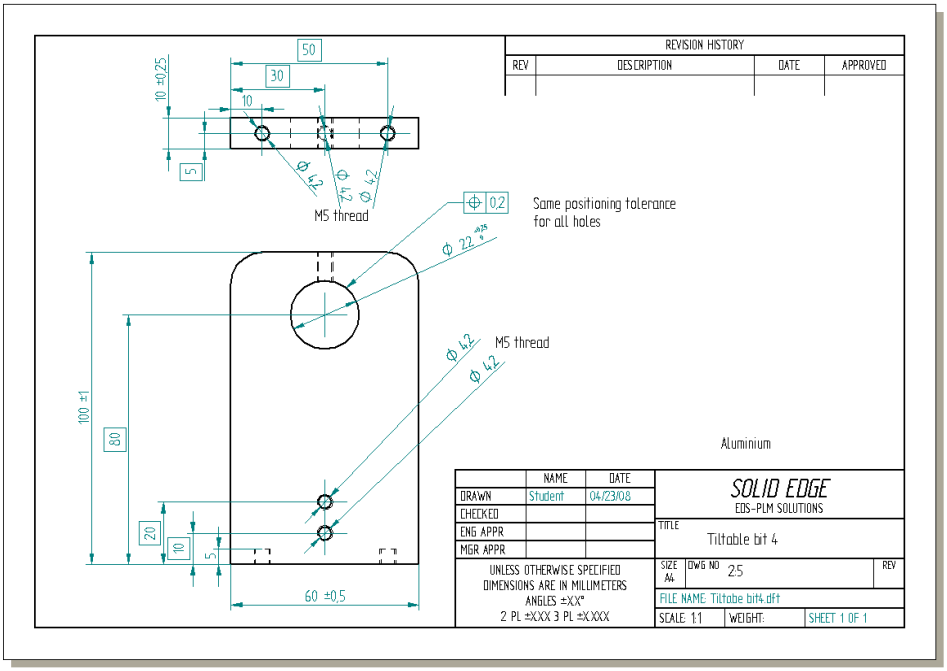
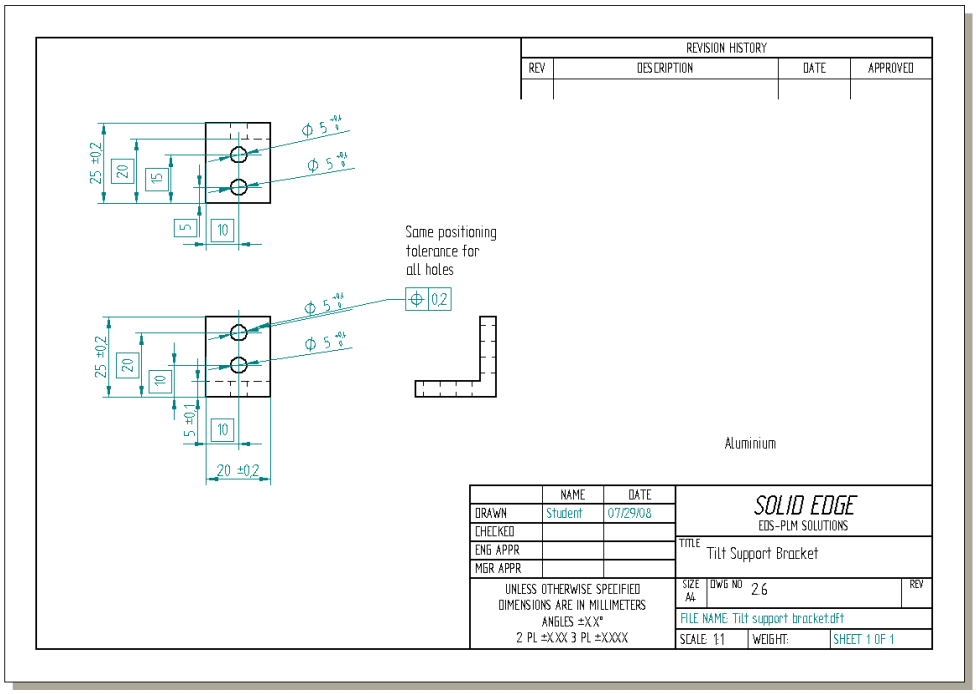
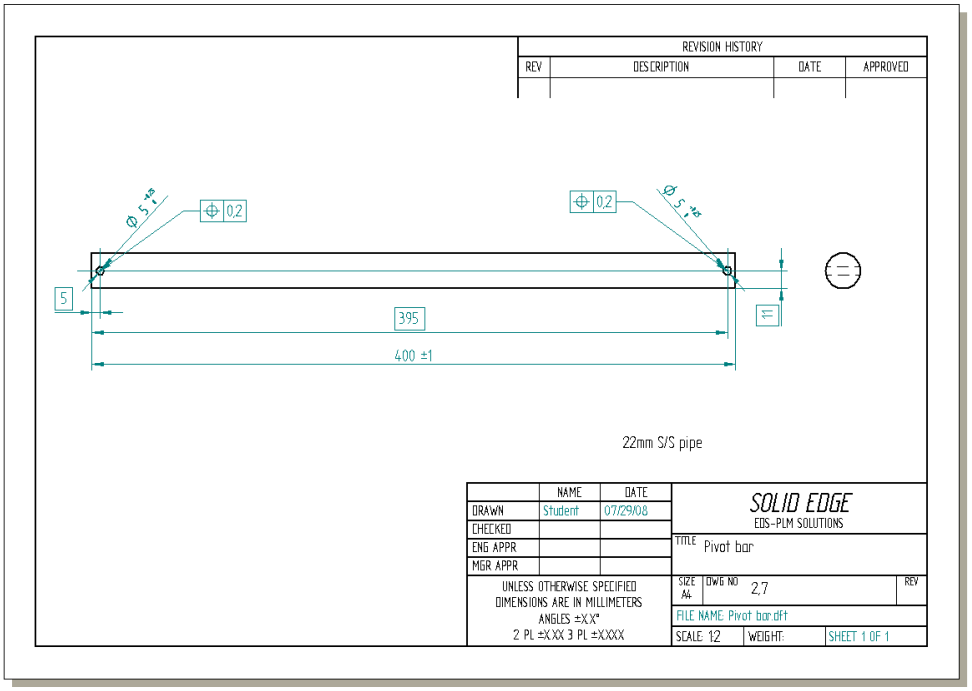
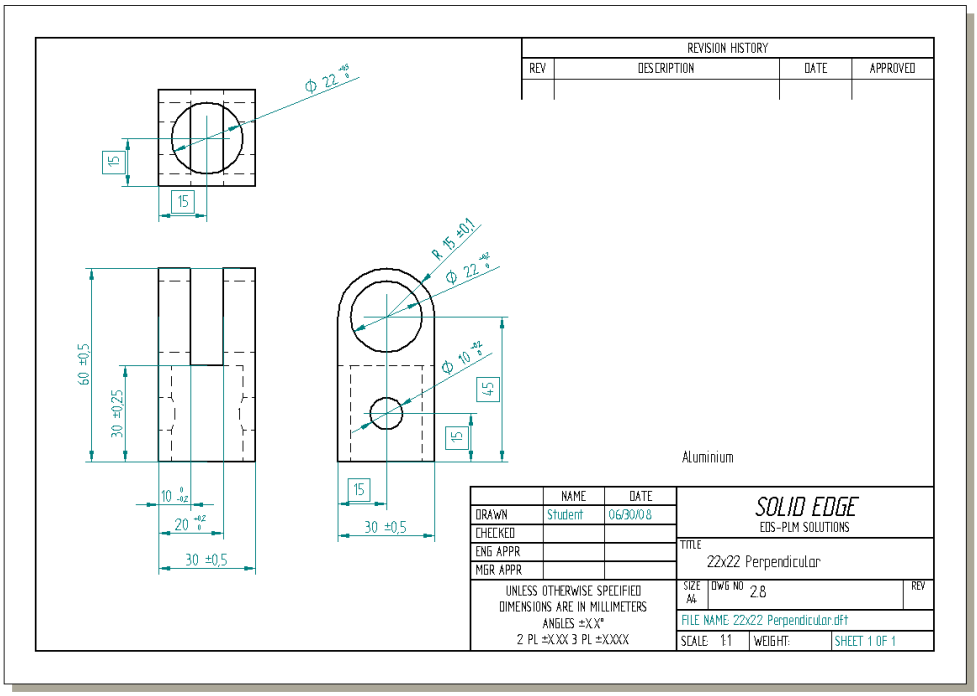
