Improvement of movement function using bespoke virtual reality based computer games

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2012

Acknowledgements

The last three years have been a test of determination and resolve, but I have thoroughly enjoyed the process and the many experiences that have come with it. There are a few thanks I would like to make;

I would like to express my appreciation to The WellChild Trust and the Institute for Health Research (Liverpool John Moores University) for funding this project. I would also like to thank Alder Hey Hospital (Liverpool) and The Movement Centre (Oswestry) for providing expertise in the area of Gait Analysis and Targeted Training respectively.

Adrian, your guidance when overseeing this research process has been invaluable. Your view from afar and timely contributions have helped to shape together a piece of work I am very proud of. I owe it to you for helping to steer things in the right direction.

Malcolm, the support you have provided me during the past three years has been greatly appreciated. You have been a fountain of knowledge, my own Wikipedia, except that you provide much more detail. Thank you for all your wisdom.

Gabor, you are the person who inspired me to move into research. Without your enthusiasm, creativity, and drive, I would not be where I am today. Thank you for providing me with the opportunity to work alongside you in an exciting area of research.

To Malcolm and Gabor, I am grateful for all the thought provoking conversations we have had as a team. I like to think of you both as my academic mentors, long may that continue!

Mum, Dad, and Rachel, your support has been unrivalled. Words are not able to describe how grateful I am for your constant love and encouragement throughout the many years leading up to this point. I owe it to you for not letting me lose sight of the end goal.

Michaela, thank you for rescuing me from the depths of despair at times, for keeping me sane, and for showing me the other side of life outside academia. Your love and relentless support have pushed me forward when I most needed it.

Last but not least, I'd like to thank my large postgraduate family, from which long lasting friendships have been born. The endless tea-trains and team nights out will live long in my memory.

Abstract

Children with cerebral palsy suffer from primary abnormalities that affect their ability to control movement of body segments. There is evidence that the core (trunk and pelvis) of the body activates prior to the periphery (extremities) during human movement, and so improvement in controlling the core first, then the periphery, could lead to carrying out activities of daily living more effectively. Virtual rehabilitation is developing as a method for the training and assessment of movement function, with evidence suggesting games controlled by the periphery can lead to improvements in activities of daily living, but virtual rehabilitation on the core is scarce. Study One (feasibility study) assessed the changes in gait in response to a six week virtual reality intervention training the core in children with cerebral palsy diplegia ($n = 5$), using a laboratory based virtual reality system. Improvement in selective motor control of the core occurred after VR training, represented by increased VR game performance (maximum settled speed). Participants showed that single plane trunk movement was better controlled than cross plane trunk movement, trunk rotation was better controlled than trunk tilt, and the trunk was controlled better than the pelvis. Changes in game performance did not transfer to improvements in gait as measured using the Gait Deviation Index. Study Two used a portable virtual reality system in primary schools to train the core and periphery in children with cerebral palsy. A randomised, cross-over design on children with cerebral palsy ($n = 8$) found that VR game performance improved after receiving VR training, represented by an increase in maximum settled speed and a reduction in variation of pass distance. Single plane movement of the trunk was better controlled than cross plane movement during each assessment, ankle control was better than knee control at each assessment, and control of peripheral segments was better than control of core segments. There were no significant differences in performance of the sit-to-stand movement in response to core training (one week) followed by peripheral training (one week), or when training order was reversed. Overall, Study One and Study Two found no improvements in activities of daily living. Low levels of exposure to virtual reality training, inappropriate outcome measures, in addition to low sample sizes, may have reduced the effect on performance of activities of daily living. Study Two demonstrated that portable virtual reality training is feasible in schools, and can be provided on a daily basis to children with movement difficulties. Overall, the findings provide an important insight into virtual reality training aimed at improving control of the core and periphery in children with cerebral palsy.

Research output relating to thesis

Barton GJ, Hawken MB, Butler P, Holmes G, & **Foster RJ**. (2009). Movement control of the trunk and pelvis in cerebral palsy diplegia. *Gait & Posture*, 30, S147-S148 18th ESMAC Meeting and Conference. London, UK. September 15th -19th. *Oral Presentation.* (Appendix 1)

Foster, R., Hawken, M., Butler, P., Holmes, G., & Barton, G. (2010). The effects of game training on trunk to pelvis coupling: A case study of a child with Cerebral Palsy. LJMU Faculty Postgraduate Research Seminar, 20th May. *Oral Presentation.* (Appendix 2)

Foster, R., Hawken, M., Butler, P., Holmes, G., & Barton, G. (2010). The effects of game training on trunk to pelvis coupling: A case study of a child with Cerebral Palsy. British Association for Sport and Exercise Sciences, Biomechanics Group Interest meeting, University of Bath, 21st April. *Oral Presentation.* (Appendix 2)

Foster, R.J., Hawken, M.B., Holmes, G., Butler, P., & Barton, G.J. (2011). Training the core in children with Cerebral Palsy using computer games: A sensitivity analysis of its impact on walking. 16th ECSS Congress, 6-9 July 2011, Liverpool/UK. *Oral Presentation* (Appendix 3)

Barton GJ., Hawken MB., **Foster RJ.**, Holmes G., & Butler PB. (2011). Playing the Goblin Post Office game improves movement control of the core: A case study. International Conference on Virtual Rehabilitation 2011. Rehab Week Zurich, ETH Zurich Science City, Switzerland, June 27 - 29, 2011. (Appendix 4)

Barton GJ., Hawken MB., **Foster RJ.**, Holmes G., & Butler PB. (2012). The effects of game training on trunk to pelvis coupling in a child with cerebral palsy. Journal of NeuroEngineering and Rehabilitation. Under review. (Appendix 5)

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List of abbreviations

ADL	Activities of Daily Living
CAREN	Computer Assisted Rehabilitation ENvironment
CP	Cerebral Palsy
fMRI	Functional Magnetic Resonance Imaging
GPO	Goblin Post Office
IMU	Inertial Measurement Unit
NHS	National Health Service
NWMAC	North West Movement Analysis Centre
PEST	Parameter Estimation by Sequential Testing
STS	Sit-to-Stand movement
TD	Typically Developed
VR	Virtual Reality

Chapter 1. Introduction

1.1 Introduction to research

Cerebral palsy (CP) is a neuro-musculo-skeletal disorder arising from damage to the immature brain. The incidence is 1 in 400 live births (Koman *et al.*, 2004). CP is a non-progressive disorder which results from a permanent static lesion to the brain. Deficient equilibrium reactions, spasticity, and loss of selective motor control are the primary abnormalities associated with CP (Gage & Novacheck, 2001). These abnormalities can lead to difficulties performing activities of daily living (ADL). The primary deficits also lead to the development of secondary musculo-skeletal abnormalities such as muscle contractures and bony deformities, which often result in a need for orthopaedic surgery. Development of treatments that alleviate the primary abnormalities could therefore delay the onset of secondary abnormalities and prevent or reduce the need for invasive treatment. The majority of treatments for children with CP are designed to alleviate the secondary abnormalities of the musculo-skeletal system, rather than to treat the primary abnormalities which hinder ADL. Treatments which aim to improve gross motor skills and performance of ADL involving whole body movements place greater emphasis on the primary abnormalities (Barber, 2008; Effgen & McEwen, 2008; Papavasiliou, 2009), and should be considered as an alternative.

Existing literature suggests that the core segments and core muscles of the body (hereafter collectively referred to as the 'core') play a large role in performing ADL and whole body movements, indicating that treatments should involve the core and not just the lower extremities (referred to as the 'periphery'). Willson *et al.* (2005) defined the core to comprise the trunk (lumbar spine), pelvis and hip joints with active (muscular elements) and passive (osseous and ligamentous) structures that enable or restrict motion of these segments. This definition can be expanded to include the thoracic spine, which plays a large role in developing stability of the trunk throughout maturation (Butler & Major, 1992). Selective motor control of the trunk when rising from a chair is considered a very demanding task biomechanically (Giansanti *et al.*, 2007), and good selective motor control of the trunk is also required for performing independent activities during standing (Butler, 1998). Indeed, the interaction between the trunk and pelvis plays a pivotal role in maintaining dynamic equilibrium during gait (Sartor *et al.*, 1999), since segmental coupling changes as a function of walking speed. The evidence implies that appropriate movement control of the core is a pre-requisite for efficient human movement, and for maintaining equilibrium during ADL, yet physiotherapy treatment remains at the periphery. Consequently, treatments that improve impaired selective motor control of the core prior to treatment of the periphery could lead to improvements in the performance of ADL.

The existing literature describes various methods for training the periphery in children with CP, although there is no general agreement on which is the most effective. In contrast, there is little research concerning training selective motor control of the core of the body. Targeted Training, described by Butler and Major (1992), uses a level-by-level approach targeting the improvement of control at proximal body segments first (i.e. the trunk), before addressing poor control of the distal segments (upper or lower extremities). A specialised training frame is used to support and fix the joint directly below the targeted joint and lower, whilst external movement perturbations are used to challenge control. The application of Targeted Training is supported by positive research findings; CP children with poor control were reported to develop head and trunk control in response to Targeted Training, and transfer good posture developed in the training frame to ADL (Butler, 1998; Farmer *et al.*, 1999; Major *et al.*, 2001). Although research supports the application of Targeted Training, a specialist physiotherapist and specific equipment are required for the successful implementation of training, preventing its wider use in physiotherapy and in the home for children with CP. Translating the principles of Targeted Training to physiotherapy methods which do not require the training frame could widen the use of such therapy in rehabilitation.

Developments in technology have led to the introduction of virtual rehabilitation (Burdea, 2003) as an alternative to conventional physiotherapy. Burdea (2003) reported that virtual rehabilitation led to greater compliance and the ability to enhance motor learning. As children mature and begin to attend school, compliance with physiotherapy is low (Bryanton *et al.*, 2006). A child's motivation to perform physiotherapy exercises alone, or with the help of family members, in the home can be particularly poor. Typically exercises are boring, repetitive, and meaningless to the child because of a lack of understanding of the benefits of therapy. In consequence finding ways to engage a child in rehabilitation exercises outside the clinic is a challenge, whilst monitoring compliance rates objectively in the home is difficult for the physiotherapist (Burdea, 2003). Provision of physiotherapy based exercises through virtual reality (VR) systems is an innovative way of increasing compliance rates (Burdea, 2003). VR is a computer generated simulation of the real world in which the user interacts with a virtual environment through a human-machine interface (Holden, 2005) . Bryanton *et al.* (2006) found that selective motor control at the ankle joint increased in response to VR based exercises, as opposed to conventional range of motion exercises, in children with spastic CP. They also reported increased compliance rates in children who received VR training instead of conventional physiotherapy. This evidence suggests that improvements in movement control occur in response to virtual rehabilitation, and that prolonged acceptance is better as opposed to conventional physiotherapy.

Existing VR based interventions train the periphery to improve movement of the upper and lower extremities (Deutsch *et al.*, 2001; Merians *et al.*, 2002; You *et al.*, 2005; Bryanton *et al.*, 2006; Merians *et al.*, 2006), yet there is limited use of VR to train the core of the body. Research by Barton *et al.* (2006) showed that quantitative analysis of segmental movements during VR game play could be used to demonstrate different movement patterns between an asymmetrical CP diplegic adolescent and a typically developing child when both were driving the game with their pelvis. The research suggests that VR games may be able to quantify differences between groups of subjects with and without pathology during an initial assessment of selective motor control of the core. There is, however, no current research which assesses whether selective motor control of the core of the body can be improved in response to VR training over a period of time, highlighting a gap in existing literature.

Virtual rehabilitation should be accessible in the community to enable the continuity of VR training once treatment begins. Accurate and reliable capture of body motion is essential for virtual rehabilitation in order for patients to immerse themselves within a virtual world and so VR training is typically confined to research laboratories. State-of-the-art optical video motion capture systems are frequently used in VR installations, but are in general permanently located within laboratories. Video motion capture systems require expensive high-quality cameras to capture body motion, in addition to high-priced software and specific expertise needed to operate the systems. Therefore a device which is accurate, affordable, and portable for use in physiotherapy is desirable to increase the availability of virtual rehabilitation. Inertial measurement units (IMU), such as the Xsens sensor (Xsens Technologies, The Netherlands), closely match the output of video motion capture systems when capturing body motion, providing angular displacement and accelerations (Roetenberg *et al.*, 2005; Thies *et al.*, 2007). IMUs combine data from rate gyroscopes, accelerometers, and magnetometers to produce information on orientation. Due to their small size and portability, IMUs can be used to sense body motion during ADL outside the laboratory setting (Cutti *et al.*, 2010; Ferrari *et al.*, 2010). IMUs present themselves as a convenient alternative to video motion capture systems for translating VR out of the constraints of a laboratory to physiotherapy departments, schools, or within the home.

Developing control of the core before the periphery of the body in children with CP could lead to improvements in ADL. Existing literature suggests that Targeted Training leads to improvements in ADL, but the limitations of Targeted Training make its widespread use as a physiotherapy technique difficult to implement. Instead, adopting certain principles of Targeted Training and implementing them through alternative methods of rehabilitation such as VR training could provide greater access to similar training. VR based training addresses the need to make physiotherapy more engaging for children through making it more enjoyable. Current provision of virtual rehabilitation for children with CP aims to improve movement at the periphery, but improvements were not shown to translate to performance of ADL. Combining the principles of Targeted Training with VR based training would provide a sequential order to virtual rehabilitation, by training selective motor control at the most proximal segment first (trunk) and working downwards (pelvis then lower extremities). The integration of IMUs into VR games could provide more access to training outside of a laboratory environment. Translating virtual rehabilitation into schools or the home could provide regular physiotherapy that is typically difficult to obtain.

1.1.1 Aims

The aim of this research is to investigate whether VR training leads to changes in performance of ADL for children with CP. A secondary aim is to develop a portable and more practical method of virtual rehabilitation in order to make VR training more readily available to children with CP.

The aims will be realised through the following programme of work:

1. Establish whether exposure to a bespoke VR game designed to train and test selective motor control of the core of the body can lead to measurable improvements of core control and ADL represented by gait function in children with CP.

2. Compare the performance of an IMU and a video motion capture system during controlled movements and VR game play.

3. Develop new VR games designed to train selective motor control of the body using an IMU.

4. Determine to what extent VR training using IMU improves selective motor control of the core and periphery of the body, with relation to performance of ADL represented by the sit-to-stand movement.

Chapter 2. Literature Review

2.1 Introduction to the research

The following sections contain a detailed discussion of present knowledge relevant to the aims and objectives of this work. The discussion begins with a review of relevant clinical and research findings in cerebral palsy (CP), before addressing the use of virtual rehabilitation to improve movement function in children with CP.

2.2 Cerebral palsy

Damage to the immature brain in children with CP is a consequence of a lack of oxygen, killing developing motor neurons (Whittle, 2007). Different areas of the brain are damaged in each case of CP, and the damage may be distributed or localised. For this reason the severity of the clinical abnormalities which develop over time in association with CP are by no means homogenous. Although CP is defined as a non-progressive disorder arising from a permanent static lesion of the brain, the effects of the brain damage are not unchanging due to the manifestation of various problems over time including muscular contractures and abnormal bone growth (Koman *et al.*, 2004). Therefore CP may be referred to as non-progressive at the level of central nervous system pathology, but will continue to evolve clinically over time with regard to motor development and anatomy.

Children with CP typically experience difficulties with balance and in performing activities of daily living (ADL) as a result of loss of selective motor control, spasticity, and deficient equilibrium reactions (Gage & Novacheck, 2001). Selective motor control is the ability to activate individual muscles or groups of muscles in isolation. Children with CP find the voluntary control and coordination of muscles difficult during functional activities. For example, co-activation of both the flexor and extensor muscles may occur to provide the desired movement at a specific joint, instead of the required muscle in isolation. Electromyography can be used to measure the timing of muscle activations to determine whether selective motor control is impaired. For example Tedroff *et al.* (2006) reported that during ankle plantar flexion, children with CP showed pre-activation of the tibialis anterior (CP hemiplegia) or co-activation of the medial hamstrings (CP diplegia) when the lateral gastrocnemius muscle was the intended prime mover. An alternative way to measure selective motor control is the Selective Control Assessment of the Lower Extremity (Fowler *et al.*, 2009). This clinical assessment tool is based on a grading system performed by healthcare professionals in relation to a child's ability to move specific joints selectively when instructed. Spasticity refers to a velocity-dependent increase in muscle tone with exaggerated tendon jerks, resulting from hyper-excitability of the stretch reflex

(Gage *et al.*, 2009). The primary abnormalities lead to development of secondary musculo-skeletal abnormalities, such as muscle contractures and bony deformities. There are a number of subtypes for categorising the extent of the impairment in child with CP. Diplegia is used to refer to those affected by spasticity in the lower extremities. Hemiplegia refers to those with unilateral involvement of the upper and lower extremity, with large asymmetry in functional movement. Triplegia affects three extremities, whilst quadriplegia typically affects all extremities as well as the trunk (Jones *et al.*, 2007).

2.3 Treatment in cerebral palsy

Advances in neonatal care provided by the National Health Service within the UK have led to an increase in the prevalence of children with CP, as more infants survive anoxia and other conditions leading to brain damage around the time of birth. In response to advances in neonatal care, the UK CP database has recorded a shift of emphasis from mortality to morbidity, with an increased focus on quality of life (Surman *et al.*, 2006). Many treatment services are available to children with CP, but there is disagreement about the most effective method. Conservative treatments include physiotherapy, occupational therapy, and the provision of orthotics, which are all aimed at enhancing functional mobility. Complementary or alternative treatment methods such as Hippotherapy (horse riding) and hyperbaric oxygen therapy are less orthodox but improvements may occur (Papavasiliou, 2009). Pharmacological treatments like Botulinum toxin and intrathecal baclofen are invasive methods used specifically in the management of spasticity. While physiotherapy is the most common form of treatment received, it typically addresses the musculo-skeletal aspect of CP rather than the primary abnormalities that result from impairment of the central nervous system. You *et al.* (2005) reported that functional reorganisation of the brain can occur in response to goal-orientated rehabilitation that addresses the functional consequences of injury. This suggests that although damage to the brain does not heal, there is evidence which supports the establishment of new neural pathways in response to the correct treatment. Hence targeting the primary abnormalities of CP rather than the secondary abnormalities could lead to greater improvements in functional mobility.

2.4 Physiotherapy: Past and present

Traditionally, the role of the physiotherapist in the management of children with CP has mainly been to facilitate passive stretching at the periphery (the periphery refers to the upper and lower extremities of the body, which form the appendicular skeleton and are distal to the trunk and pelvis segments). Passive stretching typically involves trying to increase the range of motion at a joint by gentle extension in an attempt to combat the secondary abnormalities that develop from weakness and spasticity, such as muscle contractures. However a review by Pin *et al.* (2006) found no clinically relevant evidence to suggest that passive stretching can improve range of motion, reduce spasticity, or improve gait efficiency in children with CP. Physiotherapy is not just limited to passive stretching though. Neuro-developmental treatment, also known as the 'Bobath approach' (Bobath & Bobath, 1984) facilitates typical movement patterns whilst inhibiting atypical movement using handling techniques which aim to control the position of specific body segments. Neuro-developmental treatment therefore aims to reduce the abnormalities that result from damage to the central nervous system rather than musculo-skeletal abnormalities. Whilst this is more applicable to ADL than passive stretching, there is a lack of consistent evidence to show that neuro-developmental treatment produces beneficial changes in motor development or in functional activities in children with CP (Brown & Burns, 2001; Butler & Darrah, 2001; Effgen & McEwen, 2008). A number of authors propose that advances in physiotherapy should aim to improve gross motor skills and functional mobility in activities such as sitting, standing, gait, or wheelchair use independently, rather than by facilitation from a physiotherapist (Barber, 2008; Effgen & McEwen, 2008; Papavasiliou, 2009). Aiding the child during movement prevents the child developing control of their own movements independently, thus transfer of improvements to ADL is minimal. The current role of physiotherapy should be directed more towards a goal-orientated approach to enhance the child's ability to perform activities in the context of daily life (Østensjø *et al.*, 2004).

2.5 The role of the core in activities of daily living

There is growing evidence that a goal-oriented approach to physiotherapy should not ignore the role of the core when aiming to improve performance in ADL. Akuthota and Nadler (2004) suggest that good control of the core provides the foundation for all limb movement. The core of the body is a large proportion of total body mass and so its static position and dynamic movement influences strongly the position of the centre of gravity. Lack of motor control around the core therefore makes it difficult to maintain the centre of gravity safely within the base of support, leading to instability. Hodges and Richardson (1997a, b) reported that the central nervous system initiates contraction of the trunk muscles in anticipation of reactive forces being produced at the lower extremities during hip movements. Furthermore, Allum *et al.* (1998) suggest that trunk and hip responses to perturbations play a lead role in triggering human balance corrections. The evidence provides support for the role of the core during standing balance, but control of the core during dynamic movements driven by the lower extremities is important also.

Selective motor control of the trunk during rising from a chair is considered a biomechanically demanding task (Giansanti *et al.*, 2007), with the ability to rise from a chair largely considered to be a prerequisite for functional independence. In support, Butler (1998) suggests control of the trunk is required for performing independent activities during stance, stressing that dynamic control of the core is as essential as the static components. A number of studies have evaluated the relationship between the pelvis and trunk during gait (Lamoth *et al.*, 2002; Bruijn *et al.*, 2006; Lamoth *et al.*, 2006a; Lamoth *et al.*, 2006b; Bruijn *et al.*, 2008). In non-pathological gait the pelvis and trunk exhibit an in-phase coupling in the transverse plane at slow walking speeds. As the pelvis protracts with the ipsilateral limb during the loading response of the stance phase, the trunk also protracts on the same side. As walking velocity increases, there is a shift from in-phase to anti-phase coupling (Lamoth *et al.*, 2002; Bruijn *et al.*, 2008), characterised by protraction of the pelvis with the ipsilateral limb during the loading phase whilst the trunk counter-rotates and is effectively protracting away from the contralateral limb instead. Additional evidence is provided by Bruijn *et al.* (2008) who found that at an increased walking velocity of 5.2 km/h the pelvis rotates in-phase with the thigh rather than the thorax therefore a counter-rotation develops between the pelvis and trunk. Sartor *et al.* (1999) suggest that anti-phase coupling of the trunk and pelvis aids progression of the swing limb, implying a lead role for the core during gait. In the sagittal plane the pelvis is typically held in anterior tilt throughout the gait cycle, rotating about the mediolateral axis of the pelvis over a range of no more than 5° (Vogt *et al.*, 2002). Sartor *et al.* (1999) suggest that the trunk is predisposed to extension throughout the gait cycle as a consequence of the rather fixed anterior tilt of the pelvis. These events in combination are assumed to play a pivotal role in maintaining dynamic equilibrium of the musculoskeletal system during non-pathological gait. The evidence implies that the core plays both a preparatory role and ongoing dynamic role in human movement. Physiotherapy addressing selective motor control of the core prior to the periphery could therefore lead to improvements in performance of ADL.

2.6 Confusion of terminology concerning the core

The terms "core stability" and "core strength" are frequently used interchangeably in sports medicine, rehabilitation, and in discussion of athletic performance. Confusion results from the differing definitions of each term, largely due to the varying contexts to which they occur. For example, in rehabilitation there is a need to alleviate the mechanisms of lower back pain, or performing exercises which require movement of the core under low loading. In contrast, elite athletes require control of the core during high dynamic activities under high loads (Hibbs *et al.*, 2008). Deciding whether to refer to 'stability' or 'strength' in both these contexts is therefore difficult. Faries and Greenwood (2007) state that when referring to core stability, "reference is being made to the stability of the spine, not the stability of the muscles themselves" (p.11). Conversely, core strength is the ability of the surrounding musculature to provide stability to the spine through intra-abdominal pressure and co-activation of agonistic and antagonistic muscles of the trunk. The definitions provided by Faries and Greenwood (2007) provide alternative meanings to the terminology of core stability and core strength, and their proposals are supported by further literature. Willson *et al.* (2005) state that core stability is the ability of the lumbo-pelvic-hip complex to resist buckling, and to remain in equilibrium during external perturbations, whilst Akuthota and Nadler (2004) define core strength as the muscular control required around the lumbar region to maintain functional stability. Therefore stability seems to refer to the inter-segmental relationship of the skeletal system that comprises the core, whilst strength relates to the surrounding musculature which provides support to the skeletal system. Cholewicki *et al.* (2000) state "active control of spine stability is achieved through the regulation of force in the surrounding muscles. Therefore co-activation of agonistic and antagonistic trunk muscles stiffens the lumbar spine and increases its stability" (p.1377). A synergy exists between the definitions, with both core stability and core strength required to carry out adequate movement function of the core. Consequently there will continue to be confusion in the literature concerning which term to use for different types of research. For the purpose of this research "core control" is suggested as an alternative term that encompasses both core stability and core strength. By definition, core control will refer to the efficient movement of core segments during both static and dynamic activities whilst controlling for force and momentum. As such, core control refers to both the interaction of joints between core segments, in addition to the core musculature that support the joints.

2.7 Measuring control of the core

There are a number of ways to quantify the role of the core, with existing research on the electrical activity of lumbopelvic muscles during dynamic exercises (Souza *et al.*, 2001; Marshall & Murphy, 2005) measured by electromyography, and strength measurement during isometric contractions (Leetun *et al.*, 2004). However these methods quantify the underlying muscle activity and static elements of the core without regard for the functional aspects of movement such as control of core segments and how they interact. If the dynamic role of specific segments during functional activities is ignored, it is less likely that important deficiencies in a child's functional ability will be revealed.

Video motion capture systems are routinely used to measure movement of the trunk, pelvis, and lower extremities in gait analysis (Lamoth *et al.*, 2002; Bruijn *et al.*, 2006; Lamoth *et al.*, 2006a; Lamoth *et al.*, 2006b; Bruijn *et al.*, 2008), and the sit-to-stand movement (STS) (Park *et al.*, 2003; Guarrera-Bowlby & Gentile, 2004; Hennington *et al.*, 2004; Galli *et al.*, 2008), indicating new ways in which to measure the core. Video motion capture systems track small reflective markers attached over anatomical landmarks on the body. They provide a better understanding of the dynamic interaction between the core and periphery during human movement which allows analysis to occur during demanding ADL.

2.8 Methods to train the core

A review by Akuthota *et al.* (2008) stated that exercises such as Pilates and resistance training which are used to train the core can lead to improved athletic function (Willardson, 2007), prevent sport injuries (Myer *et al.*, 2005) and alleviate lower back pain (Rydeard *et al.*, 2006; Norris & Matthews, 2008). Whilst some gains may be made, these methods centre largely on co-contraction of specific core musculature during isometric actions, or activation of individual muscle groups of the core. Training separate movement components in isolation might lead to improved strength or selective motor control, but the improvements are unlikely to transfer to co-ordinated movements across multiple joints such as those required in ADL. Akuthota *et al.* (2008) instead suggested that advanced training of the core should aim to improve balance and co-ordination while subjects perform dynamic movement in each of the three fundamental movement planes; sagittal, coronal, transverse. Benefits from training in this way are more likely to transfer to ADL or dynamic activities.

2.9 Targeted Training

Evidence of training the dynamic components of the core in children with CP is provided through research on Targeted Training. Butler and Major (1992) explain that Targeted Training aims to improve selective motor control of specific joints in the body in a top-down sequence (proximal to distal) whilst in a vertical posture. They state that for a child with motor impairment, "the simultaneous learning of control at a large number of free joints places a heavy demand on the neuromuscular system" (Butler and Major, 1992, p. 183). Targeted Training aims to reduce the number of joints at which learning takes place, by using a frame to restrict movement below the targeted joint. For a child with poor lumbar control support is provided to the hip, knee, and ankle joints to remove the degrees of freedom below the targeted joint. Movement control is then challenged via external perturbations applied using a rocker base beneath the Targeted Training frame (Figure 1). Once sufficient control is gained at the lumbar region, the support at the joint below (in this case the hip) can be removed so that only the knee and ankle are supported, extending training of control to the hip joint. Butler (1998) provided evidence that six children with CP, who previously demonstrated reduced control from the cervical spine and below, were able to maintain trunk control in a sitting position after receiving Targeted Training (average length of Targeted Training was 14 weeks, ranging from 20 min to 2 hr 30 min each day). Farmer *et al.* (1999) used Targeted Training to improve the vertical posture of a child with CP who adopted a crouched gait, which typically results from poor hip and knee control. Results showed a 20° reduction in knee flexion during standing after 6 months of Targeted Training, and a 15° reduction during walking at 9 months. The child had therefore developed a more erect posture during gait. In another supporting study Major *et al.* (2001) stated that 29 out of 30 children achieved their intended goals of independent head control, independent sitting balance, or control of hip flexion/extension after receiving Targeted Training. The top down sequence of Targeted Training therefore supports the concept that selective motor control of the core is required prior to selective motor control of the periphery to perform ADL, whilst advocating the need for peripheral training also.

Figure 1. The Targeted Training device consists of a training frame that provides rigid support just below the targeted joint, and a rocker base below the frame to provide movement perturbations during practice. In this example, the child is supported at the hip, knee, and ankle joints to train control around the lumbar joint (Butler & Major, 1992).

A number of limitations exist when trying to use Targeted Training for physiotherapy treatment in children with CP. Firstly, Targeted Training requires a specially trained physiotherapist to determine the area of weakness in a child. Targeted Training separates the trunk into seven levels; the cervical spine, upper, mid and lower thoracic spine, upper, mid, and lower lumbar spine. Due to the specific nature of locating and isolating these levels, independent assessment of the trunk is not an easy task. Butler *et al.* (2010) have recently developed a direct means for quantifying changes in trunk control that occur in response to training, Targeted Training in particular. The segmental analysis of trunk control (SATCo) procedure is designed to test static, active and reactive control at various levels, proceeding in a top-down direction whilst sitting. The assessment begins at the highest level of support, the shoulder girdle, where head control is measured, and then moves downwards through the thoracic, lumbar and sacral regions to evaluate trunk control at multiple levels. Results of a recent validation and reliability study suggest the SATCo assessment method has good concurrent validity with the previously established Alberta Infant Motor Scale, a method for assessing gross motor development in infants (Piper & Darrah, 1994). The method also exhibited high inter-rater reliability. A second limitation of Targeted Training is that the frame used to train movement is expensive to manufacture, relies on charitable funding, and is a large piece of equipment to find space for within the home. Ways in which to adapt Targeted Training without the need for the

Targeted Training frame or a specialist physiotherapist could therefore increase the widespread use of such therapy in rehabilitation.

The improvements that are achieved in children with CP in response to Targeted Training cannot be ignored, since functional benefits were noted in most children who received the training. Targeted Training emphasises the need to train movement in logical sequence, suggesting that a proximal to distal approach to training may be more beneficial than methods which train peripheral control in isolation. At present, there is insufficient research output that suggests Targeted Training provides benefits to human movement such as gait. Current video-based observations and results from the SATCo assessment suggest positive changes occur, but the mechanisms driving the changes could vary depending on the child's stage of maturation, the extent of a child's pathology, and the intensity/frequency of the intervention. The recent publication of the SATCo method of assessment will enable the dynamic changes in response to Targeted Training to be evaluated regularly, resulting in further evidence to support or disprove the unique training method. Further evidence to quantify the benefits could also be achieved through motion analysis, to understand the direct effect of movement perturbations on specific joints during training.

2.10 Virtual reality

Virtual environments have become increasingly popular for the training and assessment of movement function in children and adults with neurological dysfunction. Virtual environments have the capacity to present stimuli to the user in a controlled manner, whilst addressing three key components necessary for motor learning; motivation, repetition, and feedback (Rizzo *et al.*, 2002). These components can be manipulated to create the optimum environment for rehabilitation at the discretion of the user, clinician, or research team. Holden (2005) suggests that motor learning experienced through Virtual reality (VR) can be superior to that gained in real world tasks through the added benefit of augmented feedback which can be provided during practice. A randomised controlled study of chronic stroke patients comparing real-world versus VR-based training for obstacle avoidance tasks reported a greater improvement in a fast paced velocity test for the VR group post training (Jaffe *et al.*, 2004). These studies highlight the capacity of VR environments to enhance motor learning beyond what is typically available in conventional therapy sessions.

Provision of physiotherapy based exercises through VR systems is an innovative way of increasing compliance rates (Burdea, 2003). Reid (2004) suggests that using VR to help train children with CP can provide them with a sense of mastery or self-efficacy, attributes that are not typically associated with real-world activities due to the child's functional limitations. Additionally, enhanced feelings of control may result in improved motivation and satisfaction with performance. Individuals who find an activity intrinsically rewarding will be more likely to want to repeat it.

The use of functional Magnetic Resonance Imaging (fMRI) provides quantifiable evidence that changes in neural mechanisms associated with improved global motor function occur in response to VR training. You *et al.* (2005) provided intensive upper limb VR therapy to an eight year old boy with CP hemiplegia over four weeks. Analysis of fMRI pre- and post-intervention revealed a switch in brain activity from the ipsilateral sensorimotor cortices to the contralateral sensorimotor cortices, which was coupled with improved movement of the affected limb. The evidence related cortical reorganisation to enhanced functional motor skills such as reaching tasks, feeding and dressing. This demonstrates the capacity of the sensory and motor cortex to adapt and change in response to stimuli through learning and experience. Despite the link between motor control and the underlying neurological mechanisms that influence control in children with CP, there are few studies addressing the cortical changes that may result from other therapy interventions (Sutcliffe *et al.*, 2007). Changes due to VR intervention are positive, but more research is required to justify the use of VR due to relatively low sample sizes and no existing randomised controlled studies using fMRI.

2.11 Virtual rehabilitation in children with cerebral palsy

To date, research advocating the benefits of VR training primarily aims to improve movement at the periphery (Holden *et al.*, 1999; Deutsch *et al.*, 2001; Merians *et al.*, 2002; You *et al.*, 2005; Bryanton *et al.*, 2006; Merians *et al.*, 2006), with limited research on the core (Barton *et al.*, 2006; Hawkins *et al.*, 2008). The location and severity of the brain lesion in a child with CP determines the extent to which the child suffers from primary and secondary abnormalities. For example, periventricular leukomalacia, a form of brain injury characterised by the death of white matter near the cerebral ventricles typically leads to spastic diplegia, in which the most prominent motor impairment occurs in the lower extremities. Poor selective control of the ankle joint is common, with limited control at the knee, and fairly good control at the hip (Gage *et al.*, 2009), emphasising greater involvement of the most distal portion of the limb. Although improvements are evident as a direct result of peripheral training, control of the core is important for addressing the functional difficulties surrounding the peripheral impairment. It is suggested that the central nervous system prioritises stability of the trunk during gait due to its superior anatomical location in the musculoskeletal system (Cromwell *et al.*, 2004; Kang & Dingwell, 2009), suggesting superior segments require greater stability than inferior segments. The early onset of transversus abdominis activity previously reported (Hodges and Richardson (1997a, b) suggests the core musculature plays a large functional role in maintaining control of the core, thus targeting the periphery in isolation means that the difficulties which result from a lack of core control, such as deficient equilibrium reaction and loss of the selective motor control of the pelvis and trunk, may remain untreated.