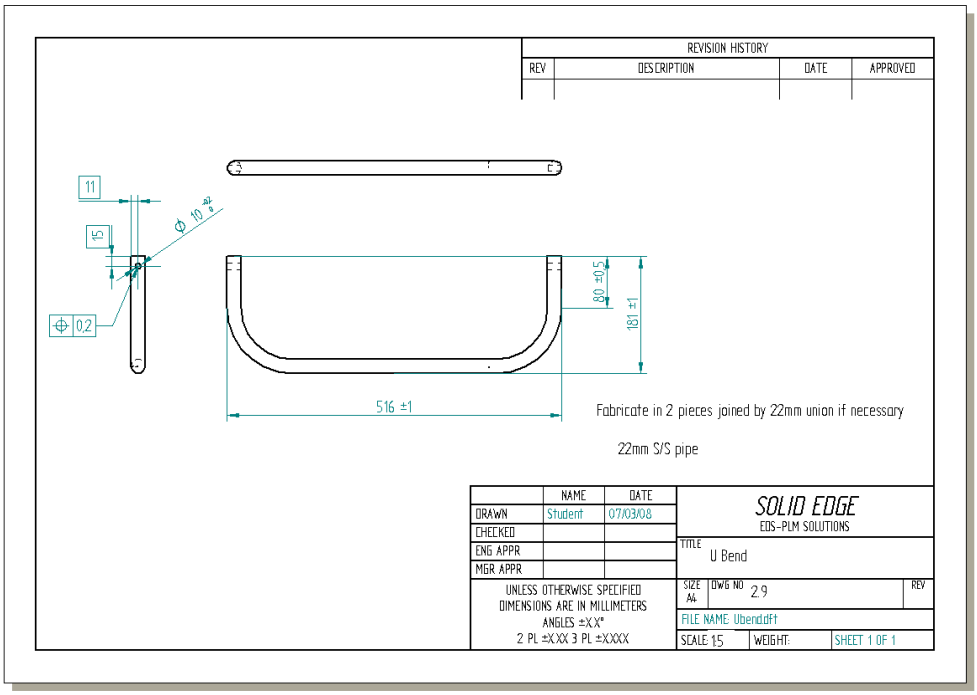
REV
DESCRIPTION
DATE
APPROVED
10 ±0,2
50 ±0,2
50 ±0,5
Aluminium
NAME
DATE
DRAWN
Student
04/23/08
CHECKED
ENG APPR
MGR APPR
SOLID EDGE
EDS-PLM SOLUTIONS
TITLE
Tiltable bit 3
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
ANGLES ±XX°
2 PL ±XXX 3 PL ±XXXX
SIZE
A4
DWG NO
2.4
REV
FILE NAME Tiltable bit3.dft
SCALE 1:1
WEIGHT:
SHEET 1 OF 1

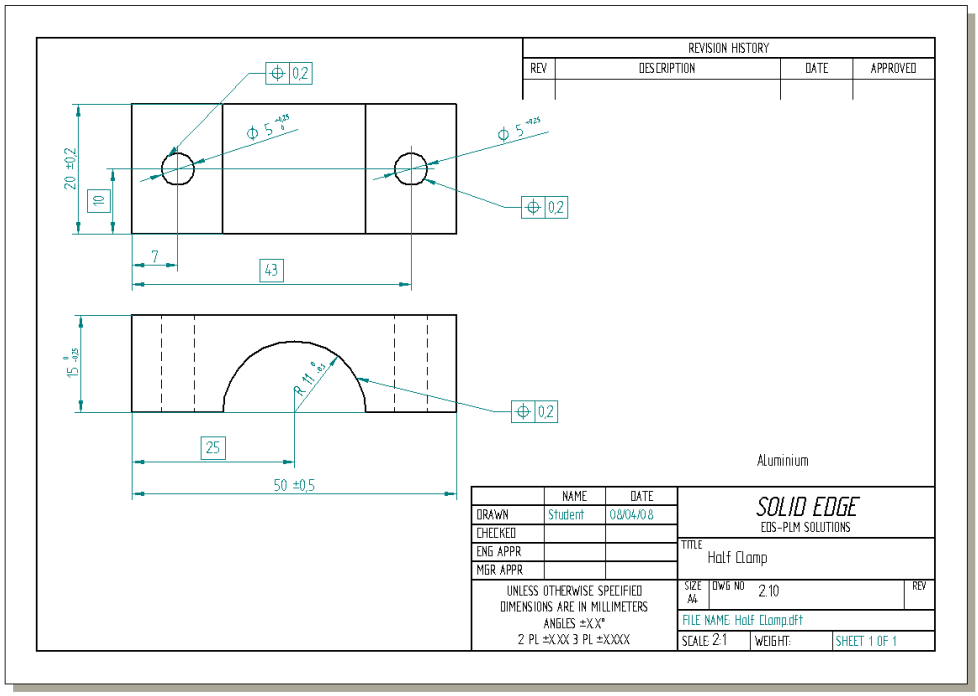

REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
50
30
10
10 ±0,25
5
Ø 4,2
Ø 7,5
Ø 4,2
M5 thread
0,2
Same positioning tolerance
for all holes
Ø 22 +0,25 0
Ø 4,2
M5 thread
Ø 4,2
100 ±1
80
20
10
5
60 ±0,5
Aluminium
NAME
DATE
DRAWN
Student
04/23/08
CHECKED
ENG APPR
MGR APPR
SOLID EDGE
EDS-PLM SOLUTIONS
TITLE
Tiltable bit 4
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
ANGLES ±XX°
2 PL ±XXX 3 PL ±XXXX
SIZE
A4
DWG NO
2.5
REV
FILE NAME Tiltable bit4.dft
SCALE 1:1
WEIGHT:
SHEET 1 OF 1

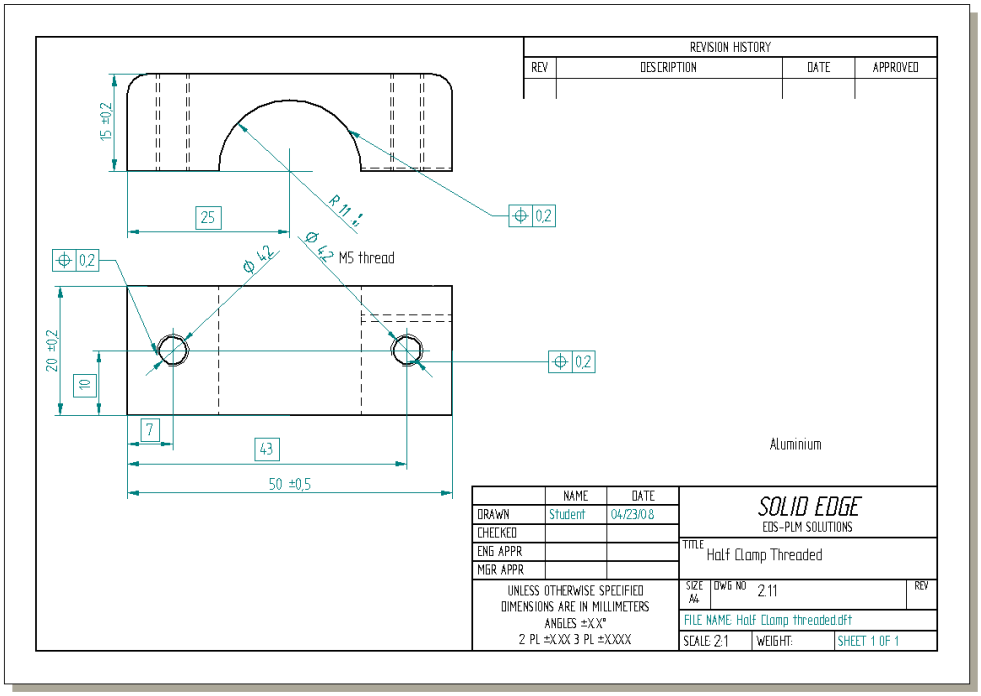

REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
Same positioning tolerance for all holes
0.2
Aluminium
NAME
DATE
DRAWN
Student
07/29/08
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
ANGLES ±X.X°
2 PL ±X.XX 3 PL ±X.XXX
SOLID EDGE
EDS-PLM SOLUTIONS
TITLE
Tilt Support Bracket
SIZE
A4
DWG NO
2.6
REV
FILE NAME: Tilt support bracket.dft
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1