Barton *et al.* (2006) designed a VR game to train and test core control with a view to targeting the primary abnormalities in CP. The aim of the VR game was to navigate a virtual object, in this case a *"Magic Carpet"*, through a virtual world and burst balloons, using movements of the pelvis to steer the carpet up/down and right/left. Whilst playing the VR game, a Vicon system captured the translation and rotation of the pelvis. Though the game was only played for one session, the results showed that alternative movement strategies were adopted by an asymmetrical CP diplegic adolescent in comparison to a typically developing child. The CP diplegic adolescent displayed less control of the *"Magic Carpet"*, changing direction constantly whilst trying to reach the target (Figure 2(a)). In contrast, the typically developed child moved directly towards the target with a series of controlled movements (Figure 2(b)). This suggests VR games may be able to discriminate between groups of subjects with and without pathology during an initial assessment of selective motor control of the core. In addition, the CP diplegic adolescent demonstrated a therapeutic response to VR game play, achieving a greater active range of motion for pelvic tilt compared to a physical examination that was carried out prior to the VR game.

Figure 2. The different movement strategies adopted by a) a CP diplegic adolescent and b) a typically developing child when approaching a balloon in a VR environment. Note that the origin represents the position of the balloon (target). The arrows indicate the pathway to the target (Barton *et al.*, 2006).

The research adopts a novel approach to quantifying selective motor control of the pelvis, but only as a cross-sectional comparison and so the effect of a sustained period of VR training is yet to be reported. The outcomes from the pilot experiment suggested that further research on a larger population of children with CP would be desirable to evaluate the changes that may result from further sessions targeting core control using VR games. Additionally, Barton *et al.* (2006) measured selective motor control of the pelvis but the theory of Targeted Training states that adequate control of the head and trunk is necessary before training the pelvis. The results produced by the CP diplegic adolescent may be influenced by poor control of body segments superior to the pelvis, and so future VR games could assess control of the trunk prior to the pelvis when testing control of the core.

2.12 Virtual reality training interventions: single-subject designs

Virtual reality interventions in children with CP consist mostly of single-subject designs (case studies), or multiple single-subject designs (Table 1). Golomb *et al.* (2010) reported the effects of VR training in three adolescents with CP (age range: 13-15 yrs), Chen *et al.* (2007) examined the effects of VR training on four children (mean age: 6.3 yrs) with spastic CP, and You *et al.* (2005) monitored the changes that resulted from VR training in an eight year old with hemiparetic CP. This type of research design is common due to the exploratory nature of VR training interventions. Often the results of single-subject designs can indicate whether the intervention does have an effect on the desired outcome. In cases where more than one subject was used it can provide preliminary data on the variation of results between subjects and help to identify consistent positive effects. This is beneficial when trying to establish if an intervention has an effect on the desired outcome. However single-subject designs may only determine the extent to which an intervention had an effect on the particular subject, and so generalising the results should be treated with caution. Ideally, group research designs provide more insight on the generality of results than single-subject design, but in some cases issues arise with the patient specific population that is being studied. The research design reported by Barton *et al.* (2006) is evidence of a concept in its preliminary stages. Further development would require a greater number of single-subject designs, but ideally a group design consisting of several individuals' measures to support the training concept.

Table 1. An overview of existing studies which use VR to train children with CP.

Authors	Subject no.	CP classification	Measures	Outcome
You *et al.*, 2005	1	Hemiplegia	fMRI	Neuroplastic change from bilateral to unilateral activation in primary sensorimotor cortices.
Chen *et al.*, 2007	4	1 x Hemiplegia 3 x Quadriplegia	Reaching kinematics, Fine motor assessment tool	Improvements in aspects of reaching kinematics, 2 children reached the minimal detectable change on the fine motor assessment tool.
Golomb *et al.*, 2010	3	Hemiplegia	Standardised occupational therapy assessment, finger range of motion, fMRI	All three participants improved hand function on occupational therapy testing, improved finger range of motion, and expanded spatial activation in the primary motor cortex

2.13 Independent outcome measures of training interventions

Treatment aims to increase the quality of life in children with CP. Transferring improved movement function, as a consequence of VR training, to ADL is therefore important. The majority of VR interventions train the upper extremity (You *et al.*, 2005; Chen *et al.*, 2007; Golomb *et al.*, 2010), with outcome measures specific to the arm or hand used to monitor improvements in motor function. As such, the outcome measures typically relate closely to the trained movement that was practiced during the intervention. For example, Golomb *et al.* (2010) reported on the effects of VR training on the affected hand in three adolescents with severe hemiplegic CP. Training led to improved function of the affected hand when measured using hand grip tests and assessing finger range of motion. Clinical gait analysis is routinely used to monitor changes in children with CP in response to interventions such as surgery and physiotherapy. However, the use of gait analysis as an independent outcome measure of VR training in children with CP is unreported. The use of gait analysis to monitor changes in response to upper extremity training interventions may not be appropriate. However the core plays a large role in gait, as described previously, and so measuring the effect that core training has on the lower extremities may be relevant.

> *The ability to rise from a chair is critical to quality of life because it is largely connected to functional independence (Giansanti et al., 2007, p969).*

An alternative method for assessing movement function in children with CP is the sit-to-stand movement (STS). Rising from a chair is regarded as a biomechanically demanding functional task undertaken during ADL (Kerr *et al.*, 1997), and is largely a prerequisite for gait (Kralj *et al.*, 1990). Activation of the core and peripheral segments is required to perform the task since the base of support and centre of mass change throughout the transition from sitting to standing (Guarrera-Bowlby & Gentile, 2004). The STS can be broken up into phases; Schenkman *et al.* (1990) refer to the start of the STS as the flexion-momentum phase (Phase 1). Initiation of the STS occurs with forward flexion of the trunk over the lower extremities. Forward momentum is generated by trunk flexion to make transition from sitting to standing easier (Park *et al.*, 2003) requiring less muscular effort in the lower extremities (Papa & Cappozzo, 2000). The pelvis rotates anteriorly as the trunk flexes forward during this phase, whilst the thigh, shank, and feet remain stationary. A transition phase (Phase 2) then occurs during which momentum produced by the trunk transfers to the rest of the body as the centre of mass transitions from horizontal to vertical translation. This phase is said to begin as the buttocks are lifted, and to end at the point where maximum ankle dorsiflexion is reached. The extension phase (Phase 3) is initiated just after maximum ankle dorsiflexion and terminates when the trunk, hip, and knee joint reach maximum extension. The phases described suggest that involvement of both the core and peripheral segments are essential for performing the STS.

The performance of the STS is sensitive to a range of pathologies. Janssen *et al.* (2008) showed that accelerations recorded during the STS were able to discriminate between typically developed (TD) adults and adults who had suffered from a stroke. Park *et al.* (2003) reported that children with CP were slower in performing the task, with increased anterior pelvic tilt and hip flexion when compared to TD children. The STS may be a more sensitive outcome measure related to ADL which involves both the core and the periphery, rather than gait analysis which focuses mostly on the lower extremities.

2.14 Making virtual rehabilitation accessible

Accurate and reliable capture of body motion is essential for virtual rehabilitation in order for patients to receive accurate feedback on their movements when immersed within a virtual world. State-of-the-art video motion capture systems, for example the Vicon system, are used in some VR installations, but the systems require expensive high-quality cameras to capture body motion, coupled with high-priced software. Special training is needed to operate the systems which are normally installed permanently in specialised laboratories. Virtual rehabilitation is often criticised for being expensive, complex, and therefore difficult to use in physiotherapy.

Games consoles are an alternative to VR based video motion capture systems, and have a number of advantages. The *Nintendo Wii* and motion capture devices like the *Microsoft Kinect* are commercial games consoles which use hand held controllers and sense body position and/or orientation to control game play. The consoles benefit from the availability of commercial games which are engaging for children, and together form an affordable package for use in physiotherapy centres or the home. However, the potential use of commercial gaming systems for virtual rehabilitation is limited by their reduced accuracy in comparison to video motion capture systems, and a lack of quantitative feedback from the games consoles regarding position of body segments. A device which is able to target specific body movements, providing accurate information about position, whilst being affordable and portable for use in physiotherapy is desirable to increase the application of virtual rehabilitation.

2.15 Inertial measurement units

Inertial measurement units (IMUs) are able to target specific body movements, are affordable and portable, and it may be easier to implement the device within current physiotherapy practice compared to a video motion capture system. IMUs provide measurements which are comparable in part to those of video motion capture systems when capturing body motion; they sense both angular displacement and linear acceleration (Roetenberg *et al.*, 2005; Thies *et al.*, 2007). IMUs consist of gyroscopes, accelerometers, and magnetometers whose outputs are combined to produce information about position and orientation. Due to their small size and limited computer processing requirements, they are capable of registering body motion during ADL outside the laboratory setting (Cutti *et al.*, 2010; Ferrari *et al.*, 2010), providing a more valid indication of movement function. There is a paucity of research reporting the use of IMUs to interact with VR games, but the potential advantages of capturing human movement in physiotherapy departments, schools, or within the home make IMUs an ideal replacement for video motion capture systems in virtual rehabilitation.

2.15.1 The Xsens Sensor

The Xsens sensor (Xsens Technologies, The Netherlands) is an example of a popular inertial measurement unit used for motion capture in research settings. The Xsens sensor has been used to measure human movement during upper limb motion tracking (Zhu & Zhou, 2004; Cutti *et al.*, 2008), clinical gait analysis (Ferrari *et al.*, 2010; Reininga *et al.*, 2011), and general movements in 1-5 month old infants (Berthouze & Mayston, 2011), indicating the various ways inertial measurement units can be used to carry out the role of a video motion capture system. Within the Xsens sensor, increasing changes in drift can occur due to the integration of angular velocity derived from gyroscopes. A complex Kalman filter algorithm works recursively in real time as a form of feedback to the sensor, providing constant measurement of gravity (accelerometers) and Earth magnetic north (magnetometers) to stabilise the drift. The orientation of the sensor is periodically corrected by input from the magnetometers.

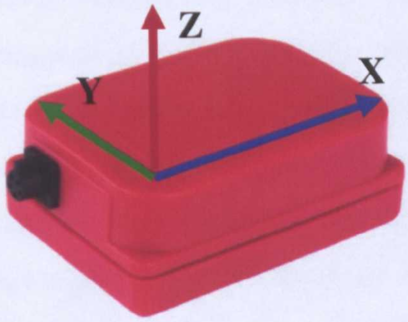


Figure 3. Xsens MTx Sensor, with the sensor fixed co-ordinate system overlaid. Rotation about the sensor-fixed co-ordinate system produces measurements of Roll, Pitch, and Yaw angles in relation to a local Earth-fixed reference co-ordinate system. Roll is defined as the rotation about the antero-posterior (X) axis, Pitch is the rotation about the medio-lateral (Y) axis, and Yaw is the rotation about the vertical (Z) axis.

2.15.2 Accuracy of the Xsens Sensor output

There have been few studies which compare the performance of Xsens sensors with that of video motion capture systems. Xsens Technologies specify a static root mean square (RMS) error of less than 1°, a dynamic RMS error of less than 2°, and an angular resolution of 0.05° in the Xsens MTx user manual. However, little information is provided on how the measurements were carried out and how the small errors were calculated, making it essential to carry out independent checks on the Xsens sensor for the purpose of particular research applications. Picerno *et al.* (2008) reported RMS errors of less than 3.6° between the Xsens sensor and a Vicon system for the duration of one gait cycle during clinical gait analysis. However the RMS error accounted for up to 41.8% when expressed as a percentage of the maximum range of motion. Similarly, Bergman *et al.* (2009) found RMS errors of 5 ± 3° for sagittal plane angles measured at the thigh, knee and ankle during stair ascent, which accounted for up to 9% of the range of motion during the task. Small angle errors mask the true performance of the Xsens sensor, and when expressed as a percentage the high error reported questions the validity of the measurements, particularly if the output is to be interpreted for the purpose of clinical decision making. In order to address these issues, Reininga *et al.* (2011) analysed the difference between upper thorax and pelvis rotations whilst walking, recorded using an Xsens sensor and an Optotrak video motion capture system (Northern Digital Inc., Waterloo, Canada). They found that the mean difference between both devices was 1 ± 1.3°. Considering data were collected for three subjects across three different walking speeds, Reininga *et al.* (2011) demonstrated high levels of consistency and reproducibility in measurements. Saber-Sheikh *et al.* (2010) support the findings of Picerno *et al.* (2008) and Reininga *et al.* (2011), with a mean difference (and standard deviation) of 0.69 ± 0.90° for X; 0.40 ± 1.05° for Y and 0.28 ± 1.63° for Z during a random 3D movement trial. The lack of information about the testing protocol in the studies by Reininga *et al.* (2011) and Saber-Sheikh *et al.* (2010) make it difficult to assess the reliability of the reported accuracy, but the small errors are encouraging for the use of the Xsens sensor in human movement. The existing research suggests there is good agreement between Xsens sensors and video motion capture systems, but highlights the need to perform independent accuracy checks of Xsens performance prior to use.

There has been limited validation of the accuracy of acceleration output. Thies *et al.* (2007) compared linear accelerations obtained from two Xsens MTx sensors placed on the upper arm and forearm. These were compared with estimates derived from position data, recorded by a Vicon video motion capture system during repeated trials of a reach and grasp task on one healthy adult. The results showed low RMS error and a strong correlation between Xsens acceleration output and Vicon derived accelerations during upper arm (RMS error ≤ 0.42 m.s^{-2}, $r \geq 0.947$) and forearm movements (RMS error ≤ 0.43 m.s^{-2}, $r \geq 0.988$) in all three directions of translation (X, Y, Z), suggesting good agreement between the two measurement systems. However, the authors fail to report the error as a percentage of the peak accelerations measured at the upper arm and forearm, but go on to state that the amplitude and frequency of accelerations recorded during the reach and grasp task are similar to those produced in many ADL. Further investigation of acceleration output produced by the Xsens sensor is required in order to support such generalised statements.

2.15.3 Magnetic disturbances in the environment affect the accuracy of the Xsens sensor

Research suggests that the error associated with the Xsens sensor when compared to a video motion capture system is small (Roetenberg *et al.*, 2007; Picerno *et al.*, 2008; Bergmann *et al.*, 2009; Saber-Sheikh *et al.*, 2010; Reininga *et al.*, 2011), but the magnetic properties of the capture volume in which the testing occurs can affect the outcome considerably. Ferromagnetic materials in the building structure or fittings, and active devices like coils and transformers, large motors and radio/cellphone base transmitters can distort the constant magnetic field direction within the capture volume. An unstable reference for heading disturbs the Kalman filter algorithm, causing deviation in the orientation output. De Vries *et al.* (2009) reported high variation in the direction of magnetic field vectors (30°) when the Xsens sensor was moved through a capture volume 5 cm above floor level (Figure 4(b)), compared to 3° when 180 cm above floor level (Figure 4(a)). With the implementation of a Kalman filter, which accounts for variations in the magnetic field, angle error reduced from 8° at 5 cm above floor level to 2° at 100-180 cm above floor level when the Xsens passed through the capture volume at a slow walking pace. The results highlight that the Kalman filter has difficulty in compensating within capture volumes containing disturbance of the magnetic field. To avoid large errors in measurement, de Vries *et al.* (2009) refer to a process of 'mapping' the magnetic field in the capture volume, which requires measuring the local magnetic field using the magnetometers housed within the Xsens sensor, before testing begins. Findings by Roetenberg *et al.* (2007) are in agreement with this, these authors demonstrated that magnetic interference in a capture volume results in slightly larger errors measured by the Xsens sensor. When subjects performed rotation of the lower arm (flexion/extension or abduction/adduction) over a period of 5 minutes, the RMS error compared to a Vicon system was 3.6 ± 0.6° in the presence of ferromagnetic materials. Without magnetic interference the associated RMS error was 2.6 ± 0.5°, suggesting that capture volumes not containing ferromagnetic materials are desirable for data collection. It is important to note that the low variation in RMS error reported by Roetenberg *et al.* (2007) suggests the output produced by the Xsens sensor during motion capture is consistent.

Figure 4. Orientation of the magnetic field vector when moving the Xsens sensor throughout the measurement volume a) at 180 cm above floor level and b) 5 cm above floor level. The oval represents the greatest period of variation (taken from De Vries *et al.* 2009).

2.16 Summary

Existing physiotherapy methods aim to alleviate the secondary abnormalities of CP at the periphery. The current literature suggests that treatment should train the ability to perform ADL through a goal-oriented approach, placing greater emphasis on the primary abnormalities. There is reliable evidence that the core segments and musculature surrounding the segments activate prior to the periphery during the initiation and performance of ADL. Developing control of the core of the body before the periphery in children with CP could therefore lead to improvements in ADL. The literature on Targeted Training reports improvements in ADL for children with CP. However the limitations of

Targeted Training make its widespread use as a physiotherapy technique difficult to implement. Developing ways to provide a top-down sequence of training to the core followed by the periphery through alternative methods of rehabilitation could provide greater access to training. Virtual rehabilitation has emerged as a successful method for improving movement in children with CP, with improvements translating to better performance of ADL. Devising a VR training intervention that adopts a similar approach to Targeted Training on the core followed by the periphery may extend the benefits further.

Chapter 3. Training and testing core control in children with spastic cerebral palsy - a feasibility study (study one)

3.1 Introduction

Virtual reality (VR) training improves selective motor control of the upper and lower extremities, with benefits transferring to activities of daily living (ADL) (Merians *et al.*, 2002; You *et al.*, 2005; Bryanton *et al.*, 2006; Merians *et al.*, 2006). However, using VR to train selective motor control of the trunk and pelvis is a recent development. Barton *et al.* (2006) were able to show differences between a typically developed child and a cerebral palsy (CP) diplegic adolescent in a single VR, core-specific testing session. It has yet to be determined if continuous exposure to core-specific VR training leads to improvements in selective motor control of the trunk and pelvis, and whether those improvements can be transferred to ADL. A VR training intervention that adopts a top-down approach to training the trunk and pelvis following the principles of Targeted Training might lead to better performance in ADL, such as gait. The interaction of the trunk and pelvis plays an essential role in maintaining balance during gait and in aiding forward progression, making gait an ideal outcome measure related to ADL.

The aim of the study reported in this chapter was, by way of a feasibility study, to establish whether exposure to a bespoke VR game designed to train and test core control can lead to measurable improvements of core control and gait function in children with spastic CP.

3.1.1 Objectives

1. To establish whether VR training improves core control.

2. To establish whether improvements in core control lead to improvements in gait.

3.2 Method

3.2.1 Participants

Six male children (subsequently referred to as Participant 01, 02, 03, 04, 05 and 06) diagnosed with CP diplegia and on the NHS database of the North West Movement Analysis Centre (NWMAC, Alder Hey Hospital, Liverpool) participated in the research project. Recruitment of participants was first instigated by requesting physiotherapists at Alder Hey Hospital to shortlist children with CP who met the following criteria:

- Aged between 6-12 years old.
- No history of surgical intervention prior to the study.
- No more than 10° fixed contractures at the ankle, knee or hip joints.

- Had the cognitive capacity to play computer games (as advised by their physiotherapist).
- Able to stand unaided (without a walking device or holding on to surrounding apparatus).
- No exposure to any form of core specific rehabilitation, or Botulinum treatment within six months prior to the study.

Parents of the children shortlisted were approached by the child's physiotherapist to see whether they would be interested in allowing their child to participate in the research project. Parents were provided with a participant information sheet to be read to or by the child (Appendix 6) and a detailed parent/guardian information sheet about the project (Appendix 7). Parents and children were next invited to an open evening at Liverpool John Moores University to visit the research facility where the VR training intervention would occur, and listen to a short presentation on what the research project entailed. Parents and children were asked to sign consent forms (Appendix 8 and Appendix 9 respectively) at the end of the open evening if they agreed to take part. Ethical approval for the study was granted by the Wrightington, Wigan and Leigh Research Ethics Committee (NHS) and Liverpool John Moores University Research Ethics Committee.

3.2.2 Research design

A randomised controlled trial design was used for this study. Participants were randomly assigned to a *core group* (experimental group) or a *control group* using a random number generator. Each participant received an independent gait assessment at NWMAC before completing an initial VR assessment of selective motor control using the trunk, then the pelvis, at the research laboratory at Liverpool John Moores University. The *core group* participants then received six weeks of VR training on a game called *The Goblin Post Office* (GPO), aimed at training the trunk and pelvis. Participants attended the research facility twice a week and received 30 minutes of training during each VR session. The *control group* participants received six weeks of VR training using a handheld joystick to control the GPO game. Each participant completed a second VR assessment at the end of the VR training period. A second gait assessment was performed at NWMAC within five days of each participant's final VR assessment to avoid decay of any potential training effect (Figure 5). A one-way repeated measures ANOVA with a between-subject factor of group (*core* or *control group*), and a within-subject factor of time (pre- and post-training assessment) was proposed to assess if there were any significant differences in VR performance and gait in response to VR training.

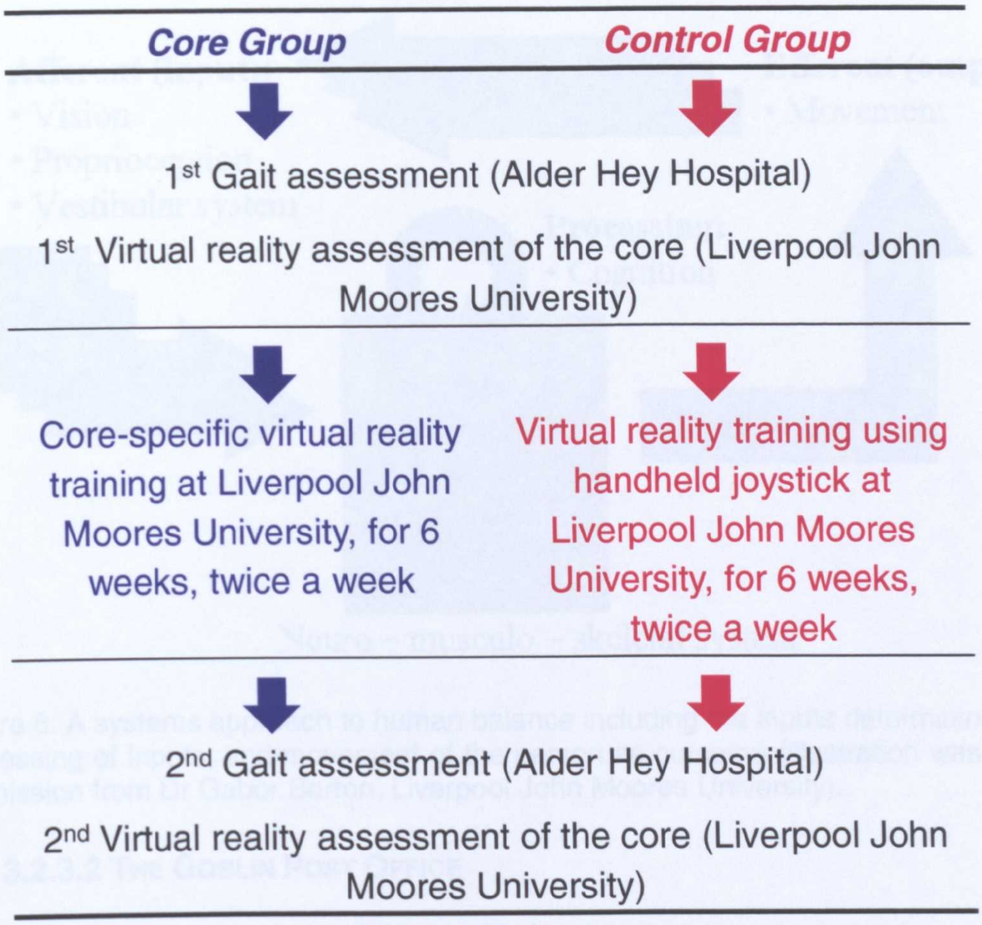


Figure 5. Flow chart illustrating the order of testing and training for both the *core* and *control group.*

3.2.3 Equipment and Software

3.2.3.1 VIRTUAL ENVIRONMENT

The Computer Assisted Rehabilitation ENvironment (CAREN, Motek Medical, Amsterdam, The Netherlands) was used to provide a VR environment within the research laboratory at Liverpool John Moores University. The laboratory consisted of an 8-camera Vicon 612 VMC system (Oxford Metrics, London, UK) and a moving platform (Bosch Micromotion 600 (CAREN system), Motek Medical, Amsterdam, The Netherlands), with a virtual scene driven by a custom CAREN software application. The moving platform is a Stewart platform (Stewart, 1965) controlled by six computer-driven hydraulic actuators and has six degrees of freedom. Details of the platform's operational characteristics can be found in Lees *et al.* (2007). When a participant moved within the CAREN systems three-dimensional volume they formed part of a real-time feedback loop. Input was provided to the subject through their vision, proprioception, and vestibular system using a visual display and the moving platform. The participant's movement responses were then monitored in real time using a video motion capture system and used to inform the visual display (Figure 6).

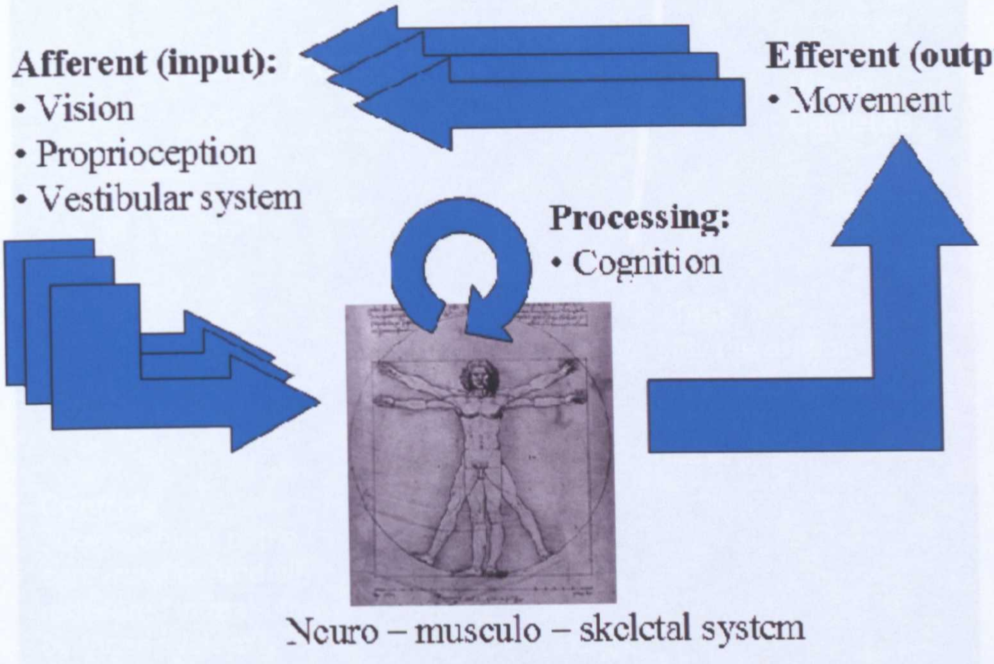


Figure 6. A systems approach to human balance including the inputs determining balance, processing of inputs, and movement of the person as outcome (illustration was used with permission from Dr Gabor Barton, Liverpool John Moores University).

3.2.3.2 THE GOBLIN POST OFFICE

The GPO is a computer game which provided an interactive method to train core control.

The aim of the GPO was to use the trunk or pelvis (separately) to navigate a dragon through a virtual cave, using the horn protruding from the dragon's head to burst randomly appearing bubbles/balloons (targets) that contain virtual envelopes (Figure 7). The story attached to the GPO game is that the child is helping to collect post for the Goblin community who live inside the cave. The virtual cave within the GPO consisted of repeated straight sections known as *blocks*, each containing nine targets providing eight movement trajectories between targets (*trials*). A continuous set of *blocks* (typically six to eight *blocks)* was defined as one *run* in the GPO game. A description of the important features of the GPO game and specific training conditions are presented next.

Figure 7. The Goblin Post Office, illustrating the virtual cave and dragon. Vicon cameras relay information about body segment position during virtual reality game play, which controls the virtual scene displayed in front of the participant.

3.2.3.3 ADAPTIVE ALGORITHM ADJUSTS SPEED OF FORWARD PROGRESSION

The starting forward speed for each *run* performed by a participant was always 50 $m.s^{-1}$, whilst the minimum speed was 15 $m.s^{-1}$. An adaptive algorithm (Parameter Estimation by Sequential Testing (PEST)) (Taylor & Creelman, 1967) was incorporated in the GPO game in order to adjust the forward speed of the virtual dragon during game play to vary game difficulty. This ensured that children with varying levels of selective motor control of the core were able to play the game. The speed of the game was constant between targets, but increased in response to a successful target collision, thus increasing the difficulty of the game, and decreased if a target was missed. The algorithm adjusted the size of speed increments automatically over time, with speed converging towards a settled value where increments were minimal if participants reached a stable level of performance. Large increments were indicative of transient changes in performance. The speed of the game was used as an outcome measure to quantify performance.

3.2.3.4 CORE CONTROL SCHEME

A triangular arrangement of retro-reflective markers was attached to both the trunk and pelvis using double sided adhesive tape to allow registration of motion of these two segments during VR game play. Rotation about the longitudinal axis of the trunk or pelvis in the transverse plane steered the dragon left and right (trunk or pelvic rotation) (Figure

8(a)), and tilt about the mediolateral axis of the trunk or pelvis in the sagittal plane steered up and down (trunk or pelvic tilt) (Figure 8(b)). Angular displacement of the body segment controlled the speed of the corresponding left/right and up/down motion, not displacement of the dragon. This is termed velocity control, it was chosen so that participants did not spend a high proportion of time tilted or twisted which position control would have required. Participants used single plane control schemes to play the GPO game to begin with, which meant the dragon could only travel along either the horizontal or vertical plane within the game. Once control in both directions was established through single plane control, a cross plane control scheme was introduced which required both rotation and tilt of the same segment simultaneously to steer the dragon towards virtual targets. Silsupadol *et al.* (2006) found that participants demonstrated greater improvements in balance tasks when receiving cross plane training, as opposed to single plane training.

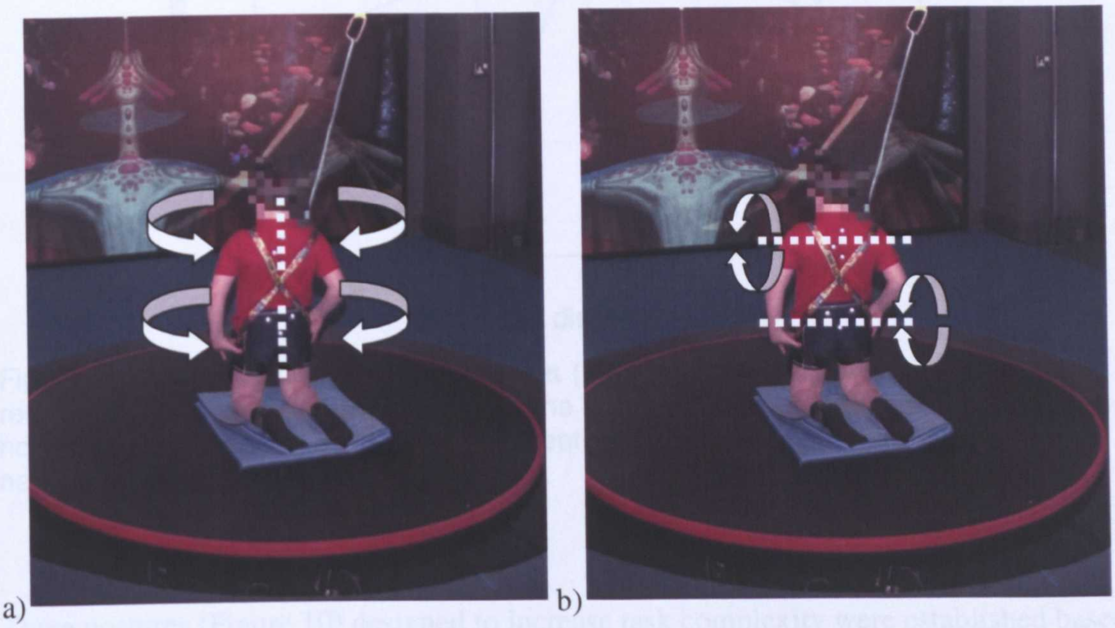

a) b)

Figure 8. a) Rotation about the longitudinal axis of the trunk or pelvis in the transverse plane steered the dragon left and right. b) Tilt about the mediolateral axis of the trunk or pelvis in the sagittal plane steered up and down.

3.2.3.5 TARGET POSITIONING

Eight movement trajectories were created for steering the GPO using cross plane motion (Figure 9). Each movement contained both a horizontal and vertical component, requiring a small rotation about one axis and a large rotation about the other axis to provide varied practice between *trials* (Figure 9). Each *block* produced one occurrence of each movement trajectory but the order in which they appeared was random for each *block*. Note that as each movement has a mirror image, in whatever order the movements are presented the dragon ends up in the same position after all eight movements and thus is not required to fly outside the cave wall. Movements between *targets* had to appear unpredictable in presentation to the participant, but were systematic across training levels so that comparisons within- and between- participants during analysis could occur. For single plane motion the vertical component was removed from target position when steering the dragon right and left. The horizontal component was removed when steering up and down.

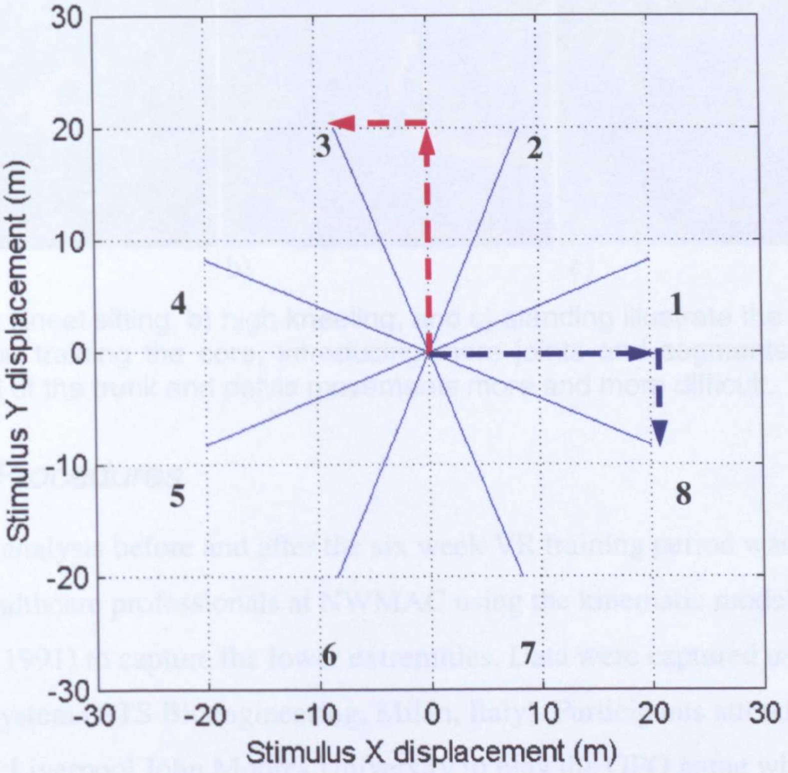


Figure 9. Target position of the eight trials (1-8) within one block in the virtual cave relative to the position of the dragon at the origin. Combinations of small and large horizontal and vertical rotations (represented by the red and blue arrows) were necessary to navigate towards the targets.