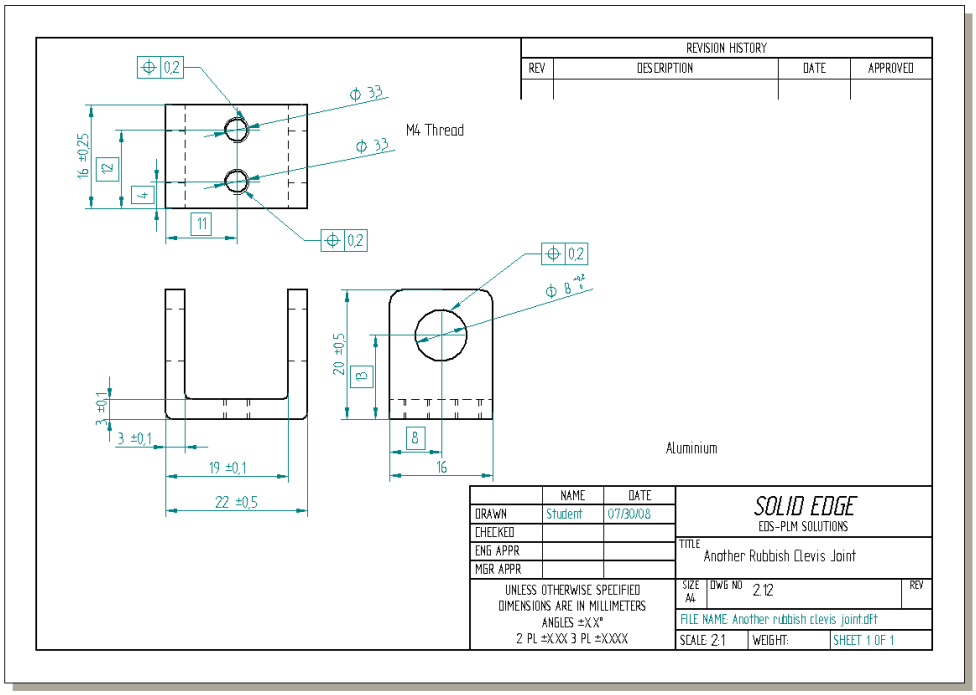

REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
0.2
0.2
395
400 ±1
22mm S/S pipe
NAME
DATE
DRAWN
Student
07/29/08
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
ANGLES ±X.X°
2 PL ±X.XX 3 PL ±X.XXX
SOLID EDGE
EDS-PLM SOLUTIONS
TITLE
Pivot bar
SIZE
A4
DWG NO
2.7
REV
FILE NAME: Pivot bar.dft
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1


REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
Ø 22 +0.5 0
15
15
R 15 ±0.1
Ø 22 +0.5 0
Ø 10 +0.2 0
45
15
60 ±0.5
30 ±0.25
10 +0.2 0
20 +0.2 0
30 ±0.5
15
30 ±0.5
Aluminium
NAME
DATE
DRAWN
Student
06/30/08
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
ANGLES ±XX°
2 PL ±XXX 3 PL ±XXXX
SOLID EDGE
EDS-PLM SOLUTIONS
TITLE
22x22 Perpendicular
SIZE A4
DWG NO 2.8
REV
FILE NAME 22x22 Perpendicular.dft
SCALE 1:1
WEIGHT:
SHEET 1 OF 1


REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
11
15
Ø 10 +0.2 0
0.2
80 ±0.5
181 ±1
516 ±1
Fabricate in 2 pieces joined by 22mm union if necessary
22mm S/S pipe
NAME
DATE
DRAWN
Student
07/03/08
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
ANGLES ±XX°
2 PL ±XXX 3 PL ±XXXX
SOLID EDGE
EDS-PLM SOLUTIONS
TITLE
U Bend
SIZE A4
DWG NO 2.9
REV
FILE NAME Ubend.dft
SCALE 1:5
WEIGHT:
SHEET 1 OF 1


REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
0,2
Φ 5 +0,25
20 ±0,2
10
7
43
15 -0,25
R 11 -0,5
25
50 ±0,5
Aluminium
NAME
DATE
DRAWN
Student
08/04/08
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
ANGLES ±X.X°
2 PL ±XXX 3 PL ±XXXX
SOLID EDGE
EDS-PLM SOLUTIONS
TITLE
Half Clamp
SIZE
A4
DWG NO
2.10
REV
FILE NAME: Half Clamp.dft
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1


REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
15 ±0,2
25
R 11 +0,5
0,2
Ø 4,2
Ø 4,2 M5 thread
20 ±0,2
10
7
43
50 ±0,5
Aluminium
NAME
DATE
DRAWN
Student
04/23/08
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
ANGLES ±X.X°
2 PL ±XXX 3 PL ±XXXX
SOLID EDGE
EDS-PLM SOLUTIONS
TITLE
Half Clamp Threaded
SIZE
A4
DWG NO
2.11
REV
FILE NAME: Half Clamp threaded.dft
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1


REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
0,2
Φ 3,3
Φ 3,3
M4 Thread
16 ±0,25
12
4
11
0,2
0,2
Φ 8
20 ±0,5
13
8
16
3 ±0,1
3 ±0,1
19 ±0,1
22 ±0,5
Aluminium
NAME
DATE
DRAWN
Student
07/30/08
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
ANGLES ±XX°
2 PL ±XXX 3 PL ±XXXX
SOLID EDGE
EDS-PLM SOLUTIONS
TITLE
Another Rubbish Clevis Joint
SIZE
A4
DWG NO
2.12
REV
FILE NAME Another rubbish clevis joint.dft
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1

13 Appendix C

This appendix contains a copy of the category partitioning scale (CP-50) used in the sitting discomfort trials (chapter 6).