3.2.3.6 BODY POSTURES

Three postures (Figure 10) designed to increase task complexity were established based on the theory of Targeted Training (Butler & Major, 1992) to introduce body segments to the motor control task in a proximal to distal sequence. The first of three postures required children to kneel down and sit on their heels, referred to as kneel sitting (Figure 10(a)). This provided a base of support at the pelvis, making activity of the pelvis and legs redundant, focusing only on movement of the trunk. The second posture advanced from kneel sitting by requiring full extension at the hip and moving the knee into 90° flexion to incorporate movement at the pelvis, termed the high kneeling position (Figure 10(b)). In this posture activity of the shank and foot segments were redundant whilst the thigh, pelvis and trunk were active. The third posture required children to be competent to maintain free standing (Figure 10(c)) during game play, thereby requiring co-ordinated movement of all body segments involved in upright standing. In all postures, the participants began with single plane control of the trunk segment, followed by cross plane control as performance improved.

a) b) c)

Figure 10. a) Kneel sitting, b) high kneeling, and c) standing illustrate the progression of testing and training the core, introducing more joints and segments in order to make control of the trunk and pelvis movements more and more difficult.

3.2.4 Procedures

Clinical gait analysis before and after the six week VR training period was carried out by registered healthcare professionals at NWMAC using the kinematic model outlined by Davis *et al.* (1991) to capture the lower extremities. Data were captured using the BTS-GAITLAB system (BTS Bioengineering, Milan, Italy). Participants attended the research laboratory at Liverpool John Moores University to play the GPO game which assessed initial selective motor control of the trunk and pelvis in all participants. Prior to the GPO assessment game, each participant carried out a range of motion task. This enabled the investigator to determine whether the participant could move the required body segment through an appropriate range of motion to be able to interact with the GPO game. The task also familiarised each participant with the necessary control schemes required to play the game before being exposed to the first GPO level. Next, the *core group* received core training using the GPO game over a period of six weeks. The *control group* were not exposed to VR training on the core, but instead played the GPO game using a handheld joystick whilst sat at a computer desk. In total, each participant completed 11 VR training sessions. Inclusion of the *control group* was designed specifically to exclude the possibility that learning how the game worked, rather than motor control training, could improve performance. At the end of the VR training period a second test of selective motor control at the trunk and pelvis was performed by all participants using the GPO. Throughout the VR training period parents were told that their child should continue physical activity and routine physiotherapy appointments. At the end of the training period parents were asked to fill out a short questionnaire (Appendix 10), that would remain anonymous, about their thoughts and feelings concerning their child's involvement in the study. Participants were paid £10 to cover the expenses incurred whilst travelling to the research laboratory at Liverpool John Moores University for each testing and training session.

3.2.4.1 THE GOBLIN POST OFFICE ASSESSMENT

During pre- and post-training VR assessments participants began in the kneel sitting posture, using the trunk to drive single plane motion, followed by cross plane motion. Participants were informed that the trunk could be used to steer the dragon, and that the dragon could move left or right, and up or down. The next posture was high kneeling, requiring single plane then cross plane motion of the trunk, before advancing to single plane and cross plane motion of the pelvis. The last posture was standing, again completing single and cross plane motion of the trunk, followed by the pelvis. Figure 11 illustrates the levels and sequence of training adhered to during the testing session.

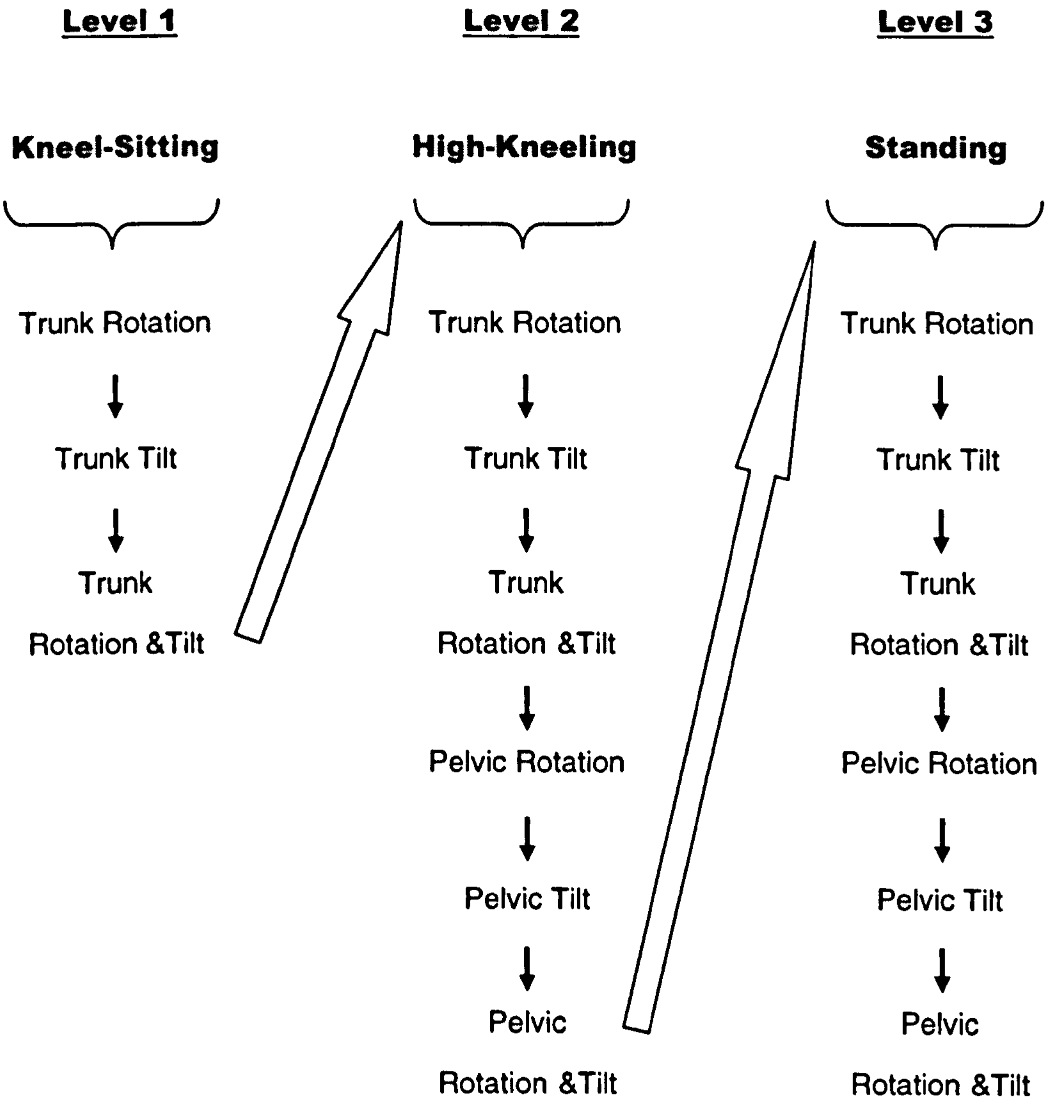


Figure 11. Flow chart representing the *Goblin Post Office* testing order during pre- and post-training assessments.

3.2.4.2 CORE GROUP TRAINING

Game speed was used to determine progression between 'levels' of the GPO game. Increases in game speed over multiple *runs* indicated that the participant was improving during training and should remain training on the current control scheme and body posture. A plateau (area of little variation) in game speed suggested the participant required an increase in the level of difficulty and should progress to the next control scheme or body posture. If the minimum game speed was achieved during game play this indicated that the participant required further training on the current control scheme and body posture.

The order of training followed the same sequence as presented in testing (Figure 11). Participants could not use pelvic tilt to play the GPO game in both high kneeling and standing, therefore pelvic tilt and cross plane motion of the pelvis were not used during game play.

3.2.4.3 CONTROL GROUP TRAINING

The *control group* used a 2-axis joystick to navigate the virtual dragon through the cave during the six week training period. Tilt of the joystick right or left (single plane motion) steered the dragon right or left respectively. Forwards and backwards tilt (single plane motion) steered the dragon towards the floor or the ceiling of the cave respectively (Figure 12). A combination of tilting the joystick right or left, and forward or backwards produced cross plane motion. During training, each participant sat in a comfortable chair with arm support to rest their elbows in an attempt to limit training of upper arm co-ordination. Participants played the GPO game with their preferred arm. As when playing the game using the core, participants in the *control group* used single plane motion to steer the dragon first before moving to cross plane motion.

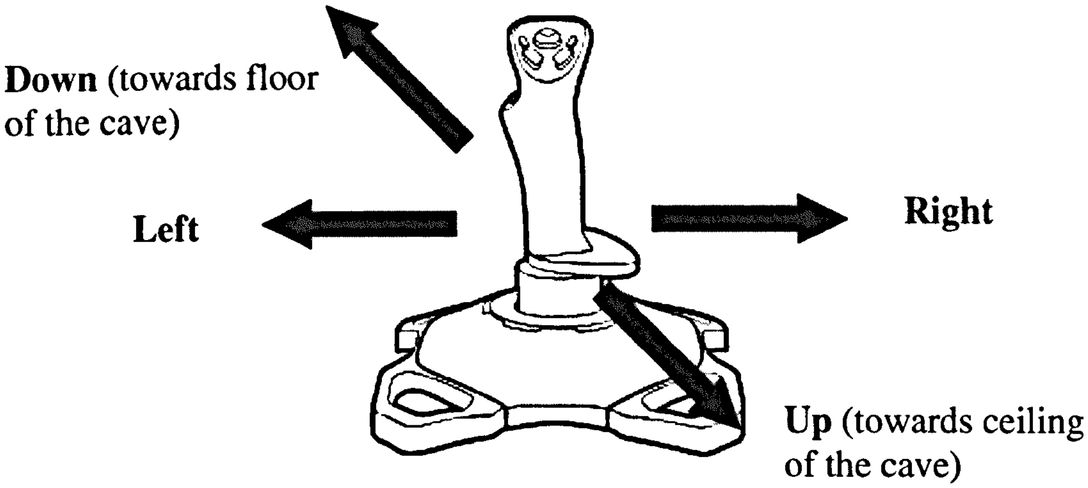


Figure 12. Control group participants used a 2-axis joystick to navigate the virtual dragon through the cave. Tilt of the joystick left or right steered the dragon left or right respectively. Forwards and backwards tilt steered the dragon towards the floor or the ceiling of the cave respectively.

3.2.4.4 DATA COLLECTION

Upon completion of one *run*, data were stored as a text file for processing. Each text file recorded the time taken to complete the *run*, trial number, target position, movement trajectory (1-8), position of the dragon in relation to the centre of the cave (X and Y position), target hit or miss and forward speed of the dragon in adjacent columns. Data were sampled at 47 Hz for each GPO body posture and control scheme.

3.2.5 Measures of performance

3.2.5.1 MAXIMUM SETTLED SPEED

A custom program written in MATLAB (version 7.10, MathWorks, UK) was used to extract the speed of the virtual dragon (speed profile, Figure 13) from each *run* performed by all participants at every level of difficulty, during each session. The program then determined the maximum (max) settled speed, which was defined as the highest mean speed achieved with the smallest speed variance during one *block* of each *run* (Appendix 11). The minimum max settled speed that could be achieved was 15 $m.s^{-1}$, which was the minimum forward game speed in the GPO game.

3.2.5.2 TRUNK-PELVIS COUPLING

A custom program written in MATLAB was used to calculate the coupling between the trunk and pelvis (Appendix 12). Angle-angle plots of trunk and pelvis rotation, normalised to their respective ranges of motion, were generated for each *trial* in every *run* performed by participant 01 when using the single plane pelvic rotation control scheme (performed in high kneeling). The area of a convex hull that contained all data points of the angle-angle plot (Figure 25) was calculated using the CONVHULL function in MATLAB. This area was used to quantify the coupling (mechanical interaction) between the trunk and pelvis for each trajectory (1-8) at both pre- and post-training, and to assess the change in coupling over the duration of the training period. Low values of area indicate in-phase or anti-phase coupling, and high values indicate either quadrature coupling or a lack of association between rotation of the trunk and the pelvis.

3.2.5.3 GAIT ANALYSIS

The gait deviation index (Schwartz & Rozumalski, 2008) was used to quantify the deviation from non-pathological gait for each participant both before and after the six-week training period. The GDI is derived from a set of 15 gait features which represent the full spectrum of normal and pathological gait based on nine joint angle curves (recorded at the pelvis, hip, knee and ankle joint) during the gait cycle. A single value is produced based on the scaled and standardised Euclidean distance of a patient from the mean of controls in the 15 dimensional gait feature data space, providing the deviation from 'normality'. The GDI score for non-pathological gait data is 100±10 (mean ± *SD*). Schwartz and Rozumalski (2008) reported that the GDI score scaled monotonically with reducing levels of the Gillette Functional Assessment Questionnaire Walking Scale, therefore a larger reduction from normality represents greater functional impairment in children with CP.

3.2.6 Statistical Analysis

Due to low participant numbers no group statistics were performed but results of game performance were analysed as single case-studies. All statistical tests were carried out using SPSS *version 17.0* (SPSS, Chicago, Illinois).

3.2.6.1 MAXIMUM SETTLED SPEED

Comparisons of max settled speed were made across all playing postures used by participants to play the GPO game. Further detailed analyses of the three playing postures (kneel sitting, high kneeling, and standing) were performed. Data were normally distributed for participants 01, 02, 05, and 06 and so parametric statistical tests were chosen to analyse the changes in max settled speed at each level and control scheme. A Paired Samples T-test assessed whether there were any significant differences ($p < 0.05$) between pre-training and post-training max settled speeds achieved by each of these participants. Data for participant 04 were not normally distributed and so the non-parametric equivalent was chosen. The Wilcoxon Matched Pairs test compared pre-training and post-training max settled speeds for significant differences ($p < 0.05$).

3.2.6.2 TRUNK-PELVIS COUPLING

Values of area within the convex hull were not normally distributed, but a natural log transform corrected the distribution (logArea). A Paired Samples T-test was carried out to compare the change in logArea between pre- and post-training for each trajectory (1-8). Linear regression was carried out to assess the change in logArea over the six-week training period to test whether logArea reduced over time.

3.2.6.3 THE GAIT DEVIATION INDEX

Due to low participant numbers, no group statistics were reported for the GDI scores.

3.3 Results

3.3.1 Summary of data obtained

Five participants completed the testing and training intervention over the six-week period. One participant (participant 03) belonging to the *control group* dropped out of the study after four training sessions, no explanation was provided for the withdrawal. Data across the six-week period was collected for three children belonging to the *core group*, and two children belonging to the *control group*. All participants were unable to play the GPO game using pelvic tilt, therefore only rotation was used during game play at the level of the pelvis. Due to low numbers recruited for each group, results are presented as case studies.

The main findings indicated that greater max settled speeds were achieved when using single plane motion of the trunk compared to cross plane motion both at pre- and post-training in the *core group*. The *core group* also demonstrated greater max settled speed when using trunk rotation compared to trunk tilt after receiving VR training, whilst trunk rotation was greater than pelvic rotation. These findings were apparent in all three playing postures. The *control group* demonstrated varied performance changes as a result of VR training. Both participants achieved higher max settled speed using single plane motion compared to cross plane motion during pre-training in all playing postures, but the patterns of performance as a result of training in the *core group* were not evident in the *control group*. Participant 01 showed an increase in coupling between the trunk and pelvis when controlling the game using pelvic rotation as a result of training. There were minimal changes to GDI scores for all participants as a result of the VR intervention.

Table 2. Participant information.

Participant Number	Group Allocation	Age (years)	Sex	Height (m)	Mass (kg)	Diagnosis
01	Core	10	Male	1.34	36.0	CP Diplegic
02	Control	7	Male	1.30	29.5	CP Diplegic
04	Control	8	Male	1.30	30.0	CP Diplegic
05	Core	6	Male	1.22	20.0	CP Diplegic
06	Core	10	Male	1.46	45.0	CP Diplegic

3.3.2 Maximum settled speed

3.3.2.1 SPEED PROFILE

Figure 13 illustrates a typical speed profile from one *run* during GPO game play. The *block* represented between trials 16-24 is an example of a period of continuous collisions with targets where the adaptive algorithm increased forward speed in large increments. Towards the end of the same *block* the forward speed became too fast for the participant, resulting in misses and a consequent decrease in forward speed. As the *block* continues the participant begins to alternative between hits and misses so the speed changes decrease in size. The *block* containing *trial* numbers 40-48 represents the period of max settled speed, which was the period where the magnitude of speed changes had converged to the minimum value.

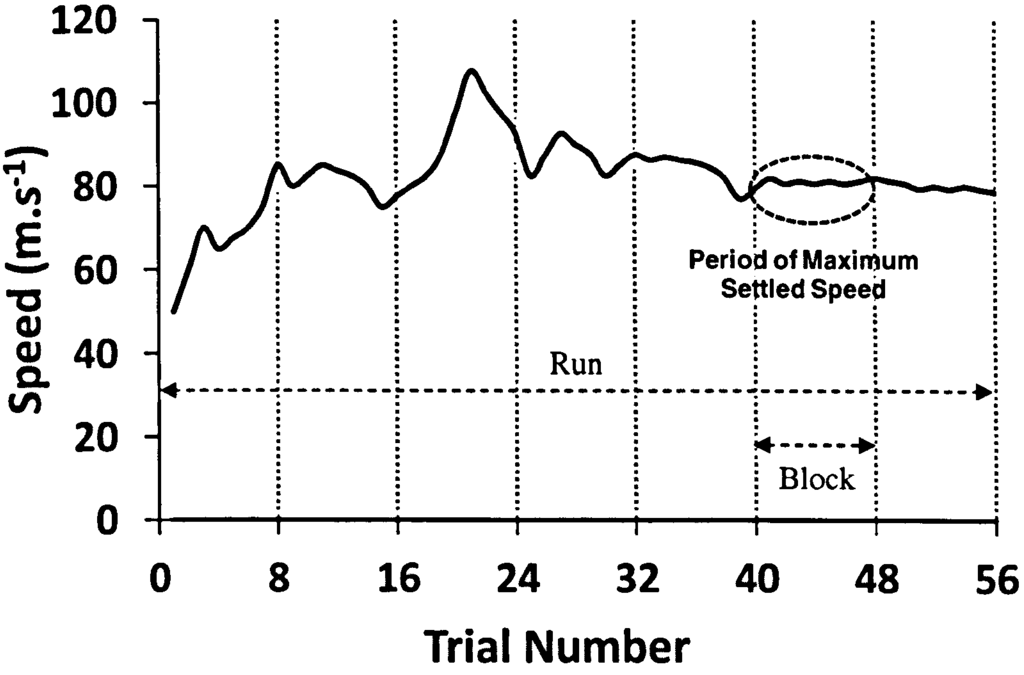


Figure 13. A typical speed profile of one *run* during GPO game play. Speed begins at 50 m.s^{-1}, and then increases or decreases in response to the participant's ability to hit the sequence of targets. In this example, the max settled speed was achieved in the block of trials 40-48.

3.3.3 Core group

3.3.3.1 PARTICIPANT 01

Participant 01 completed all levels of the GPO game for kneel sitting, high kneeling and standing during the pre- and post-training assessments.

3.3.3.1.1 Single plane versus cross plane motion of the trunk

The max settled speed reached using either single or cross plane motion at pre- and post-training showed that greater speeds were achieved in the GPO game when using trunk rotation or trunk tilt alone, as opposed to simultaneous trunk rotation and tilt. This was the case for all playing postures of the GPO game in kneel sitting (Figure 14(a)), high kneeling (Figure 14(b)) and standing (Figure 14(c)), and is confirmed numerically by a combined mean of 42.5 m.s^{-1} and 82.4 m.s^{-1} for single plane pre- and post-training respectively compared to 29.6 m.s^{-1} and 54.6 m.s^{-1} for cross plane motion (Figure 14(d)). Overall, the results demonstrated improvement in trunk control during VR training.

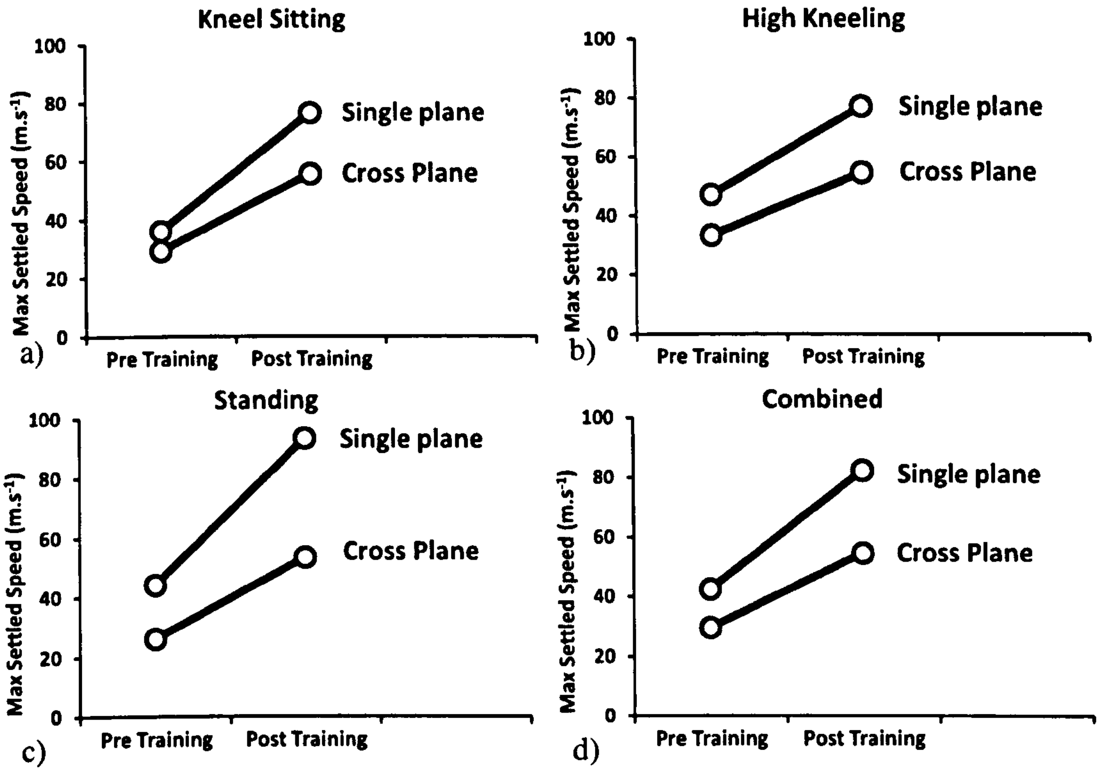


Figure 14. Participant 01 achieved higher max settled speed in a) kneel sitting, b) high kneeling, c) standing, and d) combining all three playing postures, when steering the dragon using single plane motion in comparison to cross plane motion, at both pre- and post-training.

3.3.3.1.2 Trunk rotation compared to trunk tilt

Steering the dragon using trunk rotation resulted in slightly higher max settled speed than trunk tilt, at all levels of the GPO game, with a mean difference of 6.7 $m.s^{-1}$ during pre-training, and 3.0 $m.s^{-1}$ post-training when averaging the values across levels (Figure 15).

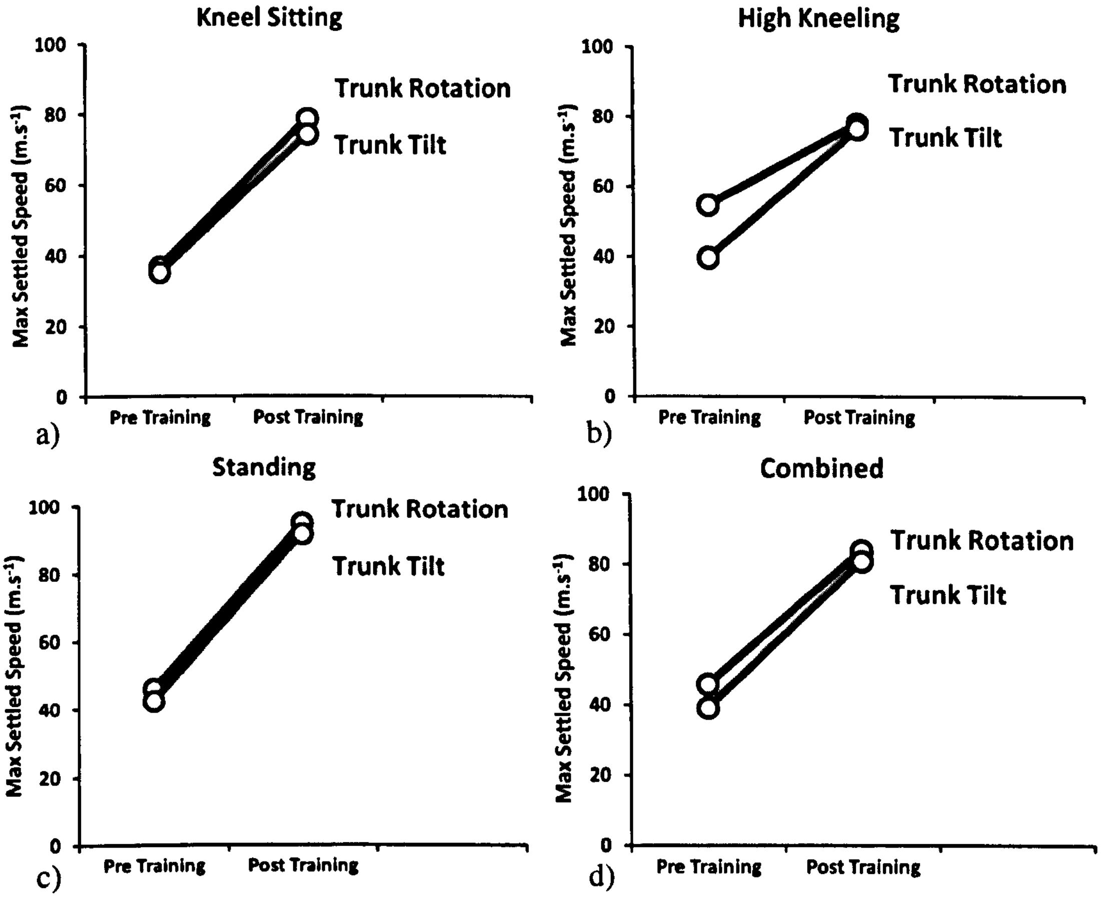


Figure 15. Participant 01 reached slightly higher max settled speed using trunk rotation in comparison to trunk tilt during a) kneel sitting, b) high kneeling, c) standing, and d) combining all three playing postures.

3.3.3.1.3 Trunk rotation compared to pelvic rotation

Higher values of max settled speed were achieved using trunk rotation compared to pelvic rotation to steer the dragon in both high kneeling and standing (Figure 16). Combining the results of high kneeling and standing, mean max settled speeds of 50.3 $m.s^{-1}$ (pre-training), and 86.4 $m.s^{-1}$ (post-training) were found when using trunk rotation, compared to 38.9 $m.s^{-1}$ (pre-training), and 60.8 $m.s^{-1}$ (post-training) when using pelvic rotation (Figure 16).

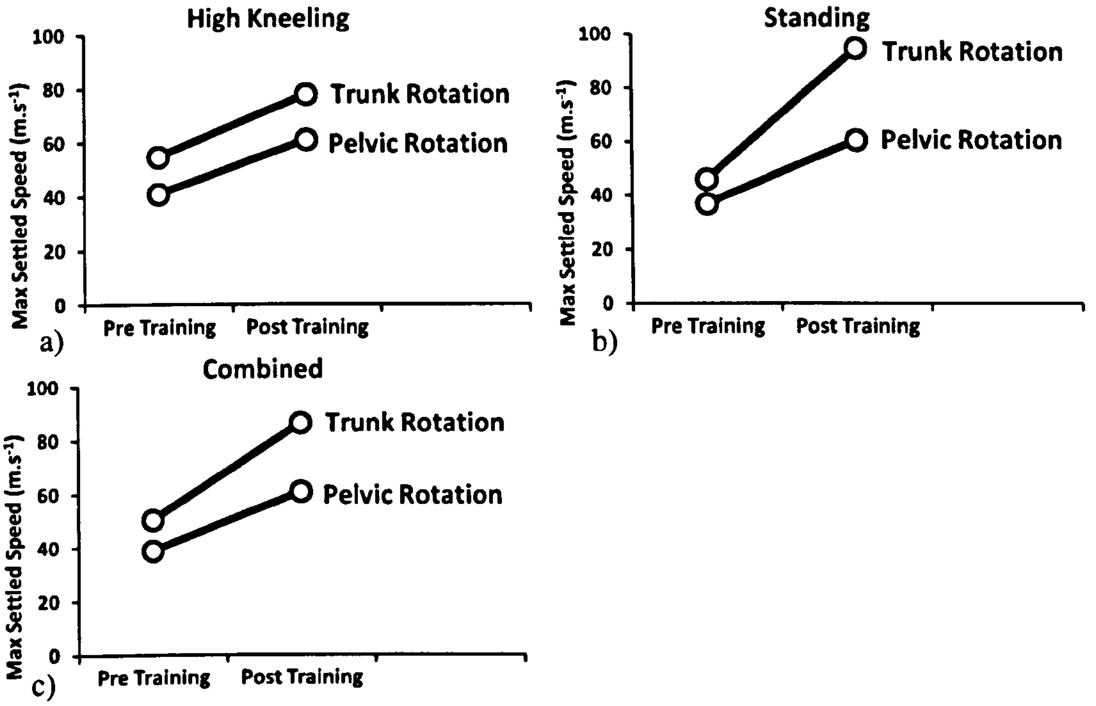


Figure 16. Participant 01 demonstrated better control using trunk rotation to steer the dragon as opposed to pelvic rotation, at both pre- and post-training.

3.3.3.1.4 Comparison of performance at three Goblin Post Office levels

The pre- and post-training max settled speed for all three playing postures and control schemes were normally distributed ($p > 0.05$). In kneel sitting there was a significant difference in performance from pre- to post-training ($t_{(2)} = -7.442$, $p = 0.018$), evidenced by an increase in mean max settled speed from 33.8 ± 4.0 m.s^{-1} to 69.6 ± 12.3 m.s^{-1} across all levels (Figure 17(a)). There was a significant difference between pre- and post-training in high kneeling ($t_{(3)} = -6.596$, $p = 0.007$), with an increase in mean max settled speed from 42.1 ± 9.0 m.s^{-1} to 67.5 ± 11.5 m.s^{-1} (Figure 17(b)). In standing there was also a significant difference between pre- and post-training ($t_{(3)} = -5.442$, $p = 0.0012$), illustrated by increases in mean max settled speed from 37.9 ± 8.7 m.s^{-1} to 75.2 ± 21.2 m.s^{-1} (Figure 17(c)).

3.3.3.1.5 Overall comparison

Max settled speed increased at all levels of the GPO game, with a mean change in speed of 32.6 ± 11.0 m.s^{-1}. The largest increase was demonstrated in standing whilst using the trunk to drive the game using single plane trunk tilt (49.3 m.s^{-1}) (Figure 17(d)).

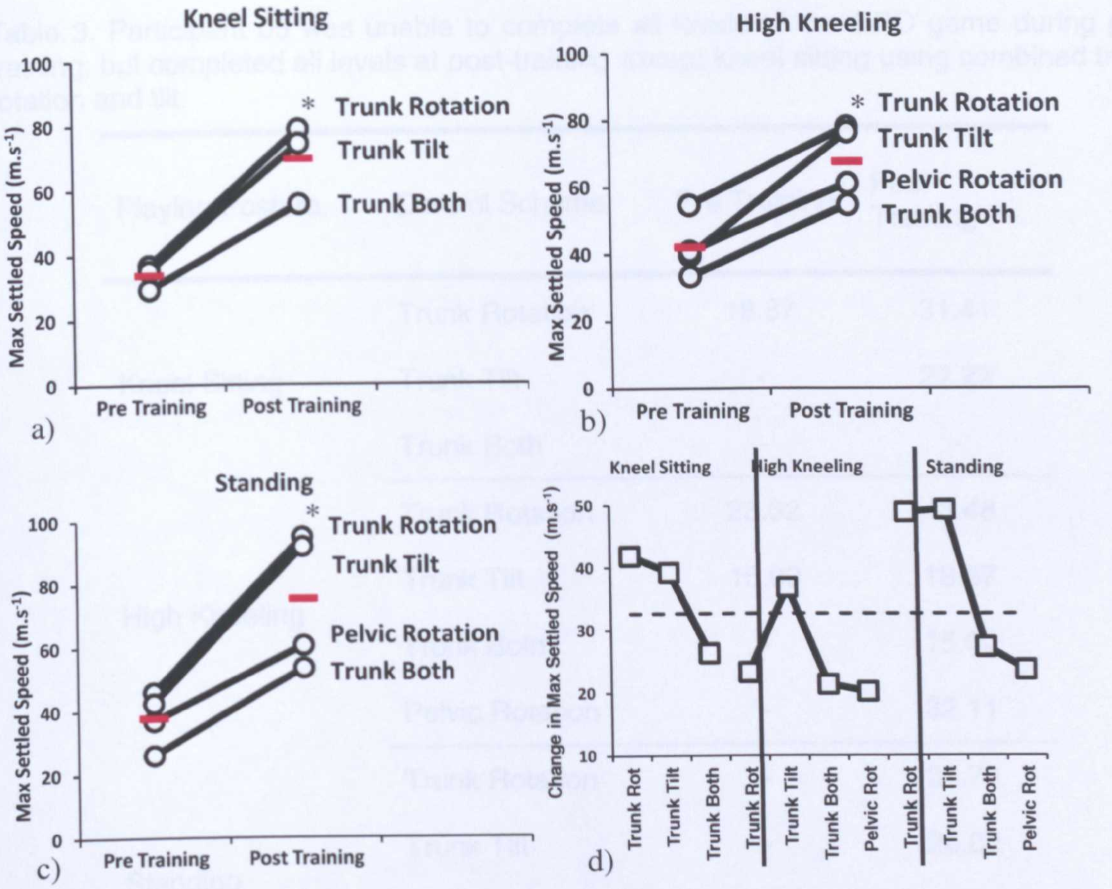


Figure 17. Higher max settled speeds were achieved using trunk rotation, followed by trunk tilt, pelvic rotation (high kneeling (b) & standing (c) only), then trunk both (red bars indicate average max settled speed achieved). Improvement in performance is highlighted by a positive change in max settled speed at post-training (d). The dashed line (d) represents mean change across all levels of the GPO game. Asterisks denote where statistically significant changes occurred between assessments.

3.3.3.2 PARTICIPANT 05

Participant 05 managed to complete only three levels of the GPO game during pre-training (Table 3). At post-training participant 05 was able to play all levels of the GPO game except in kneel sitting using cross plane motion of the trunk, showing a significant improvement in performance. A comparison of the available pre-training max settled speed values against the corresponding post-training values showed that there were no significant differences as a result of training ($t_{(2)} = -2.544$, p = 0.126). Figure 18 highlights that playing the GPO game using single plane motion (trunk rotation or trunk tilt) achieved higher max settled speed than cross plane motion (trunk both) during post-training.

Table 3. Participant 05 was unable to complete all levels of the GPO game during pre-training, but completed all levels at post-training except kneel sitting using combined trunk rotation and tilt.

Playing Posture	Control Scheme	Pre Training	Post Training
Kneel Sitting	Trunk Rotation	18.87	31.41
	Trunk Tilt	-	27.27
	Trunk Both	-	-
High Kneeling	Trunk Rotation	23.32	43.48
	Trunk Tilt	15.00	18.67
	Trunk Both	-	15.00
	Pelvic Rotation	-	32.11
Standing	Trunk Rotation	-	20.70
	Trunk Tilt	-	26.02
	Trunk Both	-	15.00
	Pelvic Rotation	-	22.15

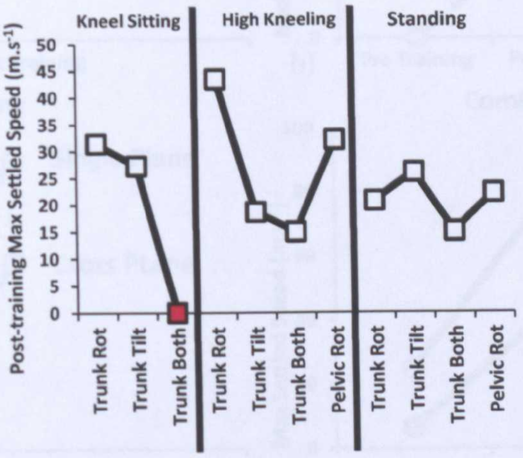


Figure 18. Participant 05 demonstrated the ability to play the GPO game in all playing postures at post-training, except in kneel sitting when using combined trunk rotation and tilt. Greater max settled speeds were achieved using single plane motion (trunk rotation, trunk tilt, and pelvic rotation) rather than cross plane motion (trunk both). The red marker denotes that the participant was unable to play the GPO game at that specific level.

3.3.3.3 PARTICIPANT 06

Participant 06 was unable to complete all of the GPO game levels during the pre-training assessment. Data were taken from both the pre-training and first training session during which participant 06 was first exposed to the GPO game, in order to provide a baseline for max settled speed scores achieved. The baseline max settled speed values were then compared to post-training, and presented as a case study.

3.3.3.3.1 Single plane versus cross plane motion of the trunk

Participant 06 was unable to complete the cross plane motion control scheme at pre-training in both the high kneeling and standing posture (Figure 19(b) & Figure 19(c) respectively), but all levels were completed at post-training indicating improvements. Greater speeds were reached using trunk rotation or trunk tilt alone compared to simultaneous trunk rotation and tilt, confirmed by a combined mean max settled speed of 85.16 m.s^{-1} for single plane motion compared to 46.72 m.s^{-1} for cross plane motion (Figure 19(d)). Overall, the results demonstrated that trunk control improved following VR training.

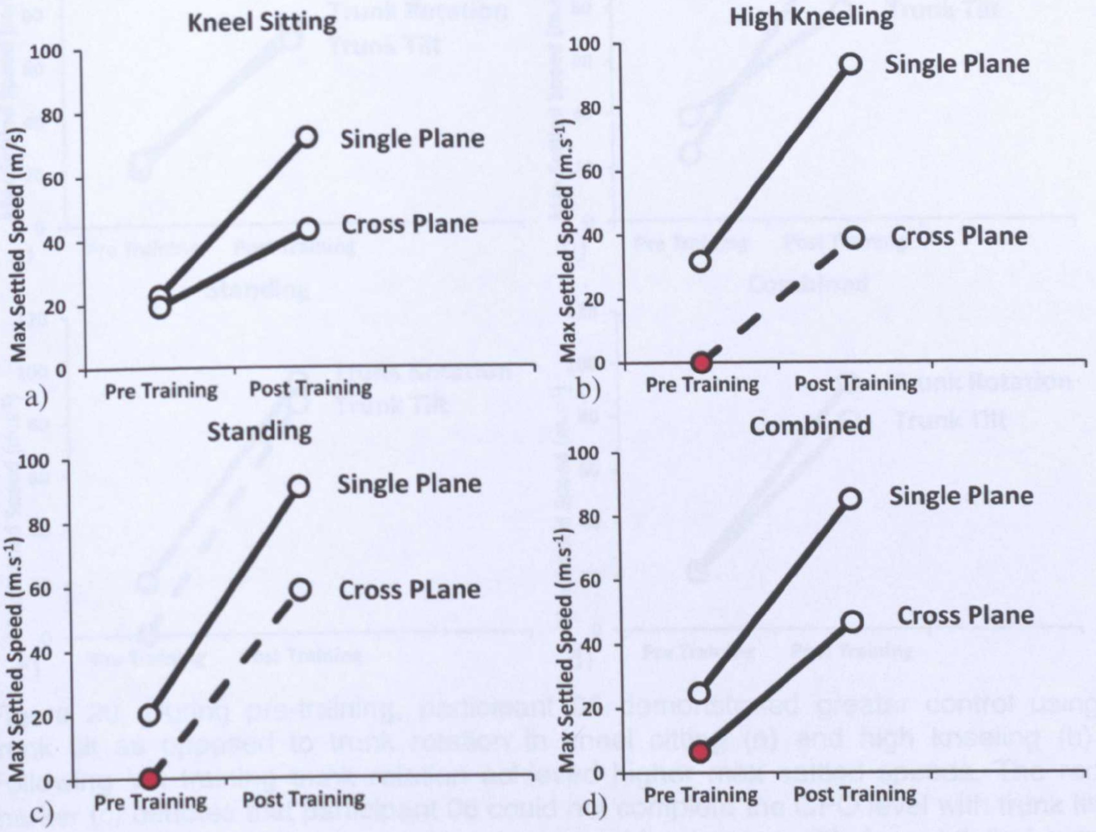


Figure 19. Figures a, b and c demonstrate that steering the dragon using single plane motion (trunk rotation and trunk tilt) resulted in higher max settled speed than using cross plane motion (trunk both). Average max settled speed (d) confirms that post-training scores were higher than pre-training. Red markers (b-c) indicate those levels of the GPO game where participant 06 was unable to reach a max settled speed resulting in a combined max settled speed that was affected by zero values (d).

3.3.3.3.2 Trunk rotation compared to trunk tilt

Steering the dragon using trunk tilt resulted in higher max settled speed than trunk rotation in kneel sitting (Figure 20(a)) and high kneeling (Figure 20(b)) during pre-training, but not in standing where trunk tilt was unplayable (Figure 20(c)). Following VR training trunk rotation demonstrated greater max settled speed than trunk tilt for all GPO playing postures, suggesting the order of control has reversed. The difference in combined max settled speed at pre-training for trunk rotation and trunk tilt was minimal (0.83 m.s^{-1}) suggesting participant 06 uses the control schemes with similar ability. Trunk rotation reached higher max settled speeds than trunk tilt at post-training, highlighted by a combined mean difference of 14.17 m.s^{-1} at post-training (Figure 20(d)).

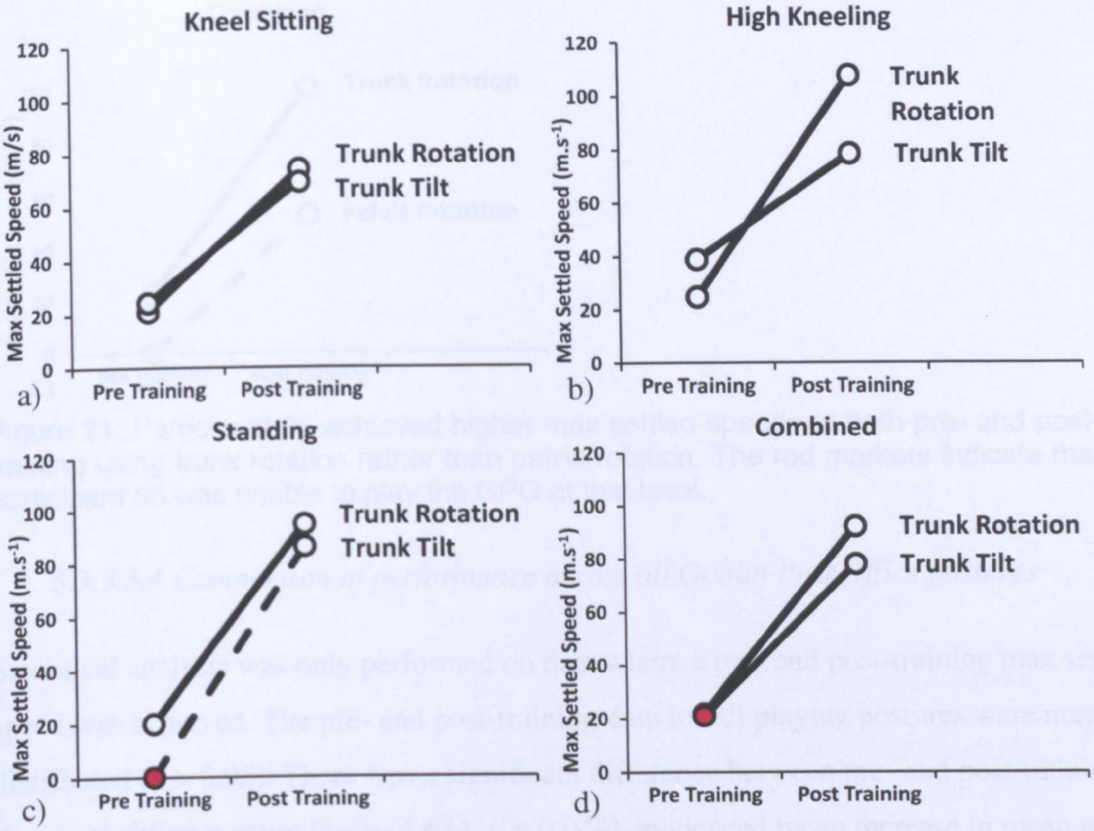


Figure 20. During pre-training, participant 06 demonstrated greater control using trunk tilt as opposed to trunk rotation in kneel sitting (a) and high kneeling (b). Following VR training trunk rotation achieved higher max settled speeds. The red marker (c) denotes that participant 06 could not complete the GPO level with trunk tilt in standing at pre-training, resulting in a combined max settled speed that was affected by zero values (d).

3.3.3.3.3 Trunk rotation compared to pelvic rotation

Participant 06 was unable to steer the dragon using pelvic rotation in both high kneeling (Figure 21(a)) and standing (Figure 21(b)) at pre-training, but completed both playing postures in post-training. During post-training trunk rotation reached higher speeds in both high kneeling (107.73 m.s^{-1}) and standing (94.69 m.s^{-1}) compared to pelvic rotation (40.63

m.s^{-1} and 65.0 m.s^{-1} respectively). The combined results indicated that the trunk is better controlled than the pelvis when using rotation to steer the dragon following VR training (Figure 21).

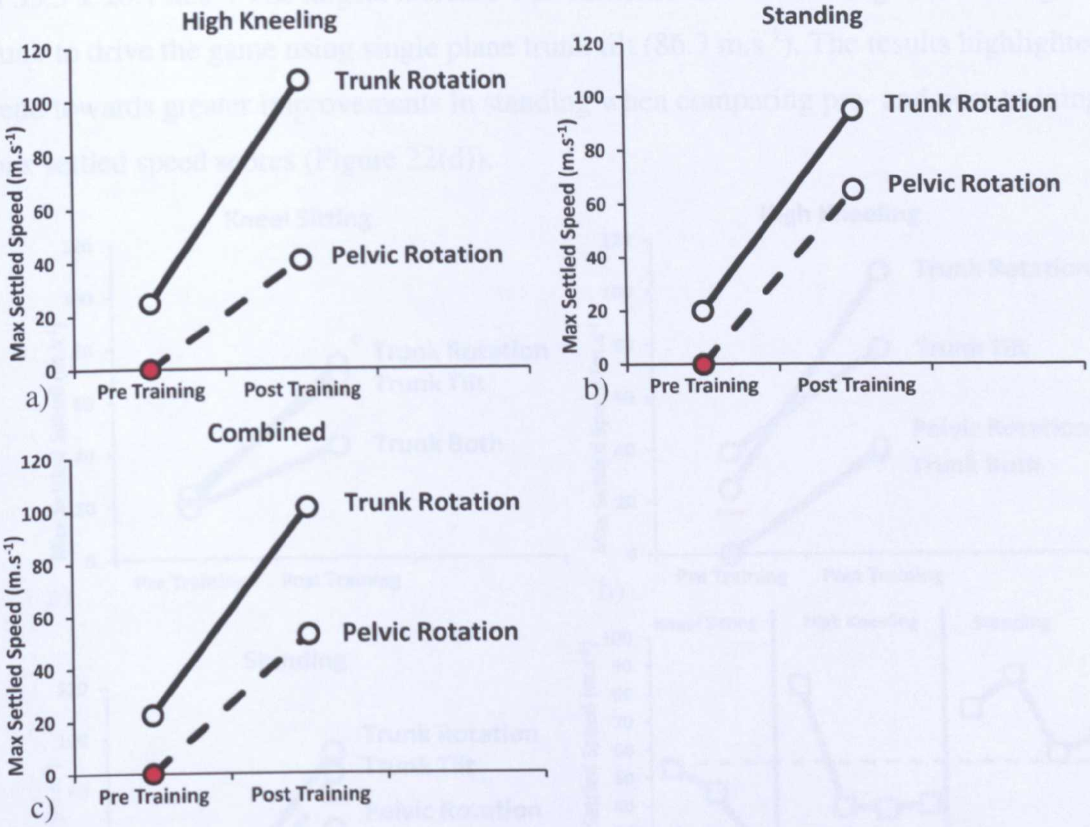


Figure 21. Participant 06 achieved higher max settled speeds at both pre- and post-training using trunk rotation rather than pelvic rotation. The red markers indicate that participant 06 was unable to play the GPO at that level.

3.3.3.3.4 Comparison of performance across all Goblin Post Office postures

Statistical analysis was only performed on data where a pre- and post-training max settled speed was achieved. The pre- and post-training data for all playing postures were normally distributed ($p > 0.05$). There was a significant difference between pre- and post-training in the kneel sitting posture ($t_{(2)} = -4.634$, $p = 0.044$), evidenced by an increase in mean max settled speed from 21.51 ± 2.63 m.s^{-1} to 62.27 ± 16.82 m.s^{-1} (Figure 22 (a)). In high kneeling and standing there were too many missing max settled speed values (Figure 22(a) and Figure 22(b)), but an overall comparison of GPO postures and control schemes that were completed indicated a significant difference between pre- and post-training max settled speed ($t_{(5)} = -5.880$, $p = 0.002$). This was evidenced by an increase in mean max settled speed from 24.7 ± 7.3 m.s^{-1} at pre-training to 77.9 ± 22.2 m.s^{-1} at post-training.

3.3.3.3.5 Overall comparison

Max settled speed increased at all postures of the GPO game, with a mean change in speed of 55.3 ± 20.1 m.s^{-1}. The largest increase was demonstrated in standing whilst using the trunk to drive the game using single plane trunk tilt (86.3 m.s^{-1}). The results highlighted a trend towards greater improvements in standing when comparing pre- and post-training max settled speed scores (Figure 22(d)).

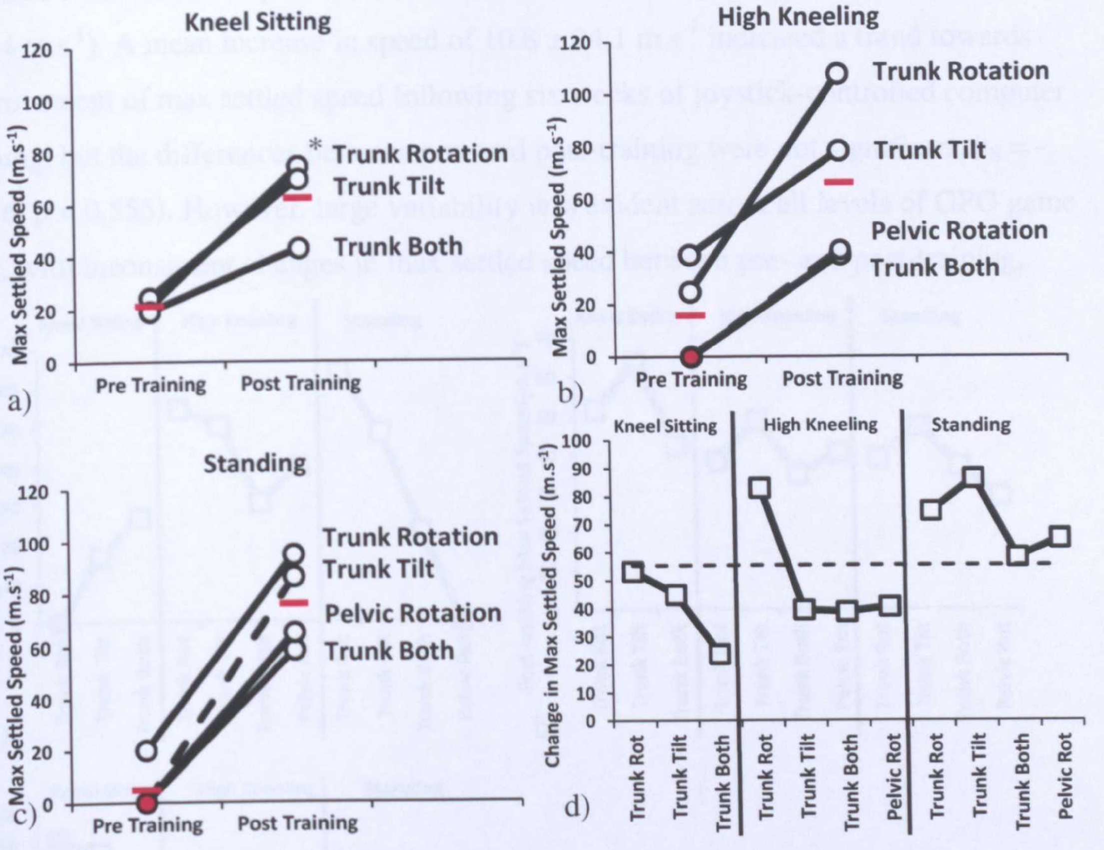


Figure 22. The highest max settled speed was achieved by participant 06 when using trunk rotation after receiving VR training. Trunk tilt, pelvic rotation (high kneeling (b) & standing (c) only), and then combined trunk rotation and tilt achieved lower max settled speeds in order (red bars indicate average max settled speed achieved). The pre-training order was not the same at each playing posture. Improvement in performance is highlighted by a positive change in max settled speed at post-training (d). The dashed line (d) represents mean change across all levels of the GPO game. The red markers indicate that the participant was unable to register a max settled speed at that GPO level. Asterisks denote where statistically significant changes occurred between assessments.

3.3.4 Control Group

3.3.4.1 PARTICIPANT 02

During the pre-training core control assessment, participant 02 demonstrated greater control of single plane motion than cross plane motion during high kneeling and standing, and trunk rotation performed better than trunk tilt (Figure 23(a)). Greater max settled speed was achieved with trunk rotation than with pelvic rotation. During the post-training assessment, participant 02 displayed better control of single plane motion than cross plane motion in all three GPO playing postures (Figure 23(b)). However, the max settled speeds did not improve on pre-training speeds. Trunk tilt was found to perform better than trunk rotation in post-training for all playing postures (Figure 23(b)). When considering the change in max settled speed between pre- and post-training, the largest increase was demonstrated in kneel sitting using trunk rotation (51.72 m.s^{-1}) (Figure 23(c)). The largest decrease in max settled speed was demonstrated in standing whilst using trunk rotation (-24.84 m.s^{-1}). A mean increase in speed of 10.8 ± 24.1 m.s^{-1} indicated a trend towards improvement of max settled speed following six weeks of joystick-controlled computer training, but the differences between pre- and post-training were not significant (t_8 = -0.616, $p = 0.555$). However, large variability was evident across all levels of GPO game play, with inconsistent changes in max settled speed between pre- and post-training.

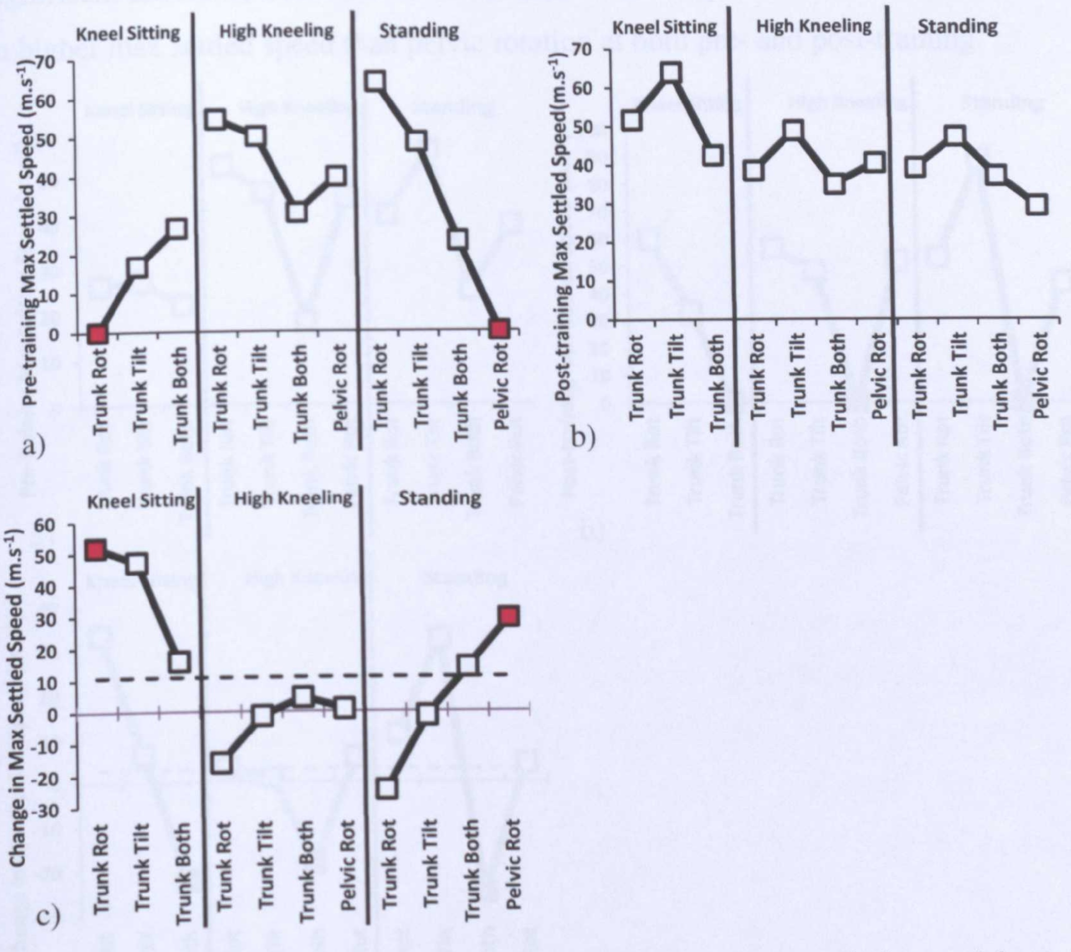


Figure 23. a) Participant 02 was unable to register a max settled speed for trunk rotation in kneel sitting and pelvic rotation in standing during pre-training (indicated by red markers). b) All GPO postures and control schemes could be completed post-training. There were both increases and decreases in max settled speed as a result of participating in the *control group*, highlighted by the varied change in max settled speed (c). The dashed line (c) represents mean change across all levels of the GPO game.

3.3.4.2 PARTICIPANT 04

During the pre-training core control assessment, participant 04 achieved greater max settled speed using trunk rotation or trunk tilt in comparison to cross plane motion, demonstrating better single plane control. Participant 04 was unable to achieve a max settled speed when using cross plane motion (trunk both) to steer the dragon during the post-training assessment. Therefore Figure 24(c) demonstrated a decrease in performance for cross plane motion (trunk both) at all three playing postures (kneel sitting, high kneeling and standing). The max settled speed increased at all other levels of the GPO game, with a mean increase of 2.81 ± 19.39 m.s^{-1} demonstrating large variability in the magnitude of the changes. A comparison of pre- and post-training max settled speed values indicated that the data were not normally distributed ($p < 0.05$), and that there was no significant difference between assessments ($Z = -0.800$, $p = 0.424$). Trunk rotation resulted in higher max settled speed than pelvic rotation at both pre- and post-training.

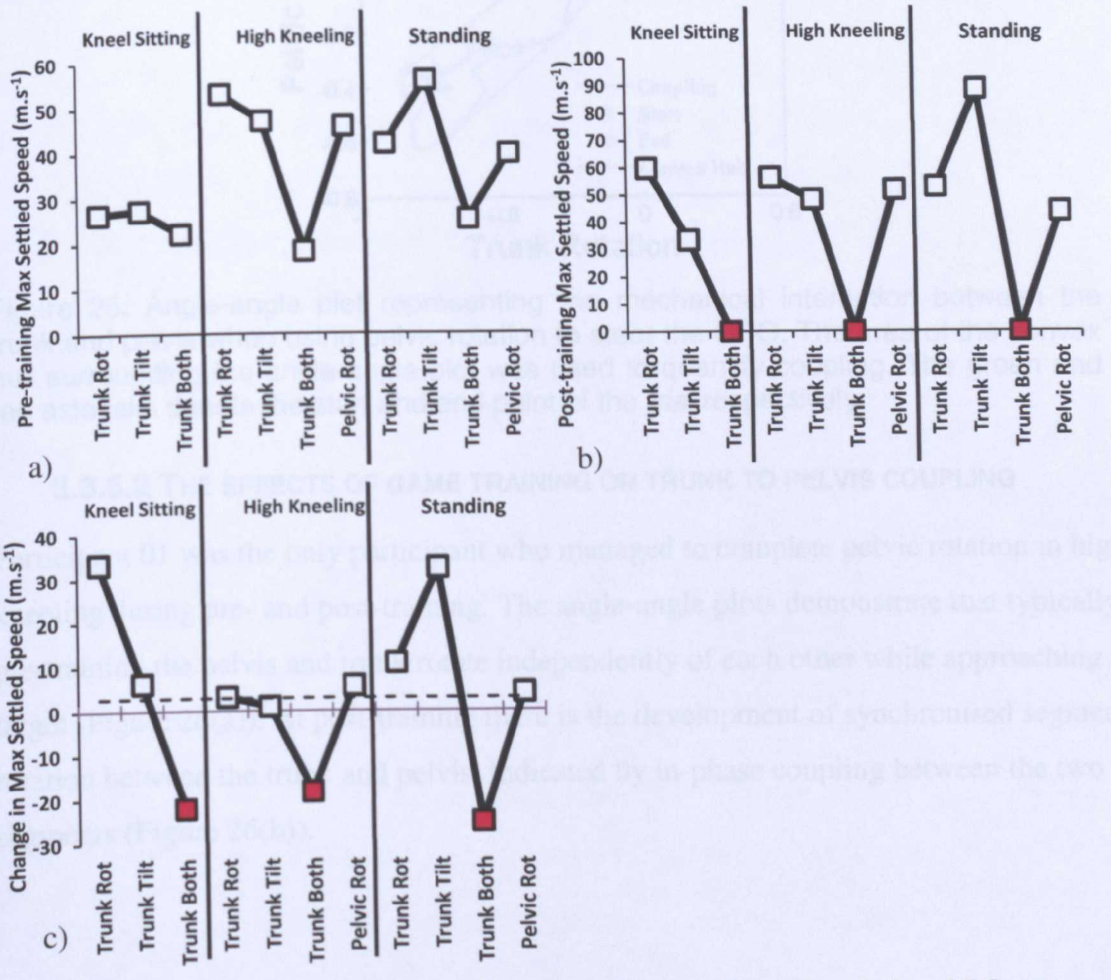


Figure 24. a) Participant 04 was able to complete all levels of the GPO in pre-training. b) Participant 04 was unable to reach a max settled speed for trunk both in kneel sitting, high kneeling, or standing (indicated by red markers) in post-training. There were both increases and decreases in max settled speed for this participant in the *control group*, highlighted by the varied change in max settled speed (c). The dashed line (c) represents mean difference across all levels of the GPO game.

3.3.5 Trunk-Pelvis Coupling

3.3.5.1 PARTICIPANT 01

Figure 25(a) provides an example of a typical angle-angle plot for rotation of the trunk and pelvis during one movement trajectory. Pelvic rotation was used to steer the dragon during GPO game play, and the interaction between pelvic rotation and trunk rotation was assessed. The red envelope that contains all data points of the angle-angle plot (Figure 25(b)) indicated the convex hull, the area of which was used to quantify coupling between the trunk and pelvis.

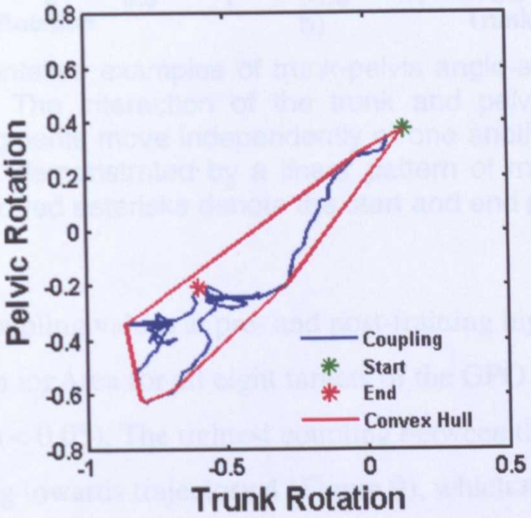


Figure 25. Angle-angle plot representing the mechanical interaction between the trunk and pelvis when using pelvic rotation to steer the GPO. The area of the convex hull surrounding the angle-angle plot was used to quantify coupling. The green and red asterisks denote the start and end point of the *trial* respectively.

3.3.5.2 THE EFFECTS OF GAME TRAINING ON TRUNK TO PELVIS COUPLING

Participant 01 was the only participant who managed to complete pelvic rotation in high kneeling during pre- and post-training. The angle-angle plots demonstrate that typically in pre-training the pelvis and trunk rotate independently of each other while approaching a target (Figure 26(a)). At post-training there is the development of synchronised segmental rotation between the trunk and pelvis, indicated by in-phase coupling between the two segments (Figure 26(b)).

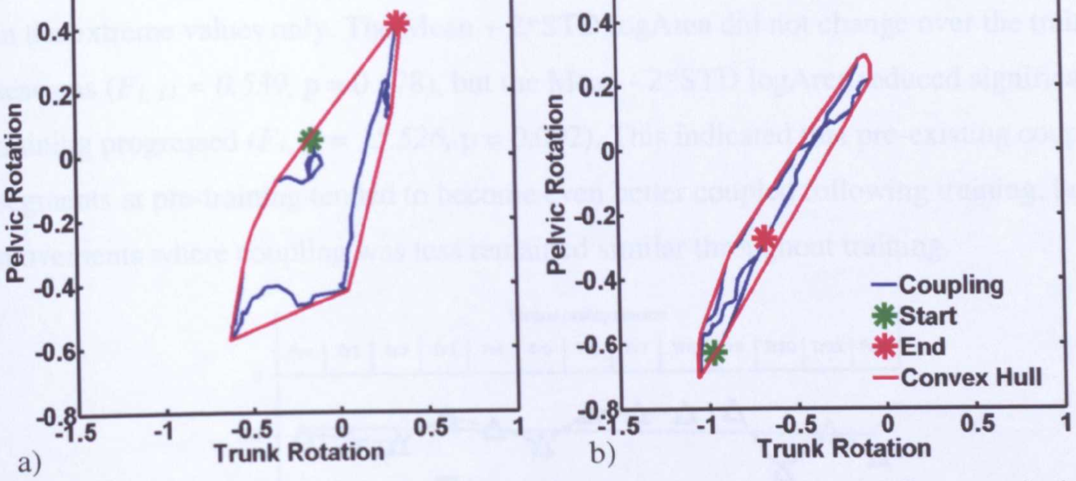


Figure 26. a) Representative examples of trunk-pelvis angle-angle diagrams before and after training. a) The interaction of the trunk and pelvis during pre-training indicates that both segments move independently of one another. b) The trunk and pelvis move in-phase, demonstrated by a linear pattern of movement during post-training. The green and red asterisks denote the start and end point of the movement trajectory respectively.

A comparison of all coupling values at pre- and post-training highlighted a statistically significant reduction in logArea for all eight targets of the GPO game in response to VR training ($t_{(7)} = 6.057$, $p < 0.05$). The tightest coupling between the trunk and pelvis was produced when moving towards trajectory 4 (Figure 9), which required the largest component of pelvic rotation (Figure 27).

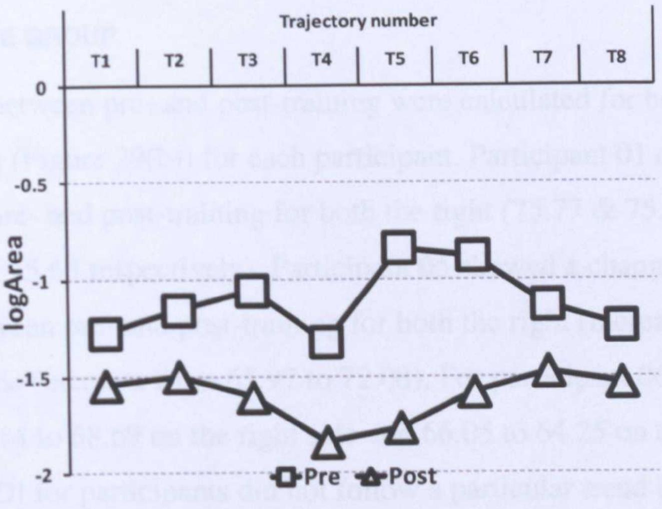


Figure 27. There is a reduction in mean logArea for each trajectory within the GPO game following six-weeks of training. Coupling was tightest (lowest logArea) when navigating the dragon towards trajectory 4, both pre- and post-training.

Coupling increased between the trunk and pelvic segment through the six-week intervention period of VR training on the pelvis, indicated by a statistically significant reduction of the logArea within the convex hull across all trials ($F_{1,11} = 7.482$, $p = 0.019$) (Figure 28). This, however, concealed more complex behaviour. Values of Mean + 2*STD and Mean – 2*STD of logArea were examined to preclude the possibility that the effect lay in the extreme values only. The Mean + 2*STD logArea did not change over the training sessions ($F_{1,11} = 0.539$, p = 0.478), but the Mean - 2*STD logArea reduced significantly as training progressed ($F_{1,11} = 15.526$, p = 0.002). This indicated that pre-existing coupling of segments at pre-training tended to become even better coupled following training, but that movements where coupling was less remained similar throughout training.

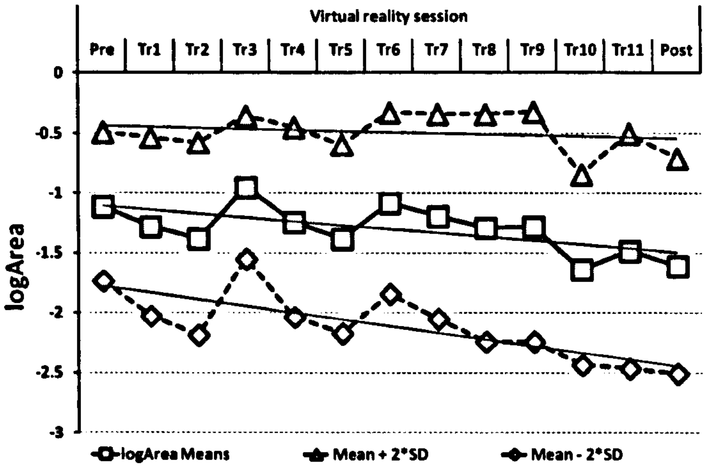


Figure 28. The reducing means of convex hull areas indicate increased coupling between the trunk and pelvis over the six-week training period (Pre-training assessment, Training sessions 1-11, post-training assessment).