Participant No……
Session/period……..

Category Partitioning Scale

You are asked to rate your overall level of comfort by selecting numbers from the adjacent scale. The scale is subdivided into 5 categories that we may commonly use in everyday life. Please start out by determining the category into which your discomfort level falls. You should then fine tune your judgement using the numbers within this category. Your rating is not limited by the largest number on the scales. Always consider the crude category as well as the number when you make a judgement.

For example: If you felt your discomfort level was high, and almost severe, you should choose category 4 (high discomfort). This category comprises the numbers 31-40. Due to the tendency towards almost severe discomfort this may result in you choosing a number close to the upper category boundary, such as 38 or 39.

0 min ……..

20 min ……

40 min ……

60 min ……..

80 min ……

100 minutes ……

	52
	51
	50
	49
	48
	47
5. Severe discomfort	46
	45
	44
	43
	42
	41
	40
	39
	38
	37
4. High discomfort	36
	35
	34
	33
	32
	31
	30
	29
	28
	27
3. Medium discomfort	26
	25
	24
	23
	22
	21
	20
	19
	18
	17
2. Low discomfort	16
	15
	14
	13
	12
	11
	10
	9
	8
	7
1. Slight discomfort	6
	5
	4
	3
	2
	1
No discomfort	0

Adapted from- Shen W and Parsons KC (1997). "Validity and reliability of rating scales for selected pressure discomfort" Int J Ind Ergon 20: 441-461

14 Appendix D

This appendix contains a copy of the scoring form for the Seated Postural Control Measure used in chapter 7.

[redacted] **SPCM Scoring Form**
SEATED POSTURAL CONTROL MEASURE January 1994

SUNNY HILL HEALTH CENTRE FOR CHILDREN
3644 Slocan Street, Vancouver, B.C. V5M 3E8

		Yr	Mo	Day		Score	Min	Max.
Name_____	Date of Assessment	___	___	___	Alignment	_____	34	48
I.D. No_____	Date of Birth	___	___	___				
Diagnosis_____	Chronological Age	___	___	___	Function	_____	12	48
Date of onset of problem_____	Rater Name _____							

Referring physician_____

LEVEL OF SITTING SCALE Check category below (see Guidelines)

___ 1 unplaceable
___ 2 supported from head downward
___ 3 supported from shoulder or trunk downward
___ 4 supported at pelvis
___ 5 maintains position, does not move
___ 6 shifts trunk forward, re-erects
___ 7 shifts trunk laterally, re-erects
___ 8 shifts trunk backwards re-re-erects

COGNITIVE LEVEL

Understands most instructions ☐
Understands few instructions ☐

COOPERATION LEVEL

Cooperates fully ☐
Cooperates with prompting ☐
Uncooperative ☐

Description of Seating System used for this test:

Date last modified: _____/_____/_____ Is present fit adequate? Yes ☐ No ☐

Type of system and general comment:

_____

_____

Indicate seating system in degrees:

_____ seat to back angle
_____ angle of seat back recline related to vertical plane (tilt in space)

Interface surface

_____ planar
_____ contour

Check seating system components which are present:

Pelvis:
_____pelvic stabilizer
_____ ASIS pads
_____ pelvic bar
_____ pelvic belt
_____ safety belt
_____ lateral support

Trunk:
_____ lateral thoracic support
_____ lumbar support
_____ anterior trunk support
_____ at shoulder
_____ chest panel

Head and Neck
_____ circumfrential head and neck support
_____ head support
_____ posterior
_____ anterior
_____ lateral
_____ posterior neck support

Thigh:
_____ medial support
_____ lateral support

Knees
_____ anterior support

Upper Limbs
_____ tray
_____ custom arm supports
_____ posterior blocks
_____ scapulae
_____ elbows

SEATED POSTURAL CONTROL MEASURE: ALIGNMENT SECTION JANUARY, 1994

Sunny Hill Health Centre for Children Vancouver, B.C.