3.3.6 Gait Deviation Index

3.3.6.1 CORE GROUP

Changes in GDI between pre- and post-training were calculated for both the right (Figure 29(a)) and left leg (Figure 29(b)) for each participant. Participant 01 demonstrated minimal change between pre- and post-training for both the right (75.77 & 75.36 respectively) and left side (75.38 & 75.63 respectively). Participant 05 showed a change towards normality in GDI score between pre- and post-training for both the right (increase from 58.26 to 69.56) and left side (increase from 65.97 to 72.08). For participant 06 the GDI score reduced from 77.14 to 68.69 on the right side and 66.05 to 64.25 on the left side. Overall the changes in GDI for participants did not follow a particular trend in response to VR training, indicating that improvements in trunk and pelvis control during GPO game play do not necessarily transfer to improvement in gait.

3.3.6.2 CONTROL GROUP

Participant 02 showed a small improvement on the right side, with GDI increasing from 68.97 to 71.45, but worsened on the left side (decrease from 74.18 to 67.82). The GDI score for participant 04 reduced from 88.23 to 74.82 on the right side, and 78.23 to 67.99

on the left side. The changes in GDI between pre- and post-training for the *control group* indicated that playing the GPO game using a joystick had no beneficial effect on gait.

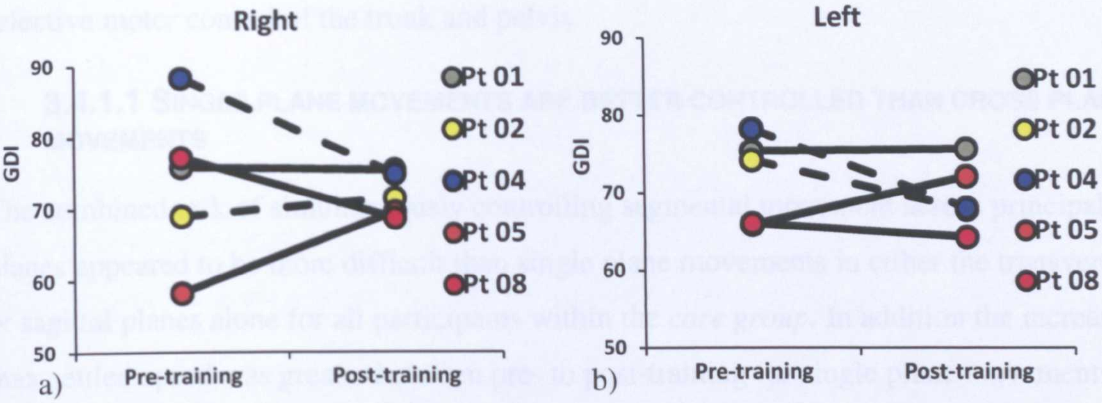


Figure 29. There is a varied GDI response to VR training for all participants, suggesting that VR training has no significant effect on change of gait relative to normality for both the right and left lower extremity between pre- and post-training. Note the discrimination between *core group* (thick line) and *control group* participants (dashed line).

3.3.7 Questionnaires

The feedback from the anonymous questionnaires suggested that children enjoyed playing the GPO game, but that *"two or three versions"* of the game should exist, or *"different games/virtual locations which still tested the same movement"* would benefit future VR training interventions. It was suggested that new games could be based on a *"sport theme"*, like existing commercial games. One parent reported: *"I thought the computer game was good, but it seemed to get boring and repetitive for the child"*. It was further noted that the swimming coach of one child had noticed *"improvements"* in swimming as a result of VR training.

3.4 Discussion

The five case studies presented illustrate that children with CP vary in their ability to drive a VR game using selective motor control of the trunk and pelvis. *Core group* participants demonstrated improvements in max settled speed across the majority of GPO postures and control schemes following VR training on the core of the body. In comparison, the *control group* showed both an increase and decrease in VR performance using the core, after receiving VR training on the dominant arm using a joystick. The contrast in results from the *core group* and *control group* participants suggests that joystick practice might improve knowledge of how to play the GPO game, but does not necessarily transfer to developing the physical ability to play the game. Overall the GDI scores reported for both training conditions show that changes in VR game play did not translate to changes in gait.

A systematic analysis of the max settled speeds reached whilst playing the GPO game may provide greater understanding regarding some of the underlying mechanisms that influence selective motor control of the trunk and pelvis.

3.4.1.1 SINGLE PLANE MOVEMENTS ARE BETTER CONTROLLED THAN CROSS PLANE MOVEMENTS

The combined task of simultaneously controlling segmental movement across principal planes appeared to be more difficult than single plane movements in either the transverse or sagittal planes alone for all participants within the *core group*. In addition the increase in max settled speed was greater between pre- to post-training for single plane movements than cross plane movements. Both participants in the *control group* demonstrated greater max settled speed for single plane movements, suggesting greater single plane control is inherent within individuals. However a larger study sample size is required to support this finding. Targeted Training reduces the degrees of freedom at multiple joints below the trunk to train selective motor control of the trunk (Butler & Major, 1992), and the findings in this study suggest that training one joint at a time leads to greater improvements in performance. Previous studies (Silsupadol *et al.*, 2006; Rochester *et al.*, 2008; Silsupadol *et al.*, 2009) reported improvements in balance as a result of training under dual-task conditions which require human movement and a cognitive task to be performed simultaneously, but there is insufficient research investigating the training of movement in combined planes of motion as a dual task. The current aim of physiotherapy is to improve gross motor skills, and combined motion of the trunk is necessary for coping with the demands of many ADL, hence training cross plane movements in rehabilitation is essential. During gait, cross plane motion occurs as trunk rotation moves in-phase or anti-phase with pelvis rotation in the transverse plane at varying walking speeds (Sartor *et al.*, 1999). In the sagittal plane the trunk is held in extension throughout the gait cycle as a consequence of the fixed anterior tilt of the pelvis. Therefore gait requires adequate control of the trunk in multiple planes to maintain stability and aid progression.

3.4.1.2 TRUNK ROTATION IS BETTER CONTROLLED THAN TRUNK TILT

Participant 01 and participant 06 achieved greater max settled speeds when using trunk rotation to steer the dragon in comparison to trunk tilt at both pre- and post-training. In addition participant 05 demonstrated better control of trunk rotation than trunk tilt in response to VR training during kneel sitting and high kneeling . Reduced control of trunk tilt in comparison to rotation may occur due to the destabilising effect of the body's centre of gravity as it translates outside the base of support, as opposed to rotation which requires less displacement of the body's centre of gravity. The trunk is usually extended throughout the gait cycle in non-pathological gait (Sartor *et al.*, 1999), suggesting changes in trunk tilt in an anterior direction is the least common action that children perform during walking. Trunk tilt is required in other important ADL such as sitting down, standing up, or reaching, meaning children do have some exposure to segmental tilt. During ADL the body's centre of gravity may accelerate outside the base of support during unstable conditions which could lead to an increased risk of falling, and so training control of trunk tilt is expected to lead to greater benefits in preventing falls and maintaining balance.

It is feasible that retraction of one side of the body is unambiguously mapped to steering the virtual dragon in the same direction when using trunk rotation to control GPO game play. In comparison, anterior tilt may be expected to produce either upward or downward movement, depending on the participant's previous experience of computer games. Flight simulators and driving games vary in the way a movement is linked to direction of control, and so previous exposure to alternative task conditions might influence the participant's ability to comply with the demands of the current task. The range of motion when rotating a body segment during GPO game play is symmetrical, but asymmetrical for segmental tilt. There was a greater range of anterior tilt available to the participant than posterior tilt, which was accounted for by adjusting the gain in the GPO game so that the small range could be used to reach the ceiling of the virtual cave. Though the altered gain made the game control efficient, the different ranges in anterior and posterior trunk tilt may be a confounding factor for the participant's ability to reach higher game speeds, especially during initial exposure to the task.

3.4.1.3 TRUNK ROTATION IS CONTROLLED BETTER THAN PELVIS ROTATION

Participant 01 and participant 06 achieved larger max settled speed when using trunk rotation in comparison to pelvic rotation. Participant 05 reached a higher max settled speed using trunk rotation at post-training in high kneeling (but not standing). The reduction found in the level of control from the trunk to the pelvis confirms the cephalo-caudal reduction in control as suggested by the theory of Targeted Training (Butler & Major, 1992). Rotation of the trunk and pelvis are unambiguously mapped to key features of the gait cycle (Sartor *et al.*, 1999; Lamoth *et al.*, 2002; Vogt *et al.*, 2002; Bruijn *et al.*, 2008), therefore when driving the GPO in the transverse plane the participants may be familiar with the required movements to control the game. During gait, the trunk segment is constrained by momentum of the upper extremities and head control, which have low inertial properties with respect to the trunk. In comparison, the pelvis segment is rigidly linked to the trunk, whilst fixed to the lower extremities. Therefore, greater inertial properties are acting on the pelvis in more than one direction, and so the ability to selectively control movement of the pelvis may be more difficult. Hence greater max settled speed was reached using trunk rotation to drive the game. The *control group's* max settled speed suggested that trunk or pelvic rotation perform equally at pre-training, hence the results are contrary to the suggestion that a cephalo-caudal reduction in control exists prior to VR training between the trunk and pelvis. In response to intervention, the *control group* achieved similar speeds with both the trunk and pelvis, whereas the *core group* demonstrated greater max settled speed using the trunk. Though participant numbers for both groups are low, the findings indicate that it may be only as a result of training that trunk rotation performs much better than the pelvis, but a larger sample size is required in order to support the current findings.

3.4.1.4 THE TRUNK AND PELVIS BECOME TIGHTLY COUPLED IN RESPONSE TO VIRTUAL REALITY TRAINING FOR PARTICIPANT 01

In response to six weeks of training there was a gradual increase in coupling of the pelvis to the trunk (Figure 28) quantified as the reduction in area within the convex hull surrounding trunk and pelvis angle-angle plots. The progressive change suggests that the trunk and pelvis have become more rigidly linked in response to training. The tighter coupling of the pelvis to the trunk could be a compensatory mechanism which enables the participant to improve control of the pelvis indirectly by locking it to the better controlled trunk. Existing literature suggests that co-contraction, which refers to the simultaneous activation of agonist and antagonist muscles during human movement, is a common motor control strategy used to improve stability and accuracy when performing an untrained task (van Roon *et al.*, 2005). In a reaching task designed to assess co-contraction of the agonist and antagonist muscles at the elbow and shoulder, Gribble *et al.* (2003) found an inverse relationship between target size and co-contraction; as target size reduced, co-contraction increased, leading to improved movement accuracy of the limb. In the present study, co-contraction of trunk and pelvis musculature to provide in-phase rotation of the segments may therefore be regarded as a strategy for improved accuracy and greater control when playing the GPO game at increasing game speeds. Gribble *et al.* (2003) observed that levels of co-contraction decreased over time, suggesting co-contraction and associated limb stiffness can be reduced in response to practice. It could be proposed that greater selective motor control of the pelvis might develop in response to further training using the GPO game. Selectivity of the pelvis could be increased by restricting motion at the trunk segment using game features similar to that of constraint induced movement therapy, which aims to physically inhibit the compensation strategies developed as a result of impaired movement (Gordon *et al.*, 2005). The GPO game can provide a similar constraint during game play by providing a visual warning to the participant if movement of the trunk occurs whilst steering the dragon using pelvic rotation. Further evaluation of this feature in relation to constraint induced movement therapy is required before using it in VR games training.

3.4.1.5 IMPROVEMENTS IN VIRTUAL REALITY GAME PLAY DO NOT TRANSLATE TO IMPROVEMENTS IN GAIT

The assessment of gait using the GDI suggests there were no significant changes in gait for each group. The change in GDI was highly variable for all participants on both sides, regardless of which training group they belonged to. Thus, no relationship was found between improvements in game speeds and changes in GDI. A limitation of using the GDI as an objective measure of performance in the present study surrounds using a single number to represent the complexity of gait. Although the GDI has been shown to correlate well with the Gillette Gait Index and Functional Assessment Questionnaire (Schwartz & Rozumalski, 2008), a single value representing the whole gait cycle fails to identify which phase of the gait cycle is most affected, and which joint contributes to the deviation from normality. A recent development is the Movement Deviation Profile (Barton *et al.*, 2010) which provides a curve representing the deviation from normality across the entire gait cycle. The Movement Deviation Profile uses a neural network to generate a representation of unimpaired gait which can be compared with patients' gait. This method can provide an added level of detail complementing the single value produced by the GDI and may be used for future research to provide a more sensitive approach to changes in gait. Alternatively, changing the independent outcome measure to an activity which requires a more active role of both the core and periphery could be more appropriate. It was previously indicated (Section 2.13) that the STS requires activation of the core during the early stages of rising from a seated position, with active involvement of the periphery to transit from seated to standing. The STS could be a suitable alternative to gait as an outcome measure to determine whether improvements in game performance transfer to ADL.

3.4.1.6 ORDER OF TRAINING

Improvements in game play controlled by the core were not translated to improved gait function. The order of training provided to the core in the current study was based on the principles of Targeted Training. The sequential nature of Targeted Training supports the concept that selective motor control of the core is required prior to selective motor control of the periphery to perform ADL, advocating the need for peripheral training. In support Farmer *et al.* (1999) found that a child with CP, who possessed adequate control of trunk already, achieved a 15° reduction in knee flexion in response to Targeted Training on the hip and knee joint after 9 months. In support of peripheral training, Borggraefe *et al.* (2010) reported that 12 sessions of robotic-assisted treadmill therapy on the lower extremities in 20 children with CP led to improvements in functional tasks such as standing and walking. Whilst there is an abundance of research on peripheral training in children with CP (Shumway-Cook *et al.*, 2003; Woollacott *et al.*, 2005; Yonetsu *et al.*, 2010), existing VR based research predominantly trains the periphery to improve movement function in stroke patients (Holden *et al.*, 1999; Deutsch *et al.*, 2001; Merians *et al.*, 2002; Jaffe *et al.*, 2004; Merians *et al.*, 2006). Indeed, reports suggest positive functional outcomes in response to VR training on the periphery in stroke patients, but evidence in children with CP is limited. Bryanton *et al.* (2006) reported that children with CP produced increased ranges of ankle dorsiflexion in response to VR training compared to moving the ankle through its range of motion during conventional physiotherapy exercises without VR training. Yet the vast majority of VR interventions for children with CP train the upper extremities rather than the lower extremities (Snider *et al.*, 2010).

Though training the periphery alone may lead to improved functional outcomes, Targeted Training suggests that training the core followed by the periphery enables sufficient control to be developed at the more proximal body segments prior to the distal segments. In this way, essential control is developed at the core before training control at the periphery. Prior activation of the core musculature when moving the lower extremities (Hodges & Richardson, 1997b, a), or in performing ADL such as rising from a chair (Giansanti *et al.*, 2007) support the concept that adequate control of both the core and periphery is required to perform functional activities efficiently. The current VR training intervention trained selective motor control of the core only without addressing the periphery and so it is not known whether training the periphery might have led to changes in gait. The development of VR therapy for children with CP may benefit from the integration of both core- and periphery-specific training to improve functional outcomes.

3.4.1.7 SMALL PARTICIPANT NUMBERS

The small number of participants ($n = 5$) recruited for this study make conclusions based on the findings of the research lacking in evidence. Low numbers resulted in low statistical power for the randomised controlled trial. This is unfortunately the case for many CP interventions as research is dominated by single-subject design studies and uncontrolled trials with small sample groups, resulting in low quality of evidence. Effgen and McEwen (2008) conducted a systematic review of investigations of physical therapy interventions used for children with CP, amounting to 196 studies. Fifteen different types of intervention were reviewed, with none meeting the criteria for Level 1/Grade A studies (a systematic review of large, randomised control trials (Sackett *et al.*, 1996).

3.4.1.8 TRAINING FREQUENCY

Training twice a week for six weeks resulted in an improvement in physical ability to play the GPO game, but improvements did not transfer to gait. Several previous studies suggest that a similar training period can lead to improvements in ADL in children with CP. McBurney *et al.* (2003) found that a lower extremity strength training programme received by children with CP twice a week for six weeks led to improvements in performing ADL. Dodd and Foley (2007) found that treadmill training increased walking speed and walking distance in children with CP in response to 30 minutes of training twice a week for six weeks. These studies indicate that the frequency of training produced improvements over a similar period of time to that used in the current VR training intervention. Support for alternative frequency and duration of training is provided by Woollacott *et al.* (2005) who found positive changes in postural balance as a result of five days of short intensive bursts of balance training. Alternatively, You *et al.* (2005) reported that 60 minutes of training, five times a week, for four weeks resulted in improvements in upper limb function, associated with cortical reorganisation in the brain. It could be argued that a more intensive period of training in the current study would have led to greater changes in gait, and this should be taken into consideration in future interventions.

3.4.1.9 LIMITATIONS AND FUTURE DIRECTIONS

Due to difficulties in recruiting participants for the current research project, the original randomised controlled trial design was incomplete. The use of a complex laboratory based VR system to test and train children with CP required participants to attend the research laboratory at Liverpool John Moores University. However, difficulties arose with participant availability, and though parents/guardians were paid expenses for travelling to and from the research facility, participant numbers remained low. There is a need to recruit more children with CP to assess the use of VR games to train core control. Portable VR training methods that can deliver virtual rehabilitation to the child within school might lead to an increase in recruitment. It was also reported by parents and children participating in the study that use of alternative training games would avoid repetition and be more engaging for the child. For future VR training interventions the following suggestions should be considered:

- Development of a portable VR system driven by an inertial measurement unit should be used instead of video motion capture systems for virtual rehabilitation.
- Further VR game development is necessary to provide children with a wider variety of training games during game play.

3.5 Conclusion

The results of the current study suggest there may be a beneficial effect of VR games training on selective motor control of the trunk and pelvis in children with CP, evidenced by increased playing speeds. The max settled speed algorithm provided a measure of motor performance in the game and enabled monitoring of changes over time throughout training. Changes in max settled speed indicate that a cephalo-caudal reduction of control exists between the trunk and pelvis. Trunk rotation is better controlled than trunk tilt, and single plane movements outperform cross plane movements during VR game play. Coupling between the trunk and pelvis suggests selectivity not only occurs in one segment, but may occur across segments (i.e. the trunk and pelvis together). Improvements in game play did not transfer to improvements in gait as measured using the GDI, but the sensitivity of the GDI is questioned as an objective measure of gait. Future development of a portable VR system that encompasses motion capture within a child's school to test and train selective motor control of both the core and periphery could be beneficial. Assessing the transfer of VR training to an independent outcome measure related to ADL is still desirable.

Chapter 4. Capturing motion using an inertial measurement unit

4.1 Introduction

The previous study (Chapter 3) revealed a number of issues. The availability of children with cerebral palsy (CP) able to carry out VR training at the research laboratory on a twice-weekly basis was limited. Parents found it difficult to commit to travelling whilst children were unable to miss school time. A way to increase participation in VR interventions for children would involve taking VR training to the child during school time. This would reduce the burden on parents travelling to the research facility regularly, cause minimum disruption to school time for children, thereby increasing the number of parents willing to allow their child to take part in a VR intervention. Providing VR training within schools would require a portable version of the virtual environment previously used (Section 3.2.3.1). Inertial measurement units (IMU) are small devices which can be used to capture human motion, and could be used as an alternative input device to the Vicon system to drive VR game play. Successful integration into VR game play would result in a portable VR system for testing and training selective movement control in children with CP within schools. In addition to driving VR game play, the IMU is capable of capturing human movement during activities of daily living (ADL).

The aim of this study was to determine the suitability of an IMU for controlling VR game play and assessing movement during ADL. The angular displacement and accelerations produced by an IMU are important for determining changes in performance of ADL, and an IMU should provide the same VR game play experience as that produced by a video motion capture system.

4.1.1 Objectives

1. Validate angular displacement of the IMU over controlled ranges of motion (Experiment One).
2. Validate accelerations produced by the IMU over a controlled displacement (Experiment Two).
3. Compare the performance of the IMU and video motion capture system during VR game play (Experiment Three).
4. Assess the application of the IMU for measuring the Sit-to-Stand (Experiment Four).

4.2 Experiment One: Measurement of angular displacement

4.2.1 Protocol

Experiment One was designed to quantify the magnitude of error in angular displacement between the Xsens sensor and Vicon motion capture system. A controlled motion stimulus was provided by a hydraulically actuated moving platform (Bosch Micromotion 600 (CAREN system), Motek, Amsterdam, The Netherlands), driven by a sine wave at a frequency of 1 Hz about three individual axes; X, Y and Z, providing a peak to peak amplitude of 30°. This range was chosen based on the viable working range of the moving platform (Lees *et al.*, 2007), and replicates the largest angular displacement required at the selected joints of the body by the VR games. Three separate durations for the trials were selected (one, two, and three minutes) to test whether the Xsens sensor output remained stable over a specific time period (Section 2.15.3). The trials aimed to replicate the length of time children typically play our custom made computer games during training sessions. Data were simultaneously captured using a Vicon opto-electronic motion capture system and an Xsens MTx Sensor for comparison of the kinematic output provided by each hardware device.

4.2.2 Instrumentation

One Xsens sensor, connected to the CAREN computer via USB 2, was attached to the platform surface. Three reflective markers were placed on the platform to create a right-handed co-ordinate system. The global co-ordinate system for each device is depicted in Figure 30(a). The original co-ordinate systems for each hardware device (Vicon, CAREN, and Xsens) were aligned to match each other using the CAREN system's user interface, and all rotations relate to the right-hand co-ordinate system used by CAREN, illustrated in Figure 30(d). The terms used to describe rotation about the rotational degrees of freedom were Roll (Z axis), Pitch (X axis) and Yaw (Y axis). A Vicon motion capture system consisting of eight high-resolution 16-megapixel cameras (T160) controlled by Vicon Nexus software version 1.4.1.144 was used to capture the 3D location of each reflective marker at a sampling rate of 100 Hz. The CAREN system software recorded the Xsens sensor output at 200 Hz.

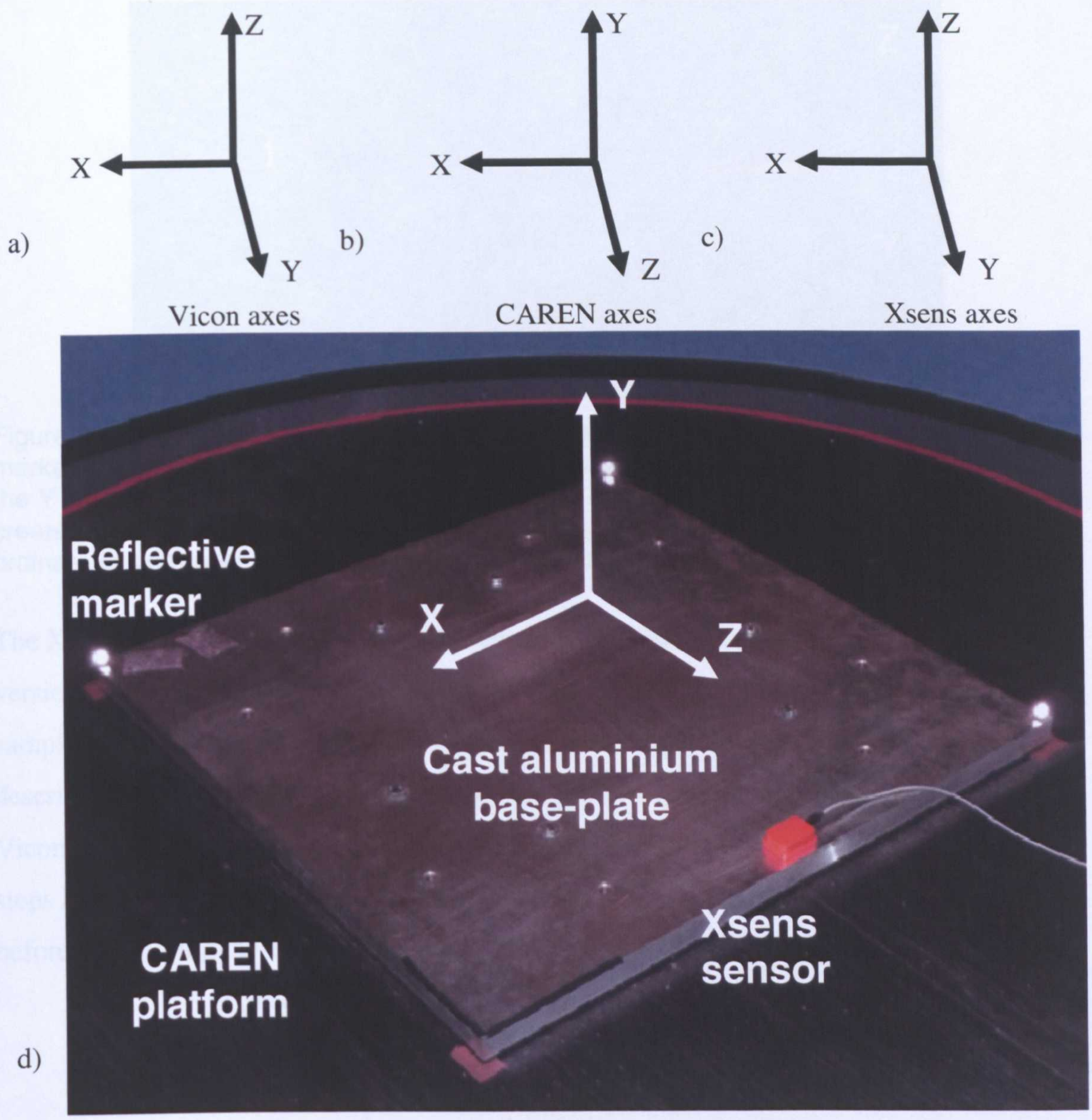


Figure 30. a) The global right-hand co-ordinate system for the Vicon, CAREN, and Xsens devices. b) The Xsens sensor and reflective markers were positioned on a cast aluminium base-plate bolted to the CAREN platform. All co-ordinate systems have been aligned to follow the right-hand Cartesian co-ordinate system of the CAREN device.

4.2.3 Data Processing

Visual 3D (C-Motion, USA) calculated the angular displacement from the marker data recorded by Vicon. The model function in Visual3D was used to build a local co-ordinate system with its origin at marker 2 (Figure 31). The X axis was aligned with marker 1, pointing laterally, the Y axis was aligned with marker 3, pointing in a posterior direction, and the Z axis was created perpendicular to X and Y, pointing in a superior (upwards) direction. Angular displacement was calculated as the angle of the local co-ordinate system relative to the laboratory's global co-ordinate system. Vicon data were low-pass filtered with a 2-pole 6 Hz Butterworth digital filter, 2 passes were used to produce a zero phase shift, before exporting the data to text format in order to carry out further processing.

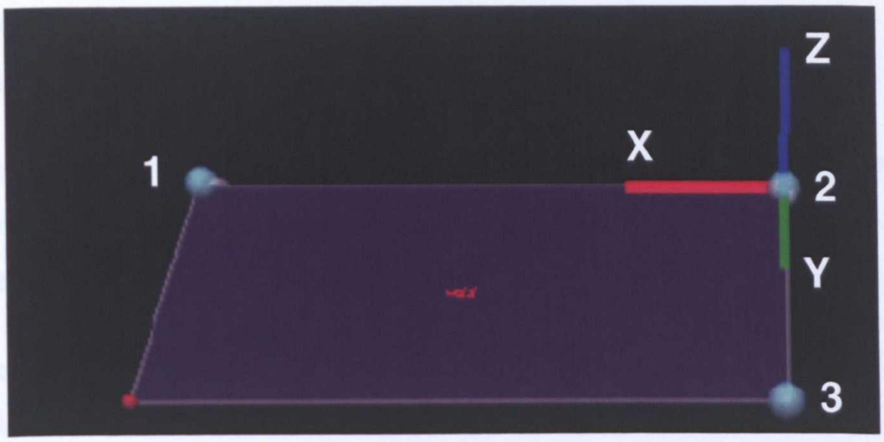


Figure 31. The local co-ordinate system attached to the base plate using three reflective markers. Marker 2 was the origin, the X axis was aligned with marker 1 pointing laterally, the Y axis was aligned with marker 3 pointing in a posterior direction, and the Z axis was created perpendicular to X and Y, pointing in a superior direction. Axes of the global co-ordinate system were in the same arrangement as the local co-ordinate system.

The Xsens data captured using the CAREN system were processed using MATLAB version 7.10 (MathWorks, UK). The Xsens data were re-sampled at 100 Hz to match the sampling frequency of the Vicon Nexus output and then filtered using the procedure described above (Section 4.2.3). There were arbitrary time and angle offsets between the Vicon and Xsens data because the respective zero points were not aligned. The following steps highlight the second stage of processing for all signals to account for the offsets, before quantifying the error:

1. Using the Vicon data as a reference signal, cross-correlation was used to quantify the time offset between signals.
2. The Xsens data captured in CAREN were then shifted in time using the time offset value, so that they matched the Vicon reference data starting point (Figure 32(c)).
3. Any bias (zero offset) present between the signals was corrected prior to comparison using the linear regression function in MATLAB. The offset between each Xsens signal relative to its comparative Vicon reference signal was calculated as the point at which the linear regression line intercepted the Y-axis.

4. Magnetic disturbance from the CAREN platform meant that there was a large amount of drift about the vertical axis (Yaw) in Xsens sensor output. This drift was systematic, possibly due to distortion of the Earth's magnetic field by steel in the moving platform, with a linear change in amplitude over time. As a result of this, a trend-line correction was applied to all data recorded about the Y axis, performed

in MATLAB. Figure 33 illustrates the change in signal as a result of the correction.

5. The angular errors between the Vicon reference signal and each CAREN signal were calculated by subtracting the Xsens signal from its corresponding Vicon reference signal (Figure 32(d)).

6. The standard deviation of the angular error was calculated as a measure of the residual error between the two signals.

4.2.4 Statistical Analysis

All signals were compared using root mean squared (RMS) error (ε) and Pearson's correlation coefficient (*r*) in MATLAB. Values for *ε* and *r* across all trials are reported, in addition to RMS error expressed as a percentage of the maximum range of motion (ε %).

4.2.5 Results

Root mean squared error and Pearson's correlation coefficient are presented in Table 4. Figure 32 demonstrates the stages of processing in MATLAB. Low RMS error values ($\varepsilon <= 0.38°$) and strong correlations ($r >= 0.9906$) exist between Vicon reflective marker output and Xsens sensor output for all time durations when rotating about separate axes. The highest RMS error ($\varepsilon = 0.38°$) occurred over a three minute period about the X axis (Pitch), whilst the smallest RMS error ($\varepsilon = 0.20°$) was apparent for the duration of two minutes about the Z axis (Roll). Errors occurring in the Y axis (Yaw) were concurrent with the errors produced about the X and Z axis. The error between both systems accounted for less than 1.27% of the total range of motion. There is no evidence to suggest that less error or a stronger relationship exists between the Vicon and Xsens sensor output for any particular axis of rotation over a specific time duration.

Table 4. Comparing Vicon angular displacement to Xsens sensor angular displacement over a one, two or three minute period rotating about X, Y or Z. The RMS values (ε), Pearson's correlation coefficient (*r*) and RMS as a percentage of the maximum range of motion (ε %) are presented.

Duration and direction of rotation	**Vicon VMC system versus Xsens sensor**		
	ε (°)	**r**	**ε %**
1 minute Rot X (Pitch)	0.29	0.9973	0.98
2 minute Rot X (Pitch)	0.30	0.9942	1.00
3 minute Rot X (Pitch)	0.38	0.9906	1.27
1 minute Rot Y (Yaw)	0.27	0.9996	0.92
2 minute Rot Y (Yaw)	0.35	0.9994	1.17
3 minute Rot Y (Yaw)	0.31	0.9996	1.03
1 minute Rot Z (Roll)	0.31	0.9997	1.02
2 minute Rot Z (Roll)	0.20	0.9999	0.67
3 minute Rot Z (Roll)	0.35	0.9996	1.16

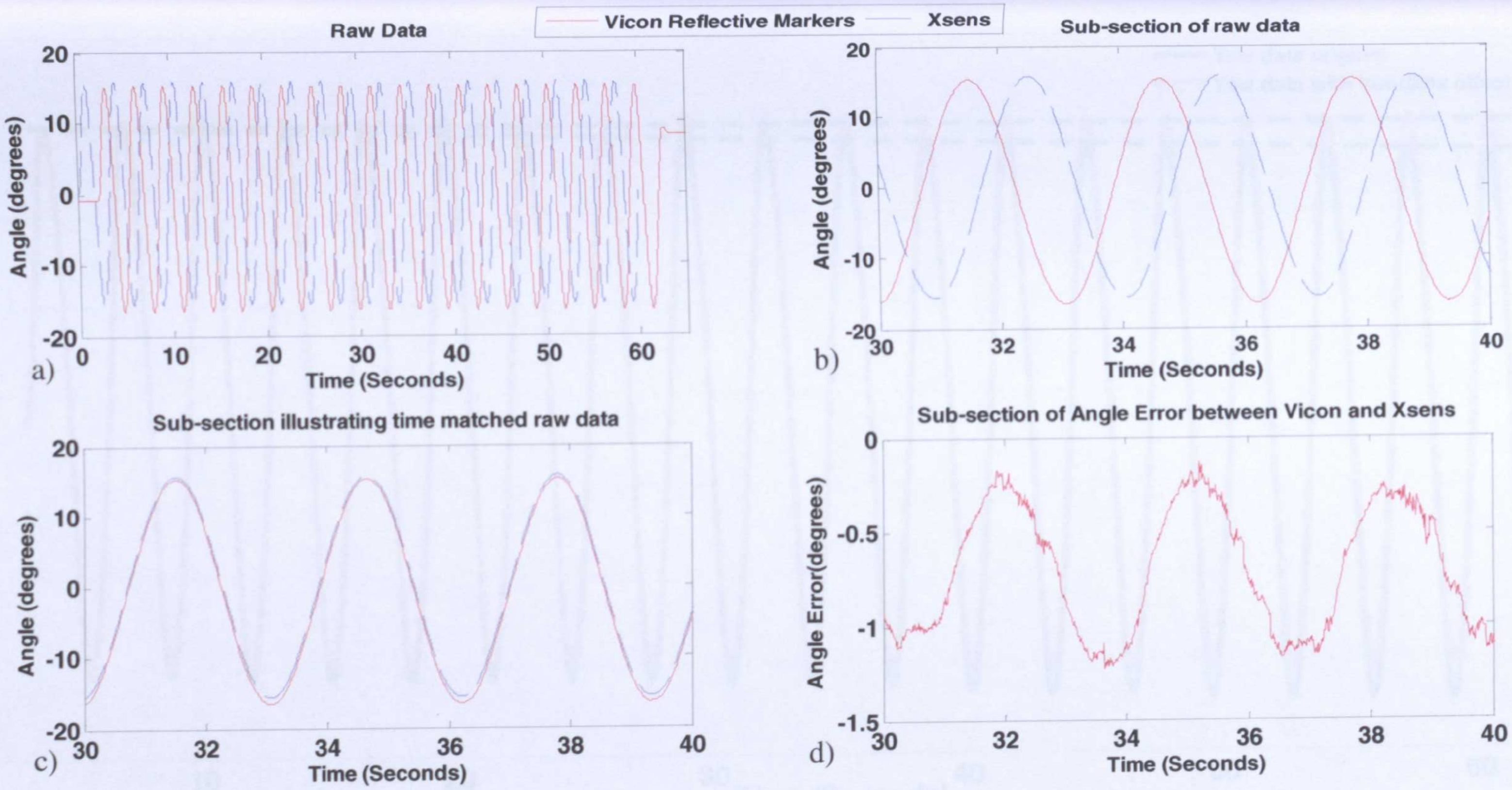


Figure 32. An example visual explanation of the post-processing that is carried out on Vicon and Xsens data in MATLAB. a) The raw Vicon and Xsens signals are plotted alongside each other. b) A time lag exists between the two signals for a sub-section of data (30-40 s). c) A sub-section of the data (30-40 s) corrected for time lag. d) The residual angle error (°) between the Vicon and Xsens signals for a sub-section of the data (30-40 s).

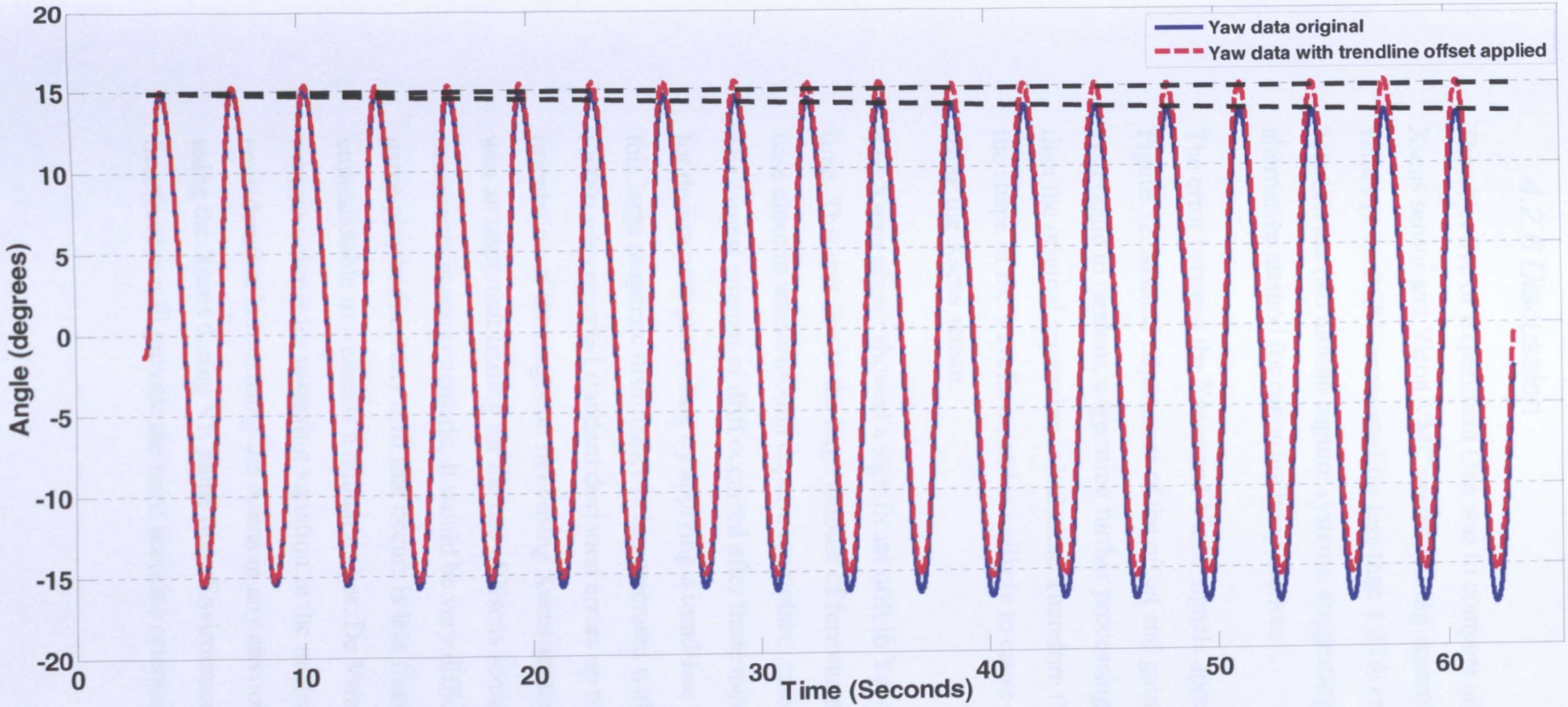


Figure 33. Xsens sensor Yaw output pre- and post-processing in MATLAB. The blue line indicates the original signal affected by the surrounding magnetic environment in the laboratory. After applying a trend-line correction offset over time, the red line indicates the corrected signal without drift. The horizontal black dashed lines represent the change in trend-line as a result of the correction being applied.

4.2.6 Discussion

The objective of Experiment One was to compare angular displacement recorded by the Xsens sensor and Vicon VMC system during controlled ranges of motion. Low RMS error values ($\varepsilon <= 0.38°$) accounted for less than 1.27% error over 30° range of motion evident between the two motion capture systems, suggesting the Xsens sensor could be used as an alternative method for capturing body motion.

The error between the Xsens and Vicon signals appeared to be systematic, as shown in Figure 32. Manual adjustment of the offset and gain altered the error signal from systematic to random, suggesting further processing was able to match the signals better than the original regression calculation. Therefore the apparent systematic error was due to the shape of the waveform, and is unlikely to cause a large change to VR game play when using the Xsens sensor.

The Xsens sensor showed a significant drift in Yaw angle which was a linear function of time. This was due to the large amount of ferromagnetic material in the CAREN platform's base close to where motion capture took place, causing considerable magnetic disturbance. The largest amount of drift occurred after three minutes (~12°), but this could be corrected for during post-processing by applying a trend-line correction offset over time. Evidence of this large magnetic disturbance is in agreement with similar findings by De Vries *et al.* (2009) who reported standard deviation errors up to 29° at floor level when measuring the orientation of the magnetic field using Xsens sensors. The effect of magnetic disturbance was an important finding for the use of Xsens sensors in VR game play because human movement is not systematic. It would be very difficult to apply any offsets during VR game play because any drift that occurs is less likely to form a linear relationship with the unpredictable movements a human makes. De Vries *et al.* (2009) suggest mapping the capture volume for assessing variation in the magnetic field should be taken into consideration before using the Xsens in any environment. This should be adhered to before using the Xsens during VR game play. Environments containing the least magnetic interference will provide the most accurate orientation output.

4.3 Experiment Two: Measurement of linear acceleration

4.3.1 Protocol

The study was designed to quantify the magnitude of error in acceleration between an Xsens sensor and a Vicon system. Both systems were moved together and recorded simultaneously in order to compare accelerations. The CAREN platform was driven by a sine wave with an amplitude of ±10 mm at a frequency of 1.3 Hz in the X axis, 1.5 Hz in the Z axis, and 2.2 Hz in the Y axis. Frequencies were chosen that did not attenuate the displacement of the platform during the trial, which can occur as a result of poor high frequency response of the hydraulic drive system. The sine wave amplitude was chosen to produce low accelerations matching those which may occur as a result of performing ADL. For each axis the trial duration was 180 seconds in order to measure the consistency of acceleration output over periods of time commensurate with those of game play. Data was captured simultaneously using a Vicon system (Oxford Metrics, UK) and one Xsens MTx Sensor (Xsens Technologies, Netherlands) for comparison of the acceleration output provided by each device. Research by Thies *et al.* (2007) compared acceleration output of the Xsens sensor to a Vicon system, and so the results of this study provided a direct comparison to their previous findings.

4.3.2 Instrumentation

The set up that was used in Experiment One (Section 4.2.2) was replicated for Experiment Two (Figure 30). A Vicon system captured the 3D position of each reflective marker at a sampling rate of 100 Hz. The CAREN system recorded Xsens sensor output at 200 Hz, within a working bandwidth of 30 Hz (Xsens Technologies). Accelerations and linear displacement were captured along each axis of the CAREN co-ordinate system for the Xsens and Vicon system respectively.

4.3.3 Data Processing

All reflective marker data captured using Vicon software (Vicon Nexus) were processed using Visual3D (C-Motion, USA), to calculate acceleration for each trial. The same local co-ordinate system outlined in Experiment One was used (Figure 31). Displacement of the markers was calculated as the change in displacement of the local co-ordinate system relative to the laboratory's global co-ordinate system. Subsequently, accelerations based on the marker displacement were calculated using double differentiation in Visual 3D, before exporting the data to text format in order to carry out further processing. Xsens sensor data captured using the CAREN system was re-sampled at 100 Hz to match the sampling frequency of the Vicon system, using MATLAB (Math-Works, USA).

The following steps detail the stages of signal processing:

1. The sine wave data for each device was filtered at 5 Hz with a 2-pole Butterworth digital filter which uses a 2-pass procedure to produce a zero phase shift. The cut-off frequency was chosen such that there was no attenuation of the acceleration signal.

2. Using the Vicon data as a reference signal, cross-correlation was used to quantify the time offset between the signals.

3. The Xsens sensor data captured in CAREN were then shifted in time using the time offset value, so that they matched the Vicon reference data starting point (Figure 34(c)).

4. Any bias (zero offset) present between the signals was corrected for before comparison using the linear regression function in MATLAB. This is required for signals with arbitrary zero points. The offset between each Xsens signal relative to its comparative Vicon reference signal was calculated as the point at which the linear regression line intercepted the Y-axis. The resulting offset was then subtracted from the Xsens signal (Figure 34(c)).

5. The error between accelerations measured by Vicon and the Xsens sensor was calculated by subtracting the Xsens signal from its comparable Vicon reference signal (Figure 34(d)).

6. The standard deviation of the error was calculated to quantify the magnitude of error between the two signals.

4.3.4 Statistical Analysis

All signals were compared for offset, gain, coefficient of determination (r^2), residual error (RMS error (ε)), and residual error as a percentage of peak accelerations that occurred in each axis (ε %).

4.3.5 Results

The descriptive statistics relating to the comparison of signals are presented in Table 5. Low RMS error values ($\varepsilon <= 0.12 m.s^{-2}$) and high coefficients of determination ($r^2 >= 0.9893$) were found between the Vicon and Xsens sensor acceleration output for all three axes. RMS errors between Vicon and the Xsens sensor accounted for less than 5.23% of the peak accelerations recorded during all sine wave trials. Small offsets ($<=0.0310 m.s^{-2}$) and high gains (>=0.9815) indicate that there was a strong match between the Vicon and Xsens sensor signals across all trials. Figure 34 demonstrates the stages of processing that were applied to the data in MATLAB. The error between Vicon and Xsens was systematic throughout the 180 second period, ranging between $-0.2m.s^{-2}$ and $0.2m.s^{-2}$ (Figure 34(d)). Therefore the RMS error provides a good representation of the residual error between both measuring devices. Figure 35 shows an example of the strong relationship between the signals recorded by Vicon and Xsens, with residual error $<0.5 m.s^{-2}$ when the greatest error between signals occurs.

Table 5. Comparing Vicon derived accelerations to Xsens sensor accelerations when displacement occurred along the X, Y or Z axis. Offset, gain, coefficient of determination (r^2), residual error (RMS error (ε)), and residual error as a percentage of peak accelerations that occurred in each axis (ε %) are presented.

Input to platform	**Vicon versus Xsens derived accelerations**				
	Offset ($m.s^{-2}$)	**Gain**	**r^2**	**ε ($m.s^{-2}$)**	**ε %**
Sine wave X	0.0166	0.9965	0.9893	0.07	5.23
Sine wave Y	0.0356	0.9997	0.9924	0.12	4.62
Sine wave Z	0.0310	0.9815	0.9915	0.06	4.63

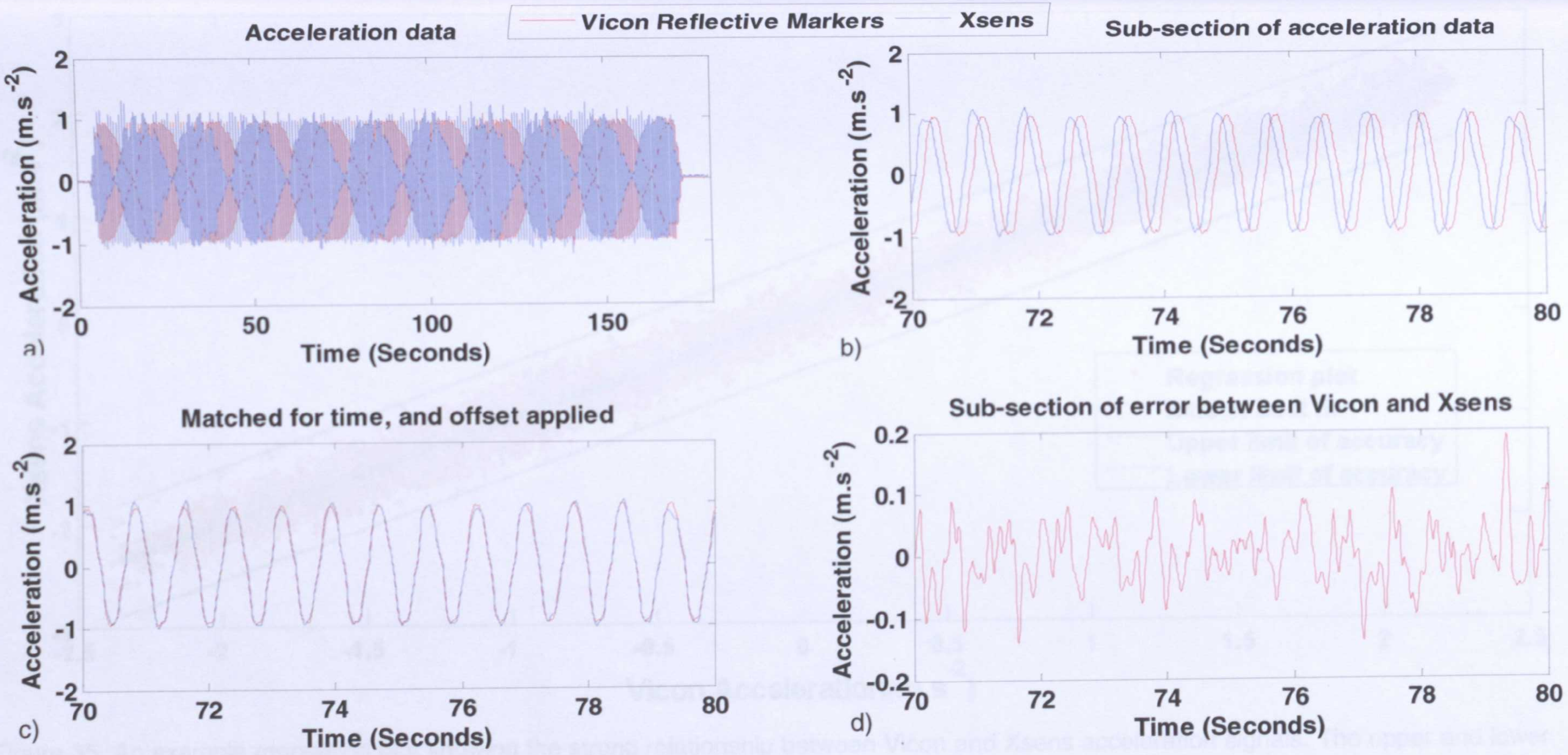


Figure 34. An example visual explanation of the post-processing that is carried out on Vicon and Xsens data in MATLAB for sine wave accelerations. (a) The full length of raw Vicon and Xsens signals were plotted alongside each other. (b) The time lag and offset is illustrated between the two signals for a sub-section of data (70-80 s). (c) A sub-section of the data (70-80 s) after correcting for time, and with the offset applied. (d) The error between the Vicon and Xsens signals for the same sub-section of the data (70-80 s).

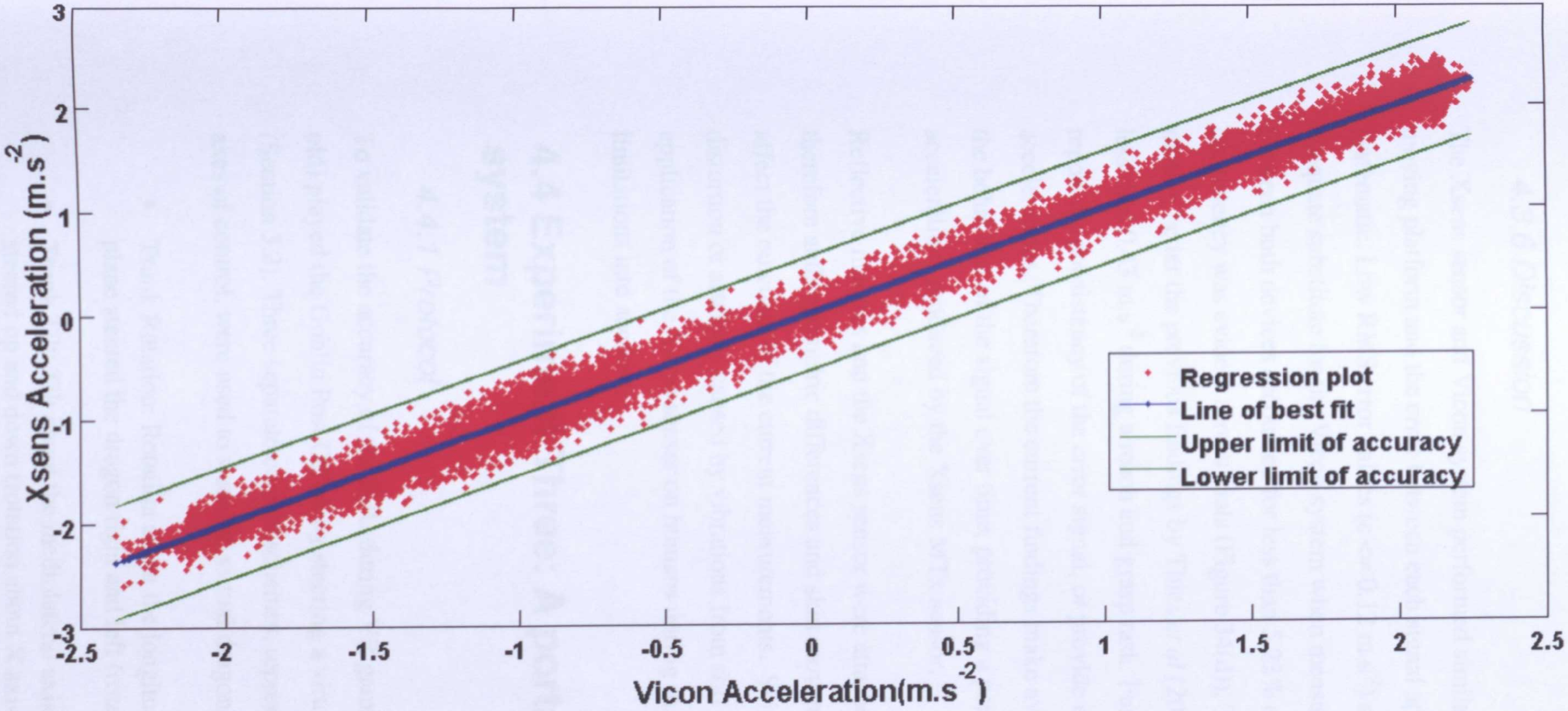


Figure 35. An example regression plot showing the strong relationship between Vicon and Xsens acceleration signals. The upper and lower limits of accuracy represent the residual error (0.5 m.s^{-2}) from the line of best fit.

4.3.6 Discussion

The Xsens sensor and Vicon system performed similarly for accelerations produced by the moving platform and the error between each signal appeared to be random rather than systematic. Low RMS error values ($\varepsilon <= 0.12\ m.s^{-2}$) suggest that the Xsens sensor is an adequate substitute for the Vicon system when measuring acceleration. The RMS error between both devices accounted for less than 5.23% of peak accelerations, and good consistency was evident across trials (Figure 34(d)). The errors reported during sine wave motion better the previous findings by Thies *et al* (2007), who reported an RMS error of less than $0.43\ m.s^{-2}$ during a reach and grasp task. Furthermore, Thies *et al.* (2007) did not report the consistency of the error signal, or provide error as a percentage of peak accelerations. Therefore the current findings make available important details concerning the behaviour of the signal over time, providing a potential baseline for the accuracy of accelerations produced by the Xsens MTx sensor.

Reflective markers and the Xsens sensor were attached to the same rigid platform, therefore anthropometric differences and skin movement or soft tissue artefacts did not affect the outcome of the current measurements. Skin mounted sensors can produce signal distortion or artefacts caused by vibrations from soft tissue and skin, therefore future application of the Xsens sensor on humans during in motion capture should take these limitations into account.

4.4 Experiment Three: A portable virtual reality system

4.4.1 Protocol

To validate the accuracy of the IMU during VR game play, one male participant (22 years old) played the Goblin Post Office by steering a virtual dragon through a virtual cave (Section 3.2). Three separate control schemes, representing rotations about the two main axes of control, were used to steer the virtual dragon during game play;

- Trunk Rotation: Rotation about the longitudinal axis of the trunk in the transverse plane steered the dragon right and left (rotation about Y axis of IMU).
- Trunk Tilt: Tilt about the mediolateral axis of the trunk in the sagittal plane steered up and down (rotation about X axis of IMU).

- Trunk Both: A combination of trunk rotation and trunk tilt together moved the dragon about an oblique axis so that cross plane movements were required (rotation about X and Y axis of IMU simultaneously).

Three trials lasting 3 minutes each were collected for each control scheme. This represented the longest time period a single VR trial would last during training. Ethical approval for the study was granted by Liverpool John Moores University Research Ethics Committee.

4.4.2 Instrumentation

One Xsens sensor and a cluster of three retro-reflective markers were attached to a cardboard template that was placed on the trunk, over the spinous process of the eighth thoracic vertebra (T8) (Figure 36). The reflective markers were used to steer the virtual dragon through the Goblin Post Office virtual cave, whilst the Xsens sensor registered the movement of the trunk for comparison. A Vicon motion capture system was used to stream live reflective marker data into the CAREN computer during VR game play. The CAREN system registered the position of the three retro-reflective markers using its internal 'MoCap' module, and converted the 3D positions of the markers into rotation using a 'Rotation' module, which in turn controlled the frontal plane speed (position) of the virtual dragon. Reflective marker data were recorded in Vicon Nexus, and Xsens sensor data were simultaneously recorded by the CAREN software. The kinematic output produced by both the Vicon and Xsens device was used to compare accuracy of the Xsens system.

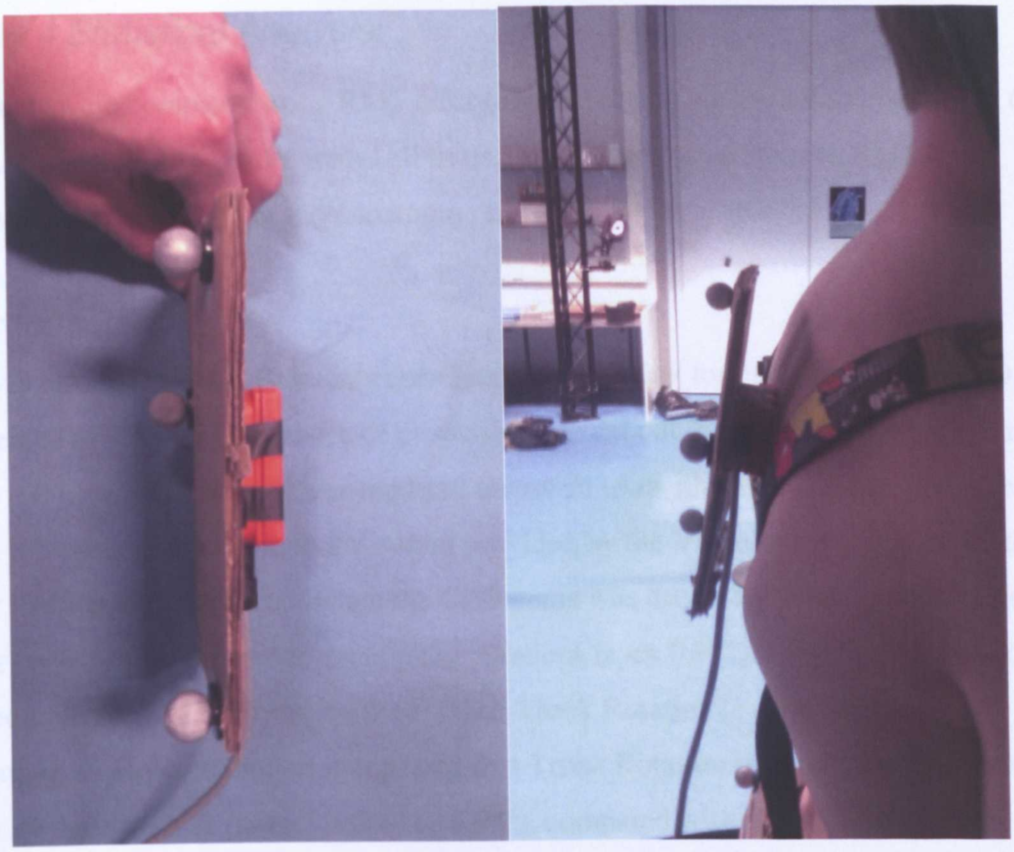


Figure 36. The Xsens sensor is taped to a rigid cardboard template, and three reflective markers are also placed on the template in an arrangement devised for the Goblin Post Office. The Xsens sensor follows the exact movement of the markers when recording trunk motion in order to compare the data from Vicon and the Xsens sensor.

4.4.3 Processing

All marker data captured using Vicon software (Vicon Nexus) were processed using Visual3D (C-Motion, USA), to provide angular displacement of the trunk during each Goblin Post Office trial. The Vicon data were filtered using the procedure described previously (Section 4.2.3). The Xsens sensor data captured using CAREN were re-sampled to 100 Hz in MATLAB, to match the sampling frequency of the Vicon Nexus output. Both the Vicon reflective marker data and Xsens sensor data were then compared to quantify the error between the two methods of capturing motion. The processing steps used to compare Vicon and Xsens data in Experiment One were repeated in Experiment Three, with the only addition being an intermediate step (3a) between stages 3 and 4, as follows:

3. (a) After matching the signals for time, the Vicon data were truncated at the beginning and end to match the number of data points to the Xsens data. Equal vector lengths of the two sets of data were necessary to be able to calculate bias.

4.4.4 Statistical Analysis

All signals were compared using RMS error (ε) and Pearson's correlation coefficient (*r*) in MATLAB. Values for *ε* and *r* across all trials are reported, in addition to RMS error expressed as a percentage of the maximum range of motion.

4.4.5 Results

All RMS error values and Pearson's correlation coefficients for each trial of the GPO are represented in Table 6. The stages of processing carried out in MATLAB are shown in Figure 37. Low RMS error values reported across all trials illustrate that the Xsens sensor output is closely comparable to the output provided by the Vicon motion capture system. Lower RMS error values exist when the GPO game was driven by single plane rotations only ($\varepsilon <= 0.39°$), compared to cross plane rotations ($\varepsilon <= 0.97°$). Specifically, Trunk Tilt resulted in lower RMS error ($\varepsilon <= 0.16°$) than Trunk Rotation ($\varepsilon <= 0.39°$). When performing cross plane motion it appeared that Trunk Rotation resulted in greater error across all three trials (ε (range) = 0.44 to 0.97°), compared with Trunk Tilt (ε (range) = 0.16 to 0.19°) (Table 6). Considering both single plane and cross plane rotations together, there is greater consistency in the error produced about the sagittal axis, indicated by lower variability in output ($\varepsilon = 0.16 \pm 0.02°$) as opposed to the longitudinal axis of the trunk ($\varepsilon = 0.50 \pm 0.25°$). For comparison between all single plane rotations and cross plane rotations, very high correlation coefficients ($r >= 0.9912$) were obtained for all trials.

Table 6. Comparing the performance of the Xsens sensor and Vicon VMC system during GPO game play. All three trials captured for each control scheme are represented in the table, with RMS error expressed as an angle (ε °), Pearson's correlation coefficients (*r*) and RMS error as a percentage of the maximum range of motion (ε %).

Duration & direction of rotation	Vicon System versus Xsens sensor					
	εX (°)	εY (°)	r X	r Y	εX (%)	εY (%)
Trunk Tilt 1	0.17	-	0.9997	-	0.35	-
Trunk Tilt 2	0.14	-	0.9998	-	0.25	-
Trunk Tilt 3	0.14	-	0.9998	-	0.26	-
Trunk Rotation 1	-	0.31	-	0.9991	-	0.62
Trunk Rotation 2	-	0.29	-	0.9993	-	0.44
Trunk Rotation 3	-	0.39	-	0.9983	-	0.64
Trunk Both 1	0.16	0.44	0.9992	0.9970	0.39	0.73
Trunk Both 2	0.19	0.59	0.9991	0.9966	0.55	0.86
Trunk Both 3	0.18	0.97	0.9994	0.9912	0.68	2.32

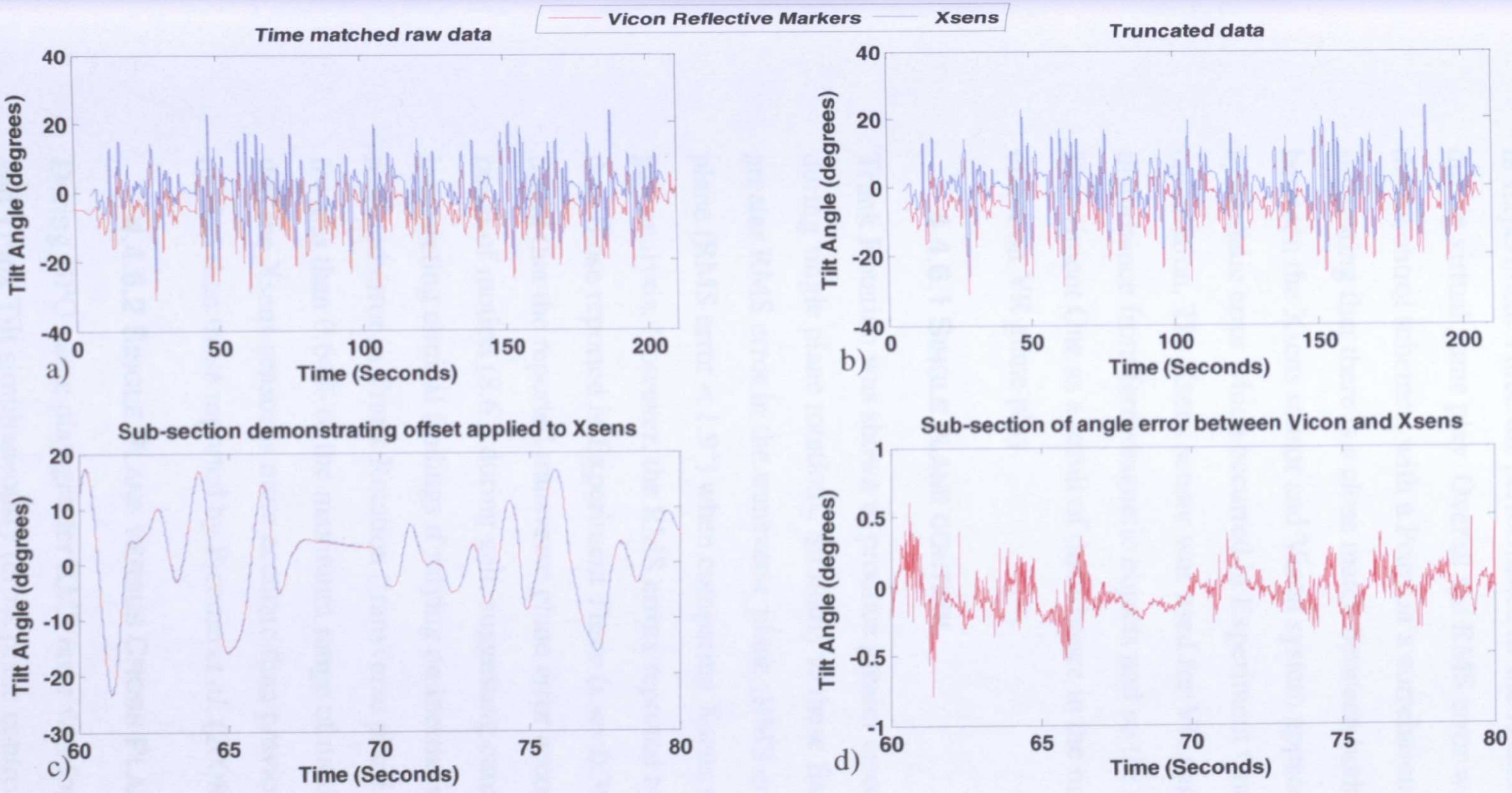


Figure 37. A visual explanation of the post-processing that was carried out on Vicon and Xsens data in MATLAB in order to compare the two methods during game play. a) The Vicon and Xsens signals were plotted alongside each other, corrected for time. b) The Vicon data were truncated at the beginning and end of the signal. c) A sub-section of the data (60-80s) matched after adjusting for offset. d) The residual angle error (°) between the Vicon and Xsens signal for a sub-section of the data (60-80s).

4.4.6 Discussion

In Experiment Three the performance of the Xsens sensor and Vicon system was compared during virtual game play. Overall the RMS error was less than 0.97° when considering all three control schemes, with a Pearson's correlation coefficient greater than 0.9912, suggesting that there is a close match between both motion capture systems. The error between the Xsens sensor and Vicon system appeared to be random, suggesting that the systematic error which occurred in Experiment One was the result of inaccuracy in the calculation. The Xsens sensor was used for VR game play in a volume containing little disturbance from ferromagnetic objects and so the drift affecting Yaw angle reported in Experiment One as a result of disturbance in the magnetic field was not present and had no effect on VR game play.

4.4.6.1 SINGLE PLANE CONTROL

Trunk Rotation was shown to produce greater error and lower correlations than Trunk Tilt during single plane rotations. Similarly to these findings, Picerno *et al.* (2008) found greater RMS error in the transverse plane (RMS error <3.6°) as opposed to the sagittal plane (RMS error < 1.9°) when comparing Xsens sensors to Vicon VMC system during gait analysis. However, the RMS errors reported by Picerno *et al.* (2008) are much greater than those reported in Experiment Three ($\varepsilon <= 0.39°$). Furthermore, Picerno *et al.* (2008) found that the reported transverse plane error accounted for up to 41.8% of the maximum range of motion (8.6°) during gait, suggesting careful consideration is required when interpreting clinical findings if relying on inertial sensors alone. In comparison, the reported error in Trunk Rotation (transverse plane motion) in Experiment Three accounted for less than 0.64% of the maximum range of motion (66°). The current findings suggest that the Xsens sensor is more accurate than previously reported, over larger ranges of motion than those reported by Picerno *et al.* (2008).