Please circle selections NB: Circle twice to score limb items.

Score: Descriptive / Numeric	Severe 1	Moderate 2	Mild 3	Normal 4	Mild 3	Moderate 2	Severe 1	Score
ANTERIOR VIEW								
PELVIC OBLIQUITY Line joining ASIS's **relative to horizontal**	≥25*	15-24	5-14	0±4	5-14	15-24	≥25	
	Right Side High				Left Side High			
TRUNK LATERAL SHIFT Line joining sternal notch to midpoint between ASIS's **relative to vertical**	≥25	15-24	5-14	0±4	5-14	15-24	≥25	
	Shift to Right				Shift to Left			
SHOULDER HEIGHT Line joining shoulders **relative to horizontal**	≥35	20-34	5-19	0±4	5-19	20-34	≥35	
	Right Side High				Left Side High			
HEAD LATERAL TILT Line joining outside corner of eyes **relative to horizontal**	≥35	20-34	5-19	0±4	5-19	20-34	≥35	
	Right Lateral Tilt				Left Lateral Tilt			
R, 6. L HIP ROTATION Angle of tibia relative to line joining ASIS's	≥35 R L	20-34 R L	5-19 R L	0±4 R L	5-19 R L	20-34 R L	≥35 R L	
	Rotated to Right				Rotated to Left			
GHT LATERAL VIEW								
PELVIC TILT Line from PSIS along posterior pelvis to seat surface **relative to vertical**	≥25*	15-24	5-14	0±4	5-14	15-24	≥25	
	Posterior Tilt				Anterior Tilt			
LUMBAR CURVE L1 - L5								
	Flexed				Extended			
THORACIC CURVE T1 - T12								
	Flexed				Extended			
TRUNK INCLINATION Line joining posterior surface T1 and median of line joining PSIS's **relative to vertical**	≥35	20-34	5-19	0±4	5-19	20-34	≥ 35	
	Anterior Inclination				Posterior Inclination			
HEAD ANT/POST TILT Line joining corner of eye to tragus **relative to horizontal**	≥16**	1-15**	14-0**	15-24	25-39	40-54	≥ 55	
	Anterior Tilt				Posterior Tilt			

* Degrees of angulation

** See note in Guidelines

SCORE: Page 2 ☐

SEATED POSTURAL CONTROL MEASURE: ALIGNMENT SECTION JANUARY, 1994

Sunny Hill Health Centre for Children Vancouver, B.C.

Please circle selections NB: Circle twice to score limb items.

Score: Descriptive / Numeric	Severe 1	Moderate 2	Mild 3	Normal 4	Mild 3	Moderate 2	Severe 1	Score
RIGHT & LEFT LATERAL VIEWS								
R, 13. L HIP FLEX/EXT Angle relative to 90° flexion			>15° R L	0 ± 15 R L	>15 R L			
			Hip Flexion		Hip Extension			
R, 15. L KNEE FLEX/EXT Angle relative to 90° flexion			>45 R L	0 ± 45 R L	>45 R L			
			Knee Flexion		Knee Extension			
R, 17. L ANKLE DORSI/PL FLEXION Angle relative to 0 degrees			>30 R L	0 ± 30 R L	>30 R L			
			Ankle Dorsiflexion		Ankle Plantarflexion			
POSTERIOR VIEW								
PELVIC ROTATION Line joining ASIS's **relative to plane of the seat back**	≥25	15-24	5-14	0±4	5-14	15-24	≥25	
			Right Side Forward		Left Side Forward			
UPPER TRUNK ROTATION Line joining shoulders **relative to frontal plane** of pelvis	≥35	20-34	5-19	0±4	5-19	20-34	≥35	
			Right Side Forward		Left Side Forward			
HEAD ROTATION Line joining ears **relative to frontal plane** of upper trunk	≥35	20-34	5-19	0±4	5-19	20-34	≥35	
			Rotation to Right		Rotation to Left			
R, 22. L HIP ADD/ABDUCTION Angle of femur in relation to line joining ASIS's	≥35 R L	20-34 R L	5-19 R L	0±4 R L	5-19 R L	20-34 R L	≥35 R L	
			Hip Adduction		Hip Abduction			

* Degrees of angulation

SCORE: Page 3

Enter total Alignment Section Score on Page 1

[redacted] **SPCM Scoring Form (cont'd)**

SEATED POSTURAL CONTROL MEASURE
Sunny Hill Health Centre for Children, Vancouver, B.C

FUNCTION SECTION

Circle score for each item.