4.4.6.2 SINGLE PLANE VERSUS CROSS PLANE CONTROL

During GPO game play greater RMS error was found when performing Trunk Rotation and Trunk Tilt simultaneously (cross plane control) rather than individually (single plane control). The error in cross plane motion accounted for up to 2.32% of the maximum range of motion produced during game play, compared to 0.64% during single plane control. The difference in error suggests that the stability of the Xsens sensor is reduced when constantly moved about more than one axis of rotation simultaneously. One possible explanation for this may relate to the Euler rotation sequence used to calculate the angles produced by the Xsens device. It is frequently reported in the literature that for a given segment, different rotation sequences can result in different angle calculations during motion (Woltring, 1991; Karduna *et al.*, 2000; Baker, 2001). Within the CAREN software used to create the GPO game, the orientation of the Xsens sensor follows the rotation sequence Y, X, Z based on the CAREN global co-ordinate system. When matched to the Vicon global co-ordinate system, this would be the equivalent of the rotation sequence Z, X, Y. This is not concurrent with the widely accepted and used X, Y, Z sequence set out by the ISB recommendations (Wu *et al.*, 2002; Wu *et al.*, 2005), and by which the Vicon recorded measurements were processed. Karduna *et al.* (2000) reported changes in angle output up to 50° for differing rotation sequences of the scapula joint, whilst Baker (2001) suggests that using the wrong rotation sequence during analysis can lead to the wrong interpretation during clinical decision making. Therefore, since the reflective marker data and the Xsens sensor did not follow the same sequence of rotations it is possible that the error produced could be a result of the rotation sequences used.

4.4.6.3 CROSS PLANE CONTROL

During cross plane motion, Trunk Rotation (ε (range) = 0.44 to 0.97°) produced greater RMS errors than Trunk Tilt (ε (range) = 0.16 to 0.19°). The Xsens Kalman filter algorithm could have contributed to the reduced accuracy about the vertical axis. When the filter is exposed to changing magnetic environments, the filter can require some time to stabilise in the new environment. As an example, de Vries *et al.* (2009) reported periods of up to 50 s before the magnetometer output stabilised. The Kalman Filter uses information from all three sensor components (accelerometers, gyroscopes, and magnetometers), but during periods of magnetic disturbance, the sensor relies less on magnetometer readings, and more on the accelerometer and gyroscope output. As previously reported by Roetenberg *et al.* (2005), a reliance on accelerometers and gyroscopes only can lead to a drift of 10-25° after 1 minute. Therefore, less reliance on magnetometers during VR game play could have led to greater RMS error between Vicon and Xsens output. Considering the RMS error for all conditions during GPO game play is minimal ($\varepsilon <= 0.97°$), and not comparable to that reported by Roetenberg *et al.* (2005), this may not be the case. Alternatively, de Vries *et al.* (2009) suggest that using the Xsens sensor in an environment where the magnetic vector is uniform but deviating away from the starting condition can lead to a change in orientation estimation by the Kalman filter. Therefore, it is possible that a slight deviation from the starting magnetic vector during GPO game play leads to drift about the vertical axis. Therefore, when using the Xsens sensor in research, the surrounding magnetic environment must be taken into account beforehand to prevent too much interference in Xsens sensor output, as was previously reported by De Vries *et al.* (2009).

4.5 Experiment Four: Measurement of the sit-to-stand movement

An appropriate independent assessment outcome was required that could be used to measure the changes in an ADL in response to VR training within schools. The sit-to-stand movement (STS) was deemed appropriate because it requires movement of the core and periphery to perform the task. The STS also requires less time for completion than gait analysis and can be assessed using a limited number of IMUs. The Xsens sensor was used to quantify the performance of the trunk and thigh during the STS movement in a small feasibility study. The aim of the study was to assess the change in performance of the STS over three separate testing days and to assess the dependent variables that can be produced.

4.5.1 Participants

One male participant (age: 25 yrs) with no prior history of surgical intervention or musculo-skeletal injuries was recruited to take part in piloting a STS protocol using the Xsens sensor. The participant visited the Liverpool John Moores University research facility for testing on three separate days, performing five STS trials each day. Ethical approval for the study was granted by Liverpool John Moores University Research Ethics Committee.

4.5.2 Sit-to-stand protocol

The participant was asked to take a seat on a stool which was adjusted to knee height. One Xsens sensor was placed on the spinous process of the eighth thoracic vertebra (T8), enabling measuring of trunk angular displacement and accelerations during the STS. The second Xsens sensor was placed on the left thigh, and secured in position using hypoallergenic double-sided tape and cohesive bandage (firstaid4sport.co.uk). Angular displacement and acceleration of the thigh were measured. With the head and trunk held upright in the starting position, the participant was instructed to perform the STS movement at a self-selected comfortable speed whilst keeping hands folded or by the side. Five successful trials were recorded on each day. A more detailed description of the STS protocol and co-ordinate systems defined by the Xsens is described in Chapter 6.

4.5.3 Analysis of the sit-to-stand movement

A custom MATLAB program (version 7.10 (MathWorks, UK)) was written to process the raw data (Appendix 13). During processing, the Xsens signals were low-pass filtered with a 2-pole 6 Hz Butterworth digital filter using 2 passes to produce a zero phase shift. Pilot measurements evaluating use of several cut off frequencies showed that a frequency of 6 Hz was adequate for the purpose of analysing low frequency STSs without attenuating the signal. The following dependent variables were then calculated: STS duration, peak flexion and extension of the trunk segment, peak dorso-ventral and axial acceleration of the trunk, peak positive and negative resultant acceleration of the trunk, peak flexion and extension of the thigh segment, peak positive and negative resultant acceleration of the thigh.

4.5.3.1 SIT-TO-STAND DURATION

The STS movement start point was defined as the point at which angular velocity of the trunk exceeded a 5°/s threshold. The end of the STS movement was defined as the point where the angular velocity of the thigh fell below 5°/s. Angular velocity was calculated using one-point differentiation of the angular displacement signal produced by the trunk and thigh Xsens sensor. The thresholds used were based on existing research for determining the duration of the STS (Guarrera-Bowlby & Gentile, 2004; Janssen *et al.*, 2005). STS duration was obtained by subtracting the time of the STS start point from the time of the STS end point.

4.5.3.2 PEAK FLEXION/EXTENSION OF THE TRUNK AND THIGH

The neutral position of the trunk was defined at the beginning of the STS when the participant was asked to keep the head and trunk upright. Peak flexion of the trunk was defined as the maximum forward rotation of the trunk from the neutral position at any point during the STS. Peak extension was the maximum backward rotation from the neutral position during the STS.

The neutral position of the thigh was defined when the participant was seated in the start position of the STS, and is almost perpendicular to the trunk. Peak flexion of the thigh was defined as the maximum increase in downward rotation of the thigh from the starting position relative to the position of the knee joint during the STS, whilst peak extension was the maximum upward rotation from the starting position relative to the knee joint.

4.5.3.3 PEAK DORSO-VENTRAL AND AXIAL ACCELERATIONS OF THE TRUNK

Peak dorso-ventral acceleration (acceleration occurring from back to front) of the trunk was defined as the maximum acceleration along the Z axis of the Xsens sensor, whilst peak axial acceleration (acceleration occurring along the spine) was defined as the maximum change in acceleration along the Y axis.

4.5.3.4 PEAK POSITIVE AND NEGATIVE RESULTANT ACCELERATION OF THE TRUNK OR THIGH

The resultant acceleration of the trunk or thigh was the magnitude of the vector sum of acceleration in the dorso-ventral and axial directions for each segment, calculated from the magnitudes of the component accelerations using Pythagoras' theorem: $a_{resultant}=\sqrt{a_x^2 + a_y^2 + a_z^2}$ where a_x, a_y and a_z are the accelerations along the X, Y and Z axes respectively. Resultant acceleration provides an indication that accelerations produced by the sensor are accurate if the resultant acceleration during static conditions is equal to g (9.81 $m.s^{-2}$).

4.5.4 Statistical Analysis

Data were normally distributed for peak dorso-ventral and axial accelerations of the trunk, and peak positive and negative resultant accelerations of the trunk and thigh. A one-way ANOVA with a between-samples factor DAY with three levels (Day 1, 2, 3) was used to assess if there were any significant differences ($p < 0.05$) in variation of each dependent variable. STS duration, and peak flexion and extension of the trunk and thigh were not normally distributed and so a non-parametric Kruskal-Wallis with a between-samples factor DAY with three levels (Day 1, 2, 3) determined if there were any significant differences in variation for each dependent variable.

4.5.5 Results

Figure 38 and Figure 39 show the relationship between trunk angle and trunk angular velocity, and thigh angle and thigh angular velocity respectively. The STS begins at the onset of trunk flexion (Figure 38), when trunk angular velocity exceeds 5°/s, whilst the STS ends when the thigh reaches full extension and thigh angular velocity is below 5°/s (Figure 39). Plots of all trials were viewed during processing to check that the algorithm was working properly.

4.5.5.1 GENERAL FORM OF THE SIT-TO-STAND MOVEMENT

The trunk was the first segment to move during the STS for all trials recorded, by flexing forward over the thigh, before extending as the body was propelled into a standing posture. The thigh started from a horizontal orientation and became more upright as the buttocks lifted off the seat prior to the trunk beginning to move in a posterior direction (Figure 40). Peak thigh flexion occurs in the start position of the STS, and Figure 40 demonstrates that there was minimal movement throughout the initial stages where trunk movement occurs. This confirms that the Xsens sensor remained stable. The thigh reached peak extension at the end of the STS (Figure 40). Dorso-ventral acceleration of the trunk always showed a distinctive positive peak which occurred during the period of trunk flexion, followed by axial acceleration of the trunk as the thigh began to extend (Figure 41). The trunk's resultant acceleration (Figure 41) tended to peak when maximum trunk flexion and dorso-ventral trunk acceleration occurred. Peak trunk negative resultant acceleration was synchronous with maximum thigh extension and axial trunk acceleration. Thigh acceleration in the dorso-ventral direction changed from 0 $m.s^{-2}$ to g 9.81 $m.s^{-2}$ due to the Xsens sensor rotating about the mediolateral axis of the global co-ordinate system during the STS (Figure 42). The point at which peak positive and negative resultant accelerations occurred during the STS differed between trials.

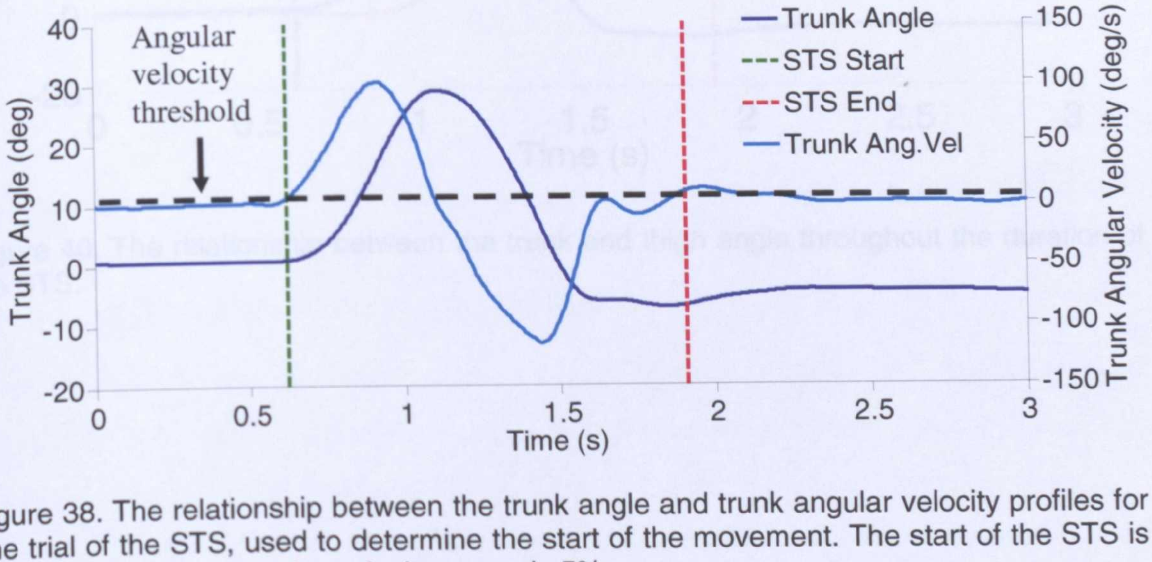


Figure 38. The relationship between the trunk angle and trunk angular velocity profiles for one trial of the STS, used to determine the start of the movement. The start of the STS is the point where the angular velocity exceeds 5°/s.

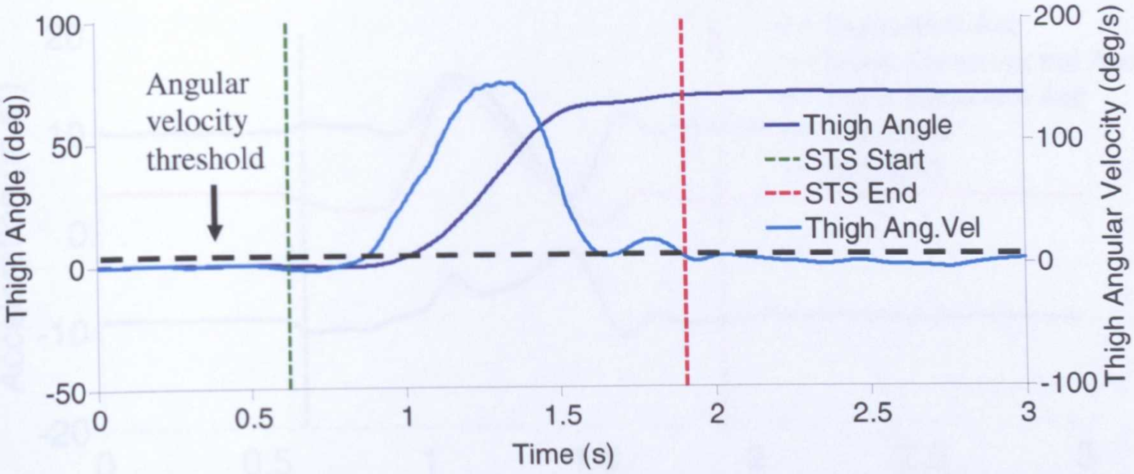


Figure 39. The relationship between thigh angle and thigh angular velocity profiles for one trial of the STS, used to determine the end of the movement. The end of the STS is determined when the angular velocity threshold is below 5°/s.

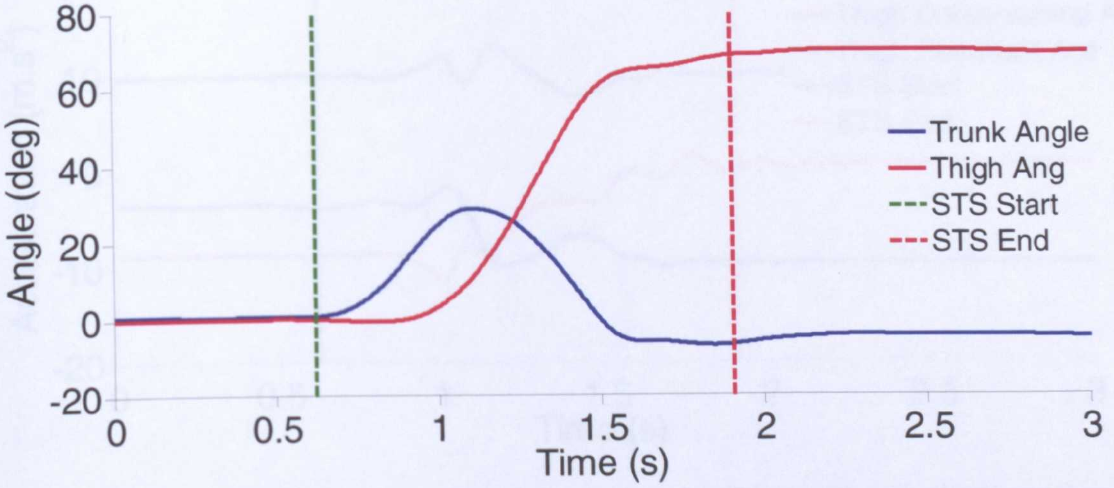


Figure 40. The relationship between the trunk and thigh angle throughout the duration of the STS.

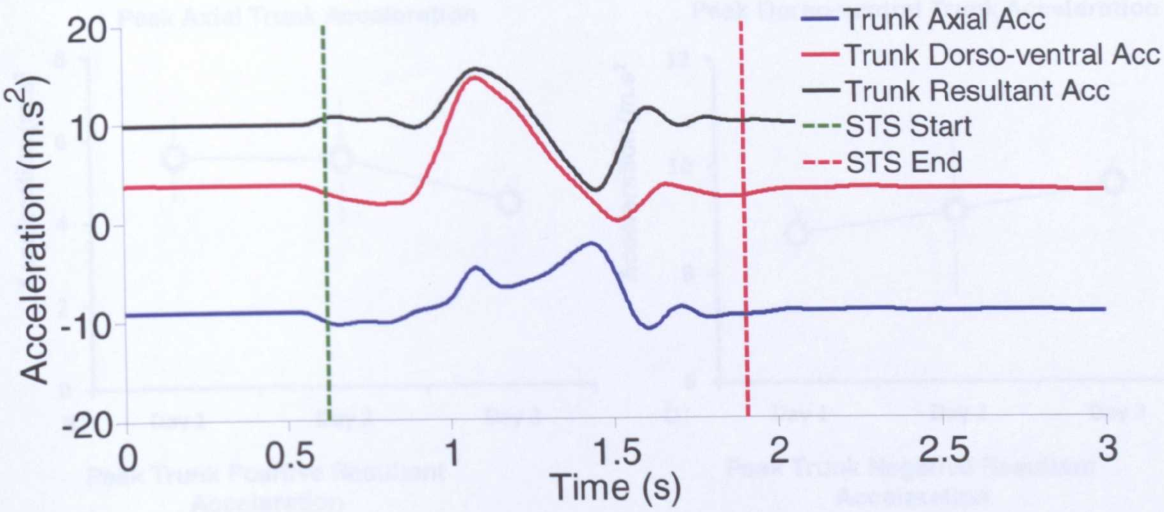


Figure 41. The axial and dorso-ventral trunk accelerations with resultant acceleration profile throughout the STS.

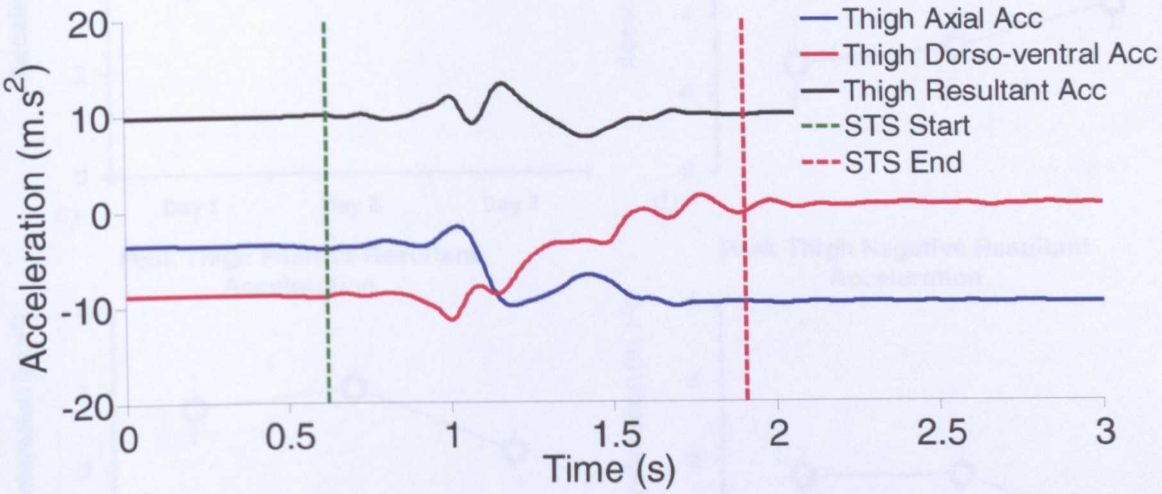


Figure 42. The axial and dorso-ventral thigh accelerations with resultant acceleration profile throughout the STS.

4.5.5.2 SIT-TO-STAND DEPENDENT VARIABLES

Statistical analysis revealed that there were no significant differences in variation between days for STS duration (Figure 44(a)), peak flexion and extension of the trunk (Figure 44(b & c)), peak dorso-ventral and axial accelerations of the trunk (Figure 43(a & b)), and peak positive and negative resultant accelerations of the trunk (Figure 43(c & d)) ($p > 0.05$). Significant differences in variation between days were evident for peak flexion and extension of the thigh (Figure 44(d & e)), and peak positive and negative resultant accelerations of the thigh (Figure 43(e & f)) ($p < 0.05$).

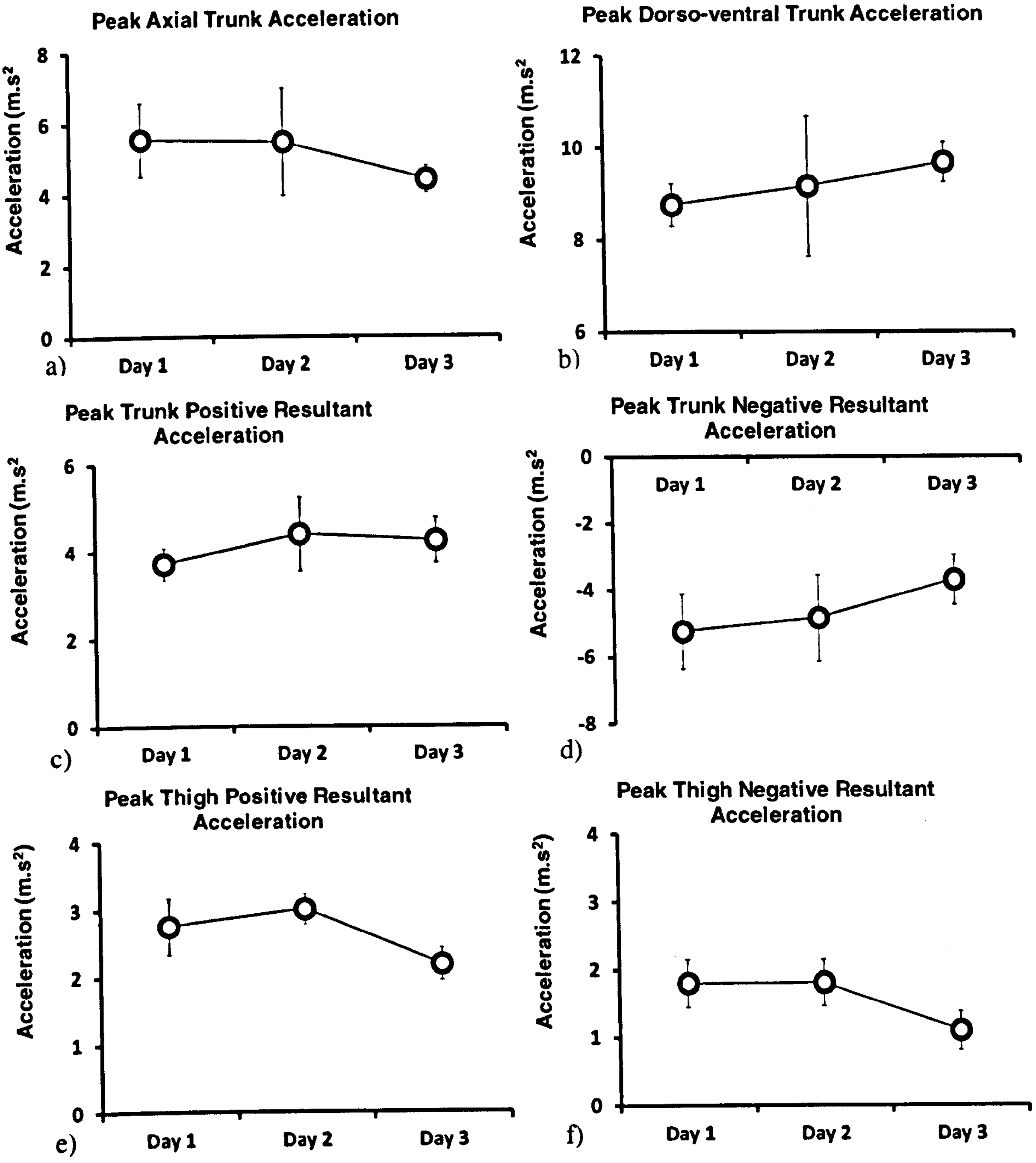


Figure 43. Dependent variables of the STS on day 1, day 2, and day 3 of testing, which were all normally distributed. Error bars represent the variation on each day for the dependent variables.

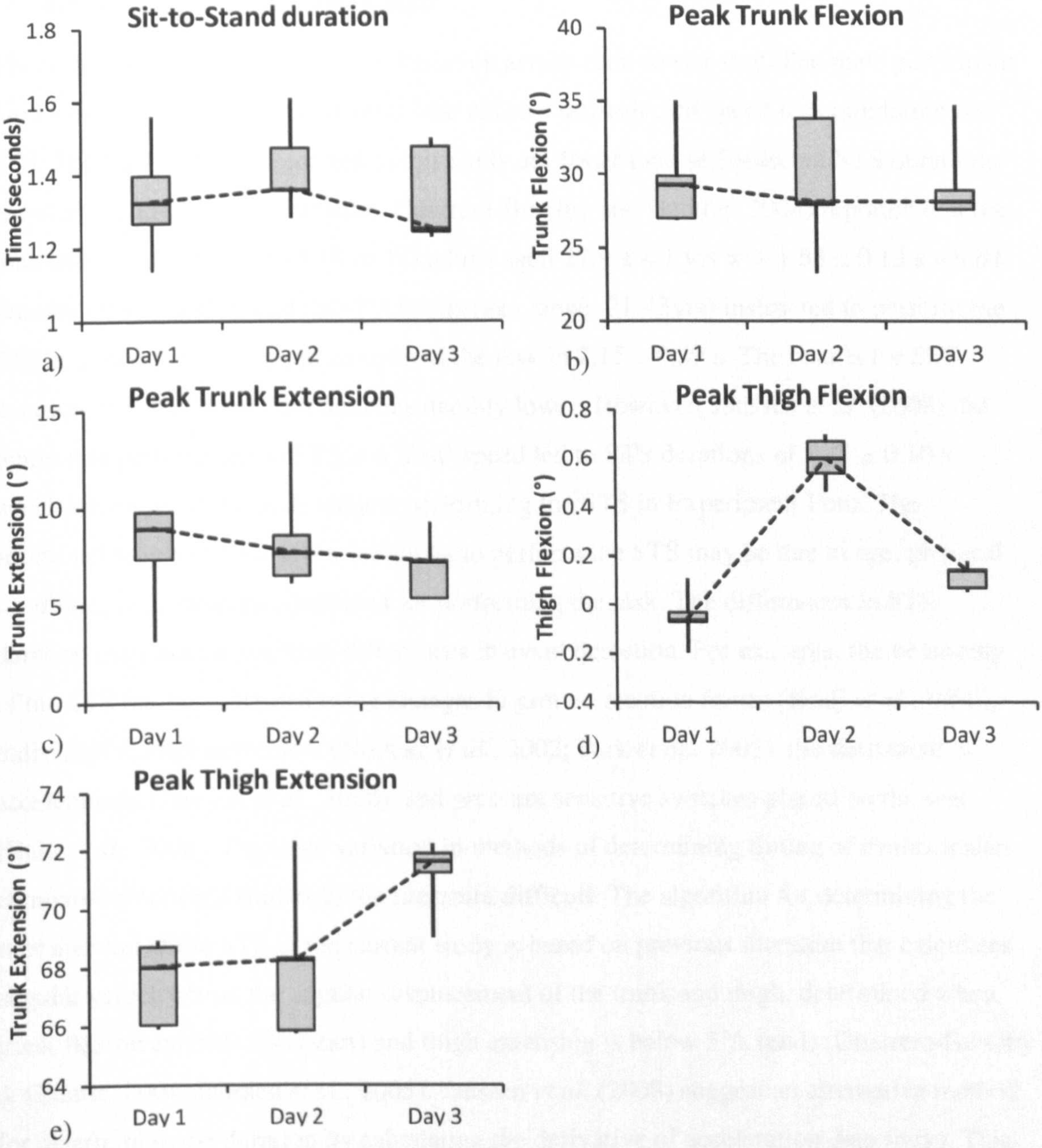


Figure 44. Dependent variables of the STS that were not normally distributed on day 1, day 2, and day 3. Box-and-whisker plots demonstrate the median, inter-quartile range, and upper/lower limits of the data for each dependent variable.

4.5.6 Discussion

Experiment Four demonstrated that the Xsens sensor can be used to quantify performance of the STS, providing important information to the experimenter regarding variation between subject trials. The Xsens sensor was able to discriminate between day to day performances of the STS for one male adult. The findings reported on the STS are difficult to generalise beyond the scope of this single-subject feasibility study, but the dependent variables that were provided are typical of what is produced during measurement of STS in the current literature.

4.5.6.1 SIT-TO-STAND VARIABLES

The STS duration was consistent in variation across each testing day. The male participant used was a typically developed adult who chose a self-selected speed for completing the STS. The STS durations reported in this study are faster than self-selected STS durations reported for adults in the literature. Guarrera-Bowlby and Gentile (2004) reported that the time taken to complete the STS in TD adults aged 27.9 ± 4.1 yrs was 1.58 ± 0.13 s whilst Janssen *et al.* (2008) found that TD adults (age range: 21-43yrs) instructed to perform the STS at a 'comfortable' speed completed the task in 2.15 ± 0.59 s. The results for STS duration in Experiment Four are considerably lower. However, Janssen *et al.* (2008) did report that performing the STS at a 'fast' speed led to STS durations of 1.41 ± 0.10 s, which are closer to the male subject performing the STS in Experiment Four. The additional length of time taken for adults to perform the STS may be due to age, physical condition, or alternative conditions for performing the task. The differences in STS duration may also derive from differences in event detection. For example, the beginning of the STS has been defined using changes in ground reaction forces (Kralj *et al.*, 1990), individual marker movement (Nikfekr *et al.*, 2002; Park *et al.*, 2003), the derivative of accelerations (Janssen *et al.*, 2008), and pressure sensitive switches placed on the seat (Galli *et al.*, 2008). The large variation in methods of determining timing of events makes comparison between studies in the literature difficult. The algorithm for determining the start and end of the STS in the current study is based on previous literature that calculates angular velocity from the angular displacement of the trunk and thigh, determined when trunk flexion exceeds 5°/s (start) and thigh extension is below 5°/s (end) (Guarrera-Bowlby & Gentile, 2004; Janssen *et al.*, 2005). Janssen *et al.* (2008) suggest an alternative method for determining the duration by calculating the derivative of acceleration data (jerk). This could be used as an alternative for future event detection and should be considered if accelerations are the only possible signal that can be measured during a STS trial. This might occur in situations where there is high magnetic interference affecting stable angular output. Further analysis which compares the difference between angular velocity and jerk for determining the start and end of the STS would be necessary to validate the method suggested by Janssen *et al.* (2008) for the Xsens sensor.

Peak trunk flexion results agree with findings in the literature (Guarrera-Bowlby & Gentile, 2004; Janssen *et al.*, 2005; Seven *et al.*, 2008), and showed the greatest amount of variation during day 2 (28.13 ± 5.9° (median ± IQR)). Guarrera-Bowlby & Gentile (2004) found that the trunk shows larger variations in range of motion than any other segment during analysis of the STS. Trunk flexion generates momentum during the initial stages of the STS therefore an increase in angle may reduce the effort required to complete the task. There is limited data reported in the literature on the size of accelerations produced during the STS. Accelerations have been used to determine the STS duration (Kerr *et al.*, 1997; Janssen *et al.*, 2005; Janssen *et al.*, 2008) or to stabilise the output of gyroscopes (Giansanti *et al.*, 2007) but the peak accelerations are typically not reported in the literature. Janssen *et al.* (2005) suggest that higher accelerations are achieved at the trunk and thigh when performing the STS at greater speeds, but the magnitude of the accelerations was not reported. Weiss *et al.* (2010) provided evidence to suggest that accelerations recorded during the STS can help discriminate between TD adults and patients with Parkinson's disease. Quantifying the magnitude of typical peak dorso-ventral and axial accelerations produced during the STS might lead to a greater understanding of how the trunk and thigh behave during the STS.

The resultant acceleration vector prior to and after STS had a magnitude of 9.81 $m.s^{-2}$ (Figure 41 & Figure 42) confirming that acceleration values provided by the Xsens sensor are accurate during the protocol. Peak positive and negative resultant accelerations have not been reported in the literature. They may provide a novel way of analysing acceleration data, but further analysis of their behaviour across a larger cohort of participants is needed.

4.6 Overall Discussion

Experiment One and Two demonstrated a high level of accuracy when validating the Xsens sensor over controlled ranges of motion. Experiments Three and Four demonstrated that the Xsens sensor is a practical alternative to video motion capture systems, both during VR game play and for the STS. The findings from each experiment address some of the important issues surrounding the first VR training intervention (Chapter 3). Importantly, integration of the Xsens sensor into VR game play could lead to future VR training taking place outside the Liverpool John Moores University research facility. This may lead to increased participant numbers in the future. Furthermore the Xsens sensor is capable of providing information about performance of a potential independent outcome measure, such as the STS.

4.6.1 Limitations

Experiment One reported that error in angular displacement can occur due to magnetic disturbance. The surrounding environment should be checked prior to future data collection to ensure minimal drift occurs as a result of interference from ferromagnetic materials. The error signal between the Xsens sensor and Vicon system appeared to be systematic. This offset was reduced in response to manual adjustments of the offset and gains and the size of these adjustments were unlikely to cause significant changes to VR game play. In fact, the error between the Xsens sensor and Vicon system during GPO game play (Experiment Three) was random rather than systematic, suggesting that VR performance was unaffected by such small errors.

In Experiment Two the accelerations produced by the sine wave trials are smaller than accelerations experienced during ADL (Janssen *et al.*, 2005; Janssen *et al.*, 2008; Weiss *et al.*, 2010). Deficiencies were highlighted in the dynamic response of the Xsens sensor when attempting to provide accelerations which matched ADL (~ 10-12 $m.s^{-2}$) using the CAREN platform (Appendix 14). However, for sine wave trials the limits of accuracy are consistent with the specification set out by Xsens Technologies, who state a linearity of 0.2% of the full scale (±50 $m.s^{-2}$). The high frequency of the sine wave input (1.3-2.2 Hz) indicates there was a good match between Vicon and Xsens, suggesting that ADL performed at similar frequencies should provide similar levels of accuracy.

It is worth considering that some of the differences found between the Xsens sensor and Vicon system in Experiment One & Experiment Two could be a result of error in the Vicon measurements. Richards (1999) discussed the error associated with seven VMC systems when measuring the orientation of a cluster of reflective markers placed on a test rig. The cluster produced a fixed angle of 95.8° and was moved around in a 3D volume over an unspecified period of time. The Vicon VMC system (370) had an RMS error of 1.42° across the trial, with a maximum error of 4.63°, suggesting that the system was not able to provide the exact fixed angle throughout the trial. The errors calculated may be a result of systematic or random errors such as camera calibration, variation in the distance between markers, the transition of markers in and out of view of cameras, marker flickering, or electronic noise (Richards, 1999; Chiari *et al.*, 2005). Therefore it is possible that errors associated with the Vicon system that are reported in the literature could explain some of the inaccuracies. It is important to note that the results from the remaining six video motion capture systems showed higher RMS error (1.76-4.49°) and maximum errors (5.06-19.25°), indicating that the Vicon system performed better than the majority of existing video motion capture systems on the market at that time.