Administer items 1 & 2 simultaneously, score separately.

1. Lifts head upright and maintains 5 sec

If child's head is not flexed forward prior to test, instruct or assist child to do so. Upright position of the head is defined as that position where central gaze is directed along the horizontal plane (+/- 15° in saggital plane).

1. does not initiate head lift
2. initiates a head lift
3. lifts head, does not attain upright, but holds for 5 sec
4. lifts head upright and maintains for 5 sec

2. Lifts head upright, in midline and maintains for 10 sec

If child's head is not flexed forward prior to test, instruct or assist child to do so. Midline position of the head is defined as that position where central gaze is directed along the horizontal plane (+/- 5 ° in coronal plane).

1. does not initiate head lift
2. initiates head lift but does not attain midline
3. attains midline but maintains for less than 10 seconds
4. lifts head to midline and maintains for 10 seconds

3. Leans forward, touches toy with preferred wrist or hand, re-erects

Place board 6" from child's stomach. Small toy placed on board at child's midline at a distance 1 arm length.

1. does not lean forward and re-erect
2. leans forward but does not touch toy
3. leans forward, touches toy, but does not re-erect
4. leans forward, touches toy, re-erects

4. Leans forward and to right or left, touches toy with OPPOSITE hand, re-erects

The intent of this item is to obtain trunk rotation; either hand may be used. Small toy placed on board in front of child on the side opposite to the reaching hand. Place toy 1 arm length of the reaching arm along the layout guide marker line, which runs 60 degrees from trunk midline.

1. does not move trunk
2. lean towards toy but does not touch it
3. leans towards and touches toy with hand, does not re-erect
4. leans towards and touches toy with hand, re-erects

5. Lifts both upper limbs free of support

1. does not lift either upper limb off support
2. lifts RIGHT or LEFT upper limb off support for less than 3 sec
3. lifts one upper limb off support for 3 sec
4. lifts both upper limbs off support for 3 sec

6. Reaches forward, grasps and releases toy with preferred hand

Small toy placed on board an "arm length" anterior to the trunk midline.

1. does not touch toy
2. touches toy with palm or fingers
3. grasps toy and lifts it off board for 3 sec
4. releases toy into large container set down in a convenient place

Administer items 7 & 8 simultaneously, score separately.

7. Removes and replaces lid of screw-type jar

Jar placed on board anterior to child's midline at any location which accommodates child's attempts to grasp jar.

1. does not touch jar
2. places one or both hands on jar
3. unscrews and removes jar lid
4. replaces jar lid and screws it closed

8. Picks up raisin (or cheerio), places into mouth with preferred hand

Raisin placed on board at any location which accommodates child's attempts to pick up raisin.

1. does not touch raisin
2. touches raisin with tips of fingers and/or thumb
3. picks up raisin and holds for 3 sec
4. releases raisin into mouth

9. Picks up pen makes mark on paper

Pen and 81/2" x 11" sheet of paper placed midline on board, pen tip pointing towards child.

1. does not grasp pen
2. grasp pen with one or both hands
3. grasp and lifts hand and/or pen clear of surface
4. marks paper with pen

10. Places dice in jar, one at a time, with preferred hand, in 30 sec

Place one die and jar on board as indicated by paper guide immediately in front of child. Request child to place dice into jar, a time, using one hand, as fast as possible. Assessor to place next dice on paper guide while child is placing previous dice in. (Do not hinder child's performance).

1. does not place any dice in jar
2. places 1 die
3. places 2 to 5 dice
4. places 6 dice

11. Moves his/her wheelchair forward 45' in less than **20** sec

Allow one practice trial to ensure child understands task

1. unable to move wheelchair forward
2. moves wheelchair forward 10' in less than 60 sec
3. moves wheelchair forward 45' in less than 60 sec
4. moves wheelchair forward 45' in less than 20 sec

12. Moves his/her wheelchair forward 19' along a 8' wide corridor, turns right or left 90 degrees and passes through 33' doorway

Allow one practice trial to ensure child understands the task. Maximum of 60 seconds allowed for completion of the task

1. does not move wheelchair forward 10' without bumping into walls
2. moves wheelchair forward 10', but does not initiate a turn
3. moves wheelchair forward 10', turns and passes through doorway, with wall contact
4. moves wheelchair forward 10', turns and passes freely through doorway

TOTAL SCORE FUNCTION_____ (Max = 48)

Enter score on page 1