4.7 Conclusion

The difference in angular displacement output produced by the Xsens sensor when compared to the Vicon system during controlled ranges of motion and VR game play is minimal ($\varepsilon <= 0.97°$). The difference in acceleration output (Experiment Two) was minimal when considering RMS error and Pearson's correlation coefficients, supporting previously reported errors. The results suggest accelerations captured below 2.5 $m.s^{-2}$ by the Xsens sensor are accurate to within 5% of the values recorded by a Vicon system. The findings of Experiment Three have significant implications for the future of virtual rehabilitation, as they provide a point of reference for the error associated with using an IMU during VR game play. To the author's knowledge, this has not been considered previously. In addition, the RMS errors reported in Experiment One and Experiment Three are comparable to or less than the error reported in previous research comparing VMC systems with the Xsens sensor. Experiment Four provided an example of a portable measurement device for recording human motion during the STS, capturing both angular displacement and acceleration simultaneously. This is expected to be useful for future VR interventions where an independent assessment of how game performance transfers to ADL may be required. Overall the Xsens sensor would be an ideal device for capturing human motion during a VR intervention which requires an IMU to control VR game play and measure ADL.

Chapter 5. Developing training games

5.1 Introduction

> *One of the major challenges facing clinicians in rehabilitation is identifying intervention methods that are effective, motivating, and that transfer to the ability to function in the 'real' world (Rizzo et al., 2004, p.4853).*

Children who require therapy regularly as a consequence of pathology, for example cerebral palsy (CP), are continually exposed to mundane and repetitive rehabilitation techniques throughout childhood and adolescence. In answer to these issues Burdea (2003) suggested that provision of physiotherapy based exercises using virtual reality (VR) technology can increase compliance rates. Rizzo *et al.* (2002) suggested virtual reality environments can be configured to provide three key components necessary for motor learning; motivation, repetition, and feedback. These aspects can be manipulated to create the optimum environment for virtual rehabilitation.

5.1.1 Developing new virtual reality training games

Chapter 3 explained the need to create new interactive VR games to maintain interest and motivation during VR training sessions. Verbal feedback (Section 3.3.7) from parents and children suggested that the use of additional VR training games would avoid repetition and be more engaging for the child. Consequently significant development of new VR games was a necessity for future VR training studies in order to maximise the motivating and fun element of VR. The results of Chapter 4 showed that the Xsens sensor is capable of providing accurate information about position and acceleration of human movement, and importantly that it is a suitable motion capture device for use in VR game play. The only existing VR game which can be controlled by Xsens sensors is the Goblin Post Office (GPO) game and so several new VR games controlled by Xsens sensors need to be developed for VR training.

This chapter describes the characteristics of new VR games driven by the Xsens sensors designed for training selective motor control at the trunk, pelvis, knee and ankle. A description of how D-Flow (CAREN specific software) and the Xsens sensor combine to create virtual environments for games training is given.

5.2 Portable virtual reality system

The Xsens sensor attaches to the host PC or laptop via a USB connection and the sensor is fastened to the targeted segment of the subject. In this configuration the CAREN system becomes portable, requiring only one laptop which runs the D-Flow system software, one or more Xsens sensors (depending on the application), and a screen with projector or a television to provide visual feedback to the subject. The D-Flow system brings each component of the CAREN system (Section 3.2.3.1) together to create VR applications that can be used for the purpose of rehabilitation and games training. One of the main components is the D-Flow editor (Figure 45) which provides the user interface that enables development of VR applications. In the D-Flow editor there are a number of modules which fit together to create a VR application. Each module can be inserted into the current application, and provides a unique function. For example, selecting an *Object* module provides the user with a 3D object in the middle of a blank virtual scene. The user is able to determine the shape, colour, position, scaling, and visibility of the object. To control the position of the object using rotation of a body segment, the user can then insert a module which returns data from the specific input device being used. In Figure 45 an *Xsens* module is used to control the position of the object. Further modules are then inserted between the *Object* and *Xsens* module to control the way in which the object moves in relation to movement of the body segment. Modules are able to communicate using simple *wiring* which sends information from one module to the next through multiple input and output channels. Modules can also communicate using *events*. An *event* is a message broadcast instantaneously to all modules in response to some change in a data value or the virtual environment (e.g. a collision between objects). Modules can be configured independently to respond in specific ways to different events.

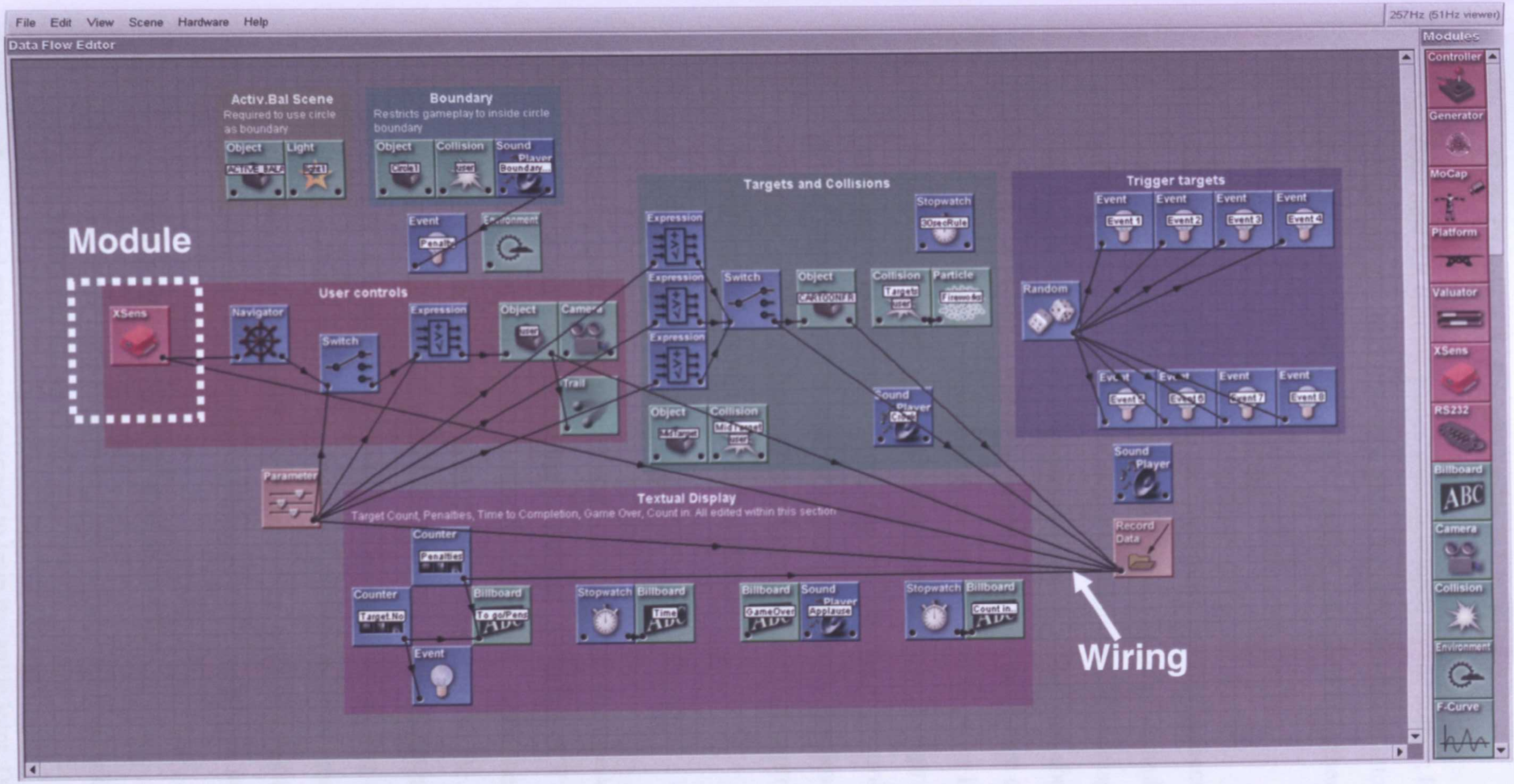


Figure 45. An example of the D-Flow editor using the modular interface provided by CAREN. The modules shown are used to create a training game called Whac-A-Frog.

5.3 Games Features

Four new VR training games were developed by the author; Pong, Whac-A-Frog, Car Dodge, and The Maze. Several game features were taken into consideration when designing the VR training games, and are described in further detail.

5.3.1 Control schemes

Games were required to train the same movement components at the trunk and pelvis that were used to control the Goblin Post Office (single plane and dual plane motion), in addition to control at the knee and ankle joints. When training the trunk or pelvis using single plane motion, training games required; 1) Rotation about the longitudinal axis of the trunk or pelvis in the transverse plane controlled movement of the virtual object right and left, 2) tilt about the mediolateral axis of the trunk or pelvis in the sagittal plane to control movement up and down. Flexion (down) and extension (up) of the knee joint about the mediolateral axis in the sagittal plane was required to control the vertical motion of the virtual object. Similarly, plantarflexion (down) and dorsiflexion (up) of the ankle joint about the mediolateral axis of the tibiotalar joint in the sagittal plane was required to control vertical motion of the virtual object.

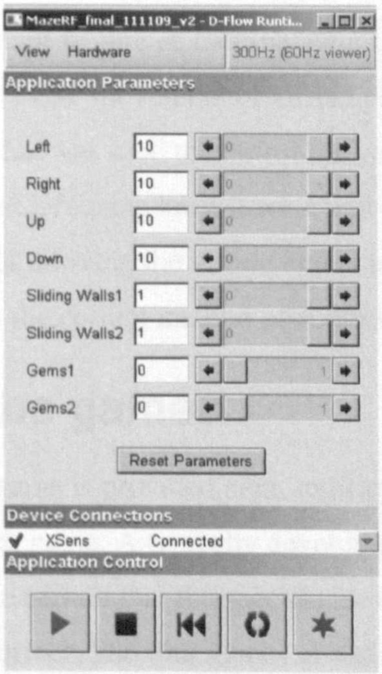
5.3.2 Method of control

Training games used position and velocity control to move virtual objects. Position control sets the X and Y position of the user object. A rotation of 5° might move the user object by 5 m (virtual metres) in one direction, and the user would therefore be required to rotate 5° in the opposite direction to bring the user object back to the start position. Velocity control sets the X and Y speed of the user object in response to angular deflection of the body segment. A rotation of 5° would set the user object moving at 5 $m.s^{-1}$ in one direction. The object will continue at the same speed until the angle of rotation changes. Velocity control therefore requires constant movement of the body segment to control the virtual object, preventing the user from maintaining an awkward bent or twisted position.

5.3.3 Adjusting levels of difficulty

> *Games are boring when they are too easy, but frustrating when they are too difficult (Hunicke, 2005, p.01).*

In a virtual environment designed to train the ankle joint, Deutsch *et al.* (2001) altered task difficulty by changing game speed, the number and location of targets, and the degree of resistance provided by a haptic feedback device used to control the direction of a virtual aeroplane. Improvements in game performance were associated with improved walking and stair climbing performance in adults who had suffered a stroke. Jack *et al.* (2001) designed VR games which increased the speed of movement and range of motion of the affected hand in stroke patients to train performance of ADL. By altering task difficulty, VR can be tailored to the patient's specific needs during game play, enhancing motivation to play the game by making it neither too difficult nor too easy. The level of difficulty in each game can be manually adjusted by the operator within the D-Flow software. This is performed using the *runtime console* (Figure 46). The *runtime console* contains adjustable *sliders* and *value fields* which can control many parameters such as speed of the game, time duration, and the number of targets. In addition to operator defined difficulty settings, games should provide changes to difficulty automatically in response to game play. Bailey & Katchabaw (2005) report that games should enable auto-dynamic difficulty settings adjustments during game play to better suit the players needs. A good example of this is the Goblin Post Office game described previously (Section 3.2.3). The game incorporates an adaptive algorithm (PEST, Taylor & Creelman, 1967) which adjusts the forward speed of the virtual dragon to maintain task difficulty at a level appropriate to each subject's ability (Barton *et al.*, 2011). Implementing this type of game feature in training games is therefore critical for sustaining high levels of motivation.



Left 10
Right 10
Up 10
Down 10
Sliding Walls1 1
Sliding Walls2 1
Gems1 0
Gems2 0

✓ XSens Connected

Figure 46. The runtime console provides manual control of task characteristics by the operator during game play.

5.3.4 Auditory Stimuli

Audio may not be perceived as the most important feature during game play, but Cunningham *et al.* (2006) suggested that the provision of auditory stimuli plays an important role in supporting user interaction with a virtual world. Additionally, McCrindle and Symons (2000) demonstrated that audio cues are effective in stimulating game play with children. Findings by Zhou *et al.* (2004) suggested that using audio in VR games can direct the attention of the user to different spatial objects that appear in the virtual world, improving task performance. They found that on average participants took 133.1 s to search for a virtual object without an audio stimulus, in comparison to 88.1 s when an audio stimulus was introduced. The VR training games that were developed played a variety of audio clips during user interaction. These occurred, for example, when virtual objects collided or a bonus point was achieved during game play. In addition to stimulating interaction during game play, audio clips provide a fun aspect to game play, and children of a young age tend to find random noises amusing. Auditory stimuli were therefore provided in each VR training game.

5.3.5 Display congruency

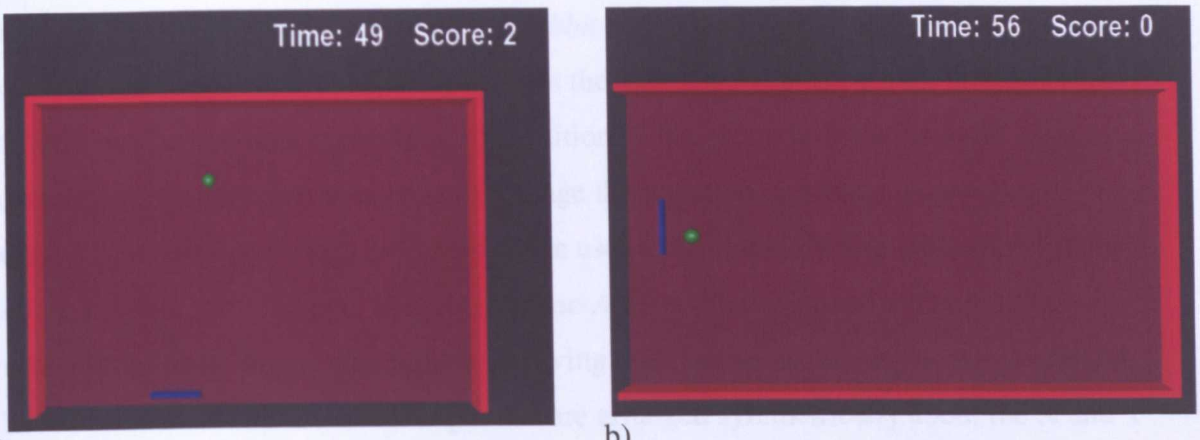
Children with CP can suffer from visual deficits as a result of their pathology, and children who have a higher motor control deficit are more likely to have greater visual impairments (Ghasia *et al.*, 2008). An important feature of training games was to maintain similar view points in each game, in order to make movement of virtual user objects within the game congruent with the motor task that was used to control the virtual object. For example, moving a virtual object right and left using knee flexion and extension is non-congruent and would be difficult to control. Moving the virtual object up and down using knee flexion and extension would be the correct method of control.

5.4 Overview of the games

A detailed description of each game is provided next, indicating how game features contributed to the design of each game. A typically developing child tested the games during the design phase to make certain that the specific movements of body segments used to drive the games were correct. The four games aimed to provide a variety of virtual environments to the participants that maintained high levels of interest during the VR training phase of the intervention. Each game was modelled on popular arcade games. Arcade based games were chosen due to the low levels of complexity when interacting with the games, but contained a number of features which increased the difficulty over time if a participant's performance improved.

5.4.1 Pong

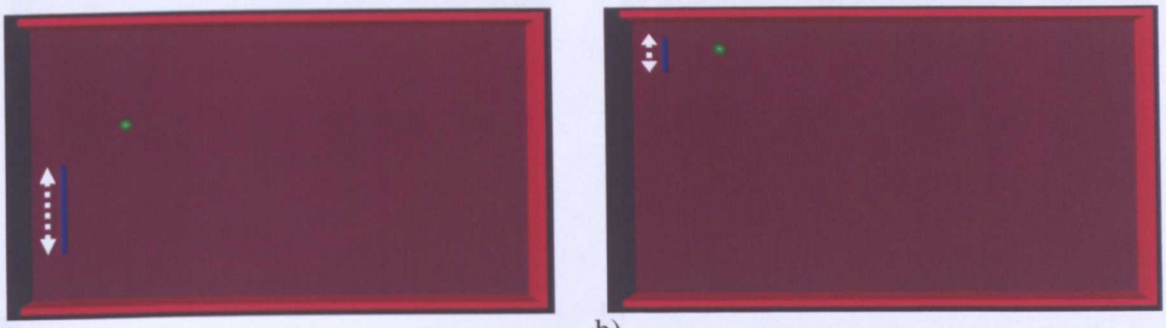
Pong is a 2D game modelled on the well known arcade classic developed by Atari in the 1970s. The game was an original creation for the purpose of this research. In this single-player version the aim was to prevent a green ball from escaping off the screen by using a blue paddle to hit the ball and keep it inside the red rectangle. The player controls the blue paddle by moving it horizontally at the bottom of the screen (Figure 47(a)) or vertically on the left side of the screen (Figure 47(b)) depending on the single plane control scheme selected. Horizontal control requires rotation about the longitudinal axis of the trunk or pelvis to steer right and left. Vertical control is driven by rotation about the medio lateral axis of the trunk, pelvis, knee or ankle to steer up and down. In *Pong*, position control was used to determine the position of the blue paddle, requiring control and accuracy when aligning the paddle with the oncoming green ball. The speed of the green ball can be increased or decreased by the operator to manipulate task complexity, using the aforementioned ***runtime console***. Furthermore, when the blue paddle makes contact with the green ball (a hit) the paddle length increases (Figure 48(a)), whilst a miss leads to a decrease (Figure 48(b)). This type of change during game play is a way to achieve auto-dynamic difficulty to increase the complexity of the task when the user is successful, but also make the task easier if unsuccessful. Points are accumulated for every hit the blue paddle makes with the green ball, and deducted each time the green ball disappears from the screen. Audio clips are played each time a hit or a miss is detected. Total points scored and the speed of the green ball can provide a measure of performance across trials and training sessions.



a) Horizontal

b) Vertical

Figure 47. a) The blue paddle in *Pong* is controlled horizontally at the bottom of the screen. b) The blue paddle is controlled vertically on the left side of the screen.



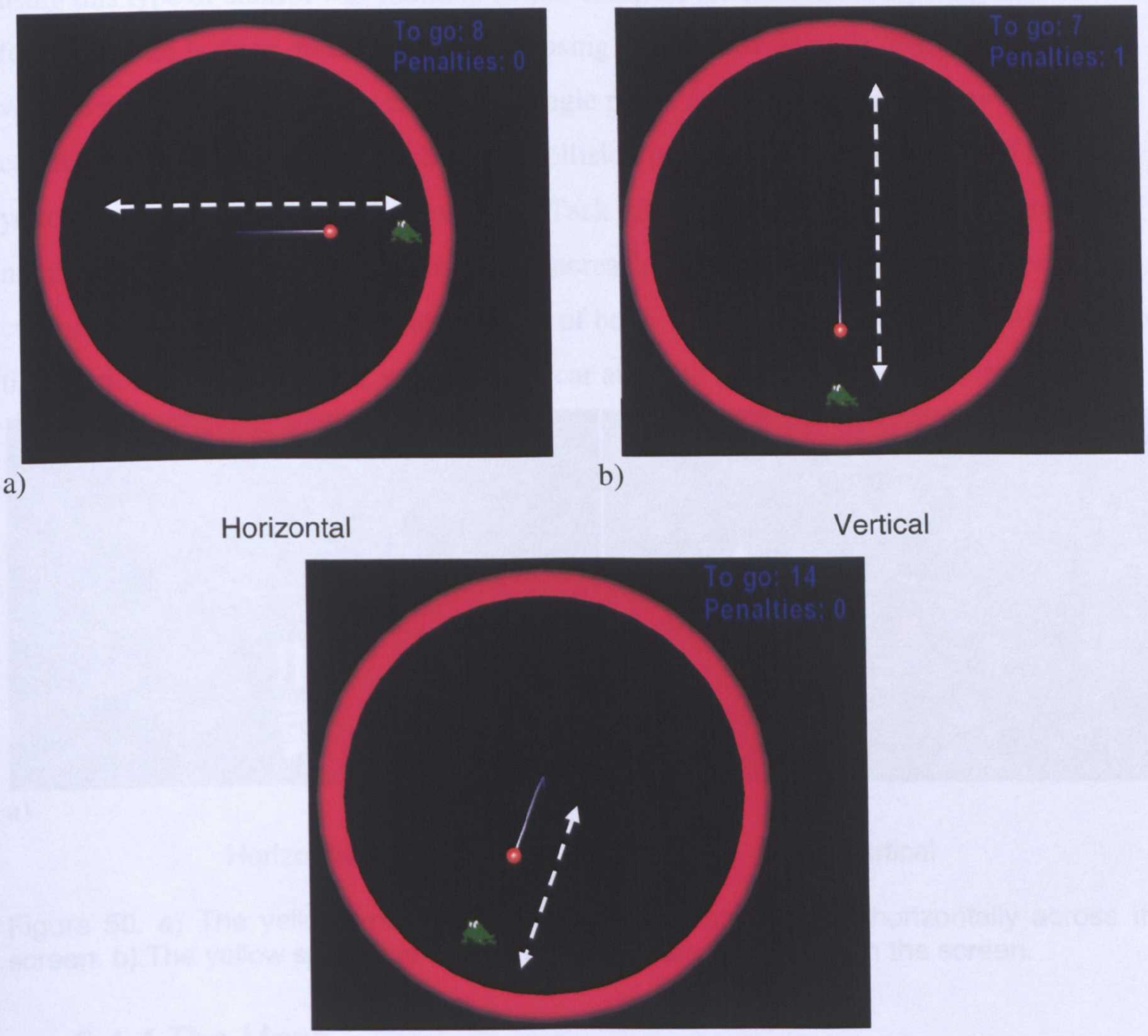
a) Increased paddle length

b) Decreased paddle length

Figure 48. An increase (a) or decrease (b) in paddle size can manipulate task difficulty during game play automatically, rather than manipulating task difficulty manually using the *runtime console*.

5.4.2 Whac-A-Frog

Based on the Whac-A-Mole arcade game, *Whac-A-Frog* (Figure 49) is an original game designed for single-player control. The player aims to *splat* all the frogs that randomly appear within the red ring (playing area) using a red ball cursor, in the shortest time possible. The red ball is controlled by single plane motion along the horizontal or vertical diameter of the red ring (Figure 49 (a & b)) or using cross plane motion to travel along an oblique axis within the red ring (Figure 49(c)). For single plane motion, rotation about the longitudinal axis of the trunk or pelvis steers right and left, and rotation about the medio-lateral axis of the trunk, pelvis, knee, or ankle steers up and down. A combination of rotation about the vertical and medio-lateral axis of the trunk or pelvis is used to steer cross plane motion. After each frog *splat*, the player must return to the centre of the red ring (start position) to activate the next frog. A *ribbit* sound was played to notify the user that a new target had appeared. The game penalises the user if the red ball cursor collides with the red ring. To maintain interaction, the position of the cursor is determined by velocity control, requiring the user to constantly change the direction of motion to prevent a penalty. The number of frogs presented to the user and allotted time to *splat* all frogs are used to monitor performance. Targets in *Whac-A-Frog* are positioned to cause the user to make a set of eight angled movements involving both horizontal and vertical components. The movements are all the same length and are arranged symmetrically about the X and Y axes, in the same manner as targets were positioned in the Goblin Post Office (Figure 9, Section 3.2.3).



a)

Horizontal

b)

Vertical

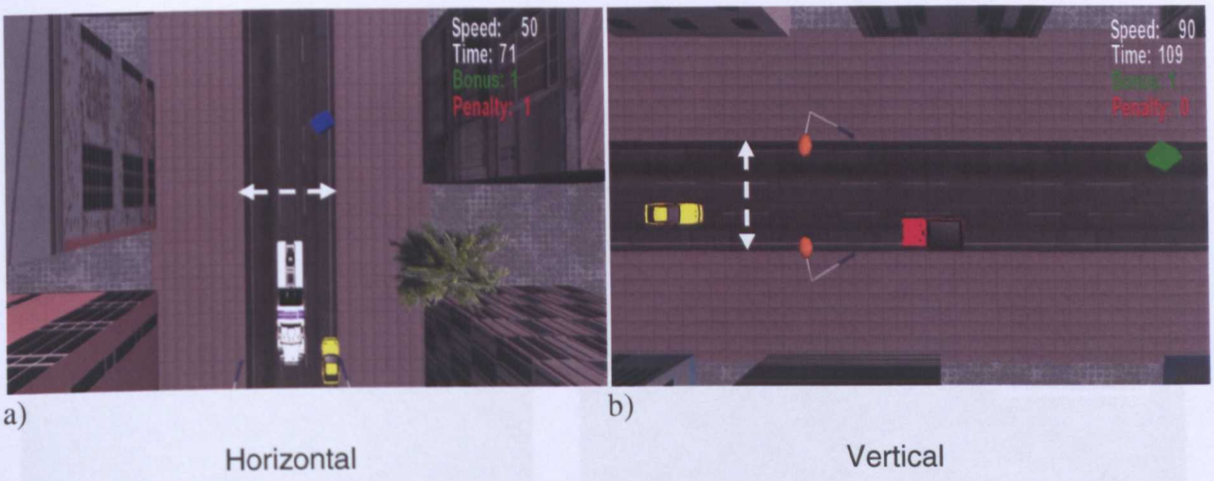
c)

Both

Figure 49. a) The red ball in *Whac-A-Frog* is controlled across the horizontal diameter of the red ring. b) The red ball is controlled across the vertical diameter of the red ring. c) Rotation about an oblique axis is used to train cross plane motion.

5.4.3 Car Dodge

Car dodge was an adaptation of an existing game developed by Motek Medical. The aim is to steer a yellow sports car along a busy road whilst avoiding oncoming vehicles (Figure 50(a & b)). Any attempt to leave the road and drive onto the pavement to avoid vehicles resulted in a penalty, signalled by a *police siren* audio clip. The game is played using single plane control only, with horizontal control driven by rotation about the longitudinal axis of the trunk or pelvis, and vertical control driven by rotation about the medio-lateral axis of the trunk, pelvis, knee or ankle. In the previous version of the game developed by Motek Medical, the forward speed was determined by acceleration control. In pilot work using this type of control was found to be too complex for children at a young age. Thus forward speed is fixed during each trial by using the *runtime console*. The horizontal and vertical position of the yellow car during single plane motion is determined by velocity control. Penalties are accrued each time a collision between vehicles occurs or if the yellow sports car drifts onto the pavement. Task difficulty is increased by increasing the number of oncoming vehicles on the road, increasing the speed at which the yellow sports car travels along the road, or a combination of both. The number of penalties within a fixed time period, and speed of the yellow sports car are used as indicators of performance.



a)

Horizontal

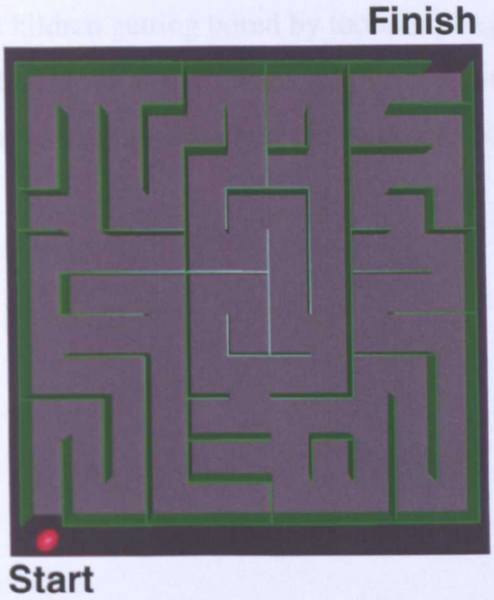
b)

Vertical

Figure 50. a) The yellow sports car in *Car Dodge* is controlled horizontally across the screen. b) The yellow sports car is controlled vertically up and down the screen.

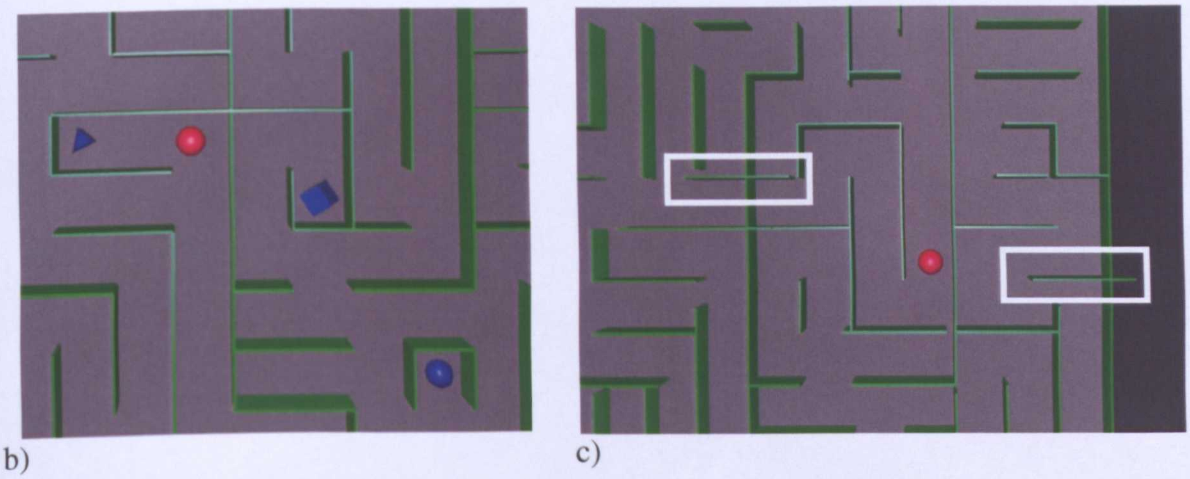
5.4.4 The Maze

The *Maze* (Figure 51(a)) is an original game which is based on the concept of a puzzle book maze. The aim is to get the red ball cursor (player object) from the start to the end of the maze in the shortest time possible whilst avoiding collisions with the maze walls. The red ball is controlled using cross plane motion, driven by a combination of rotation about the longitudinal axis and rotation about the medio-lateral axis of the trunk or pelvis segment. The position of the red ball cursor is determined by velocity control, and requires constant change in direction to avoid wall collisions. Task difficulty is increased by introducing *Gems* (Figure 51(b)) which need to be collected before completing the maze. Furthermore, *sliding walls* (Figure 51(c)) add an increased level of complexity beyond that of controlling position of the player object. Time to completion and number of wall hits can be used to monitor performance.



a)

Maze



Gems

Sliding walls

Figure 51. a) The red ball in the *Maze* game is controlled using cross plane motion of the trunk or pelvis. b) Blue gems can be introduced to increase task complexity, and should be collected before reaching the finishing line. c) Sliding walls provide an added level of complexity, by opening and closing available routes during trying to complete the M*aze*.

5.5 Summary

Four VR training games were developed for a training intervention designed to improve selective motor control of the trunk, pelvis, knee and ankle. *Pong*, *Whac-a-Frog*, *Car Dodge* and the *Maze* game were designed to provide increased levels of motivation, repetition, and feedback. Important game features were incorporated in each game to provide multiple levels of task complexity, maintain interaction during future VR training interventions, and prevent children getting bored by too much exposure to the same game. The new VR games were developed to train selective motor control of body segments so that the GPO game could be classed as a method of assessing VR game play only.

Chapter 6. Training selective motor control at the core and periphery using computer games (study two)

6.1 Introduction

The first virtual reality (VR) intervention (Chapter 3) did not provide any evidence that core-specific training was able to improve gait in children with cerebral palsy (CP). The performance of activities of daily living (ADL) require activation of both the core and periphery of the body, and evidence of training both using Targeted Training has demonstrated improvements in motor function. The development of VR training may benefit from the integration of both core- and periphery-specific training to improve motor function. It was suggested that development of a portable VR system could lead to increased exposure to VR training and improve participant recruitment. The following chapter describes the use of an existing VR system controlled by an inertial measurement unit (IMU), using training games devised to improve compliance. The Sit-to-Stand movement is used as an independent outcome measure of VR training.

6.1.1 Aims

The aim of this study was to determine whether training peripheral control of the lower extremities in children with CP can improve performance of the STS movement beyond training core control alone.

6.1.2 Objectives

1. To determine whether VR training on the core and periphery leads to improvements in control of the core and periphery.

2. To evaluate whether exposure to training the core and periphery improves performance in the STS movement.

3. To establish whether there should be an order to training selective motor control (i.e. training the core before the periphery).

6.1.3 Hypothesis

It was hypothesised that VR training of the core followed by training of the periphery would improve performance of the STS to a greater degree than training of the core only.

6.2 Method

6.2.1 Participants

Eleven children diagnosed with CP participated in the research project. Participants were selected from current NHS database at the North West Movement Analysis Centre, Alder Hey Children's Hospital, Liverpool based on the following criteria:

- Aged between 6-11 years.
- Attending primary schools within the Merseyside County.
- Had the cognitive capacity to play computer games (physiotherapist's report).
- Could understand and follow verbal instructions in English.
- Able to stand unaided (without a walking device or holding on to surrounding apparatus).
- No history of surgical intervention within six months prior to the study.
- No history of Botulinum treatment within six months prior to the study.
- No more than 10° fixed contractures at the ankle, knee or hip joints.
- No exposure to any form of core or virtual rehabilitation prior to the study.

Parents of the children who met the inclusion criteria were approached by the child's physiotherapist to see whether they willing for their child to be recruited for the study. Parents were provided with a participant information sheet to be read to or by the child (Appendix 15), and a detailed parent/guardian information sheet about the project (Appendix 16). Upon verbal agreement from the parent/guardian, contact was made with the primary school of each child to see if the school had the required space to accommodate the VR training intervention. Each school agreed to host the VR training intervention, and visits to the school were arranged to meet each child before testing and training began. Parents were invited to attend the visit, but importantly the Head Teacher of each school, head of special educational needs, or class teacher were present. The visits were necessary for children to become familiar with the principal researcher before the VR intervention started. Workspace was also allocated for equipment and testing during these visits. After the school visit, parents/guardians and children were asked to sign consent forms (Appendix 17 and Appendix 18 respectively) to formally agree their involvement in the study. Ethical approval for the study was granted by Liverpool John Moores University Research Ethics Committee. The study did not require NHS ethical approval.

6.2.2 Research design

A randomised, cross-over design was devised to address the study aims and objectives. Each child was given a participant number prior to starting the VR intervention, and a random number generator was used to assign participants to one of two groups. The groups were named the *core group* (six participants) and the *periphery group* (five participants) (Table 6), with each group labelled according to the anatomical focus of VR training during the participant's first week. Each participant performed an assessment of the STS movement before completing an initial VR assessment of selective motor control with the trunk, pelvis, knee and ankle using *The Goblin Post Office* (GPO) game. Participants carried out the two-week VR training intervention at their school. The *core group* received core-specific VR training in the first week and the *periphery group* received VR training on the periphery. Both groups received an intermediate assessment after completing the first week of VR training. During the second week participants received the alternative form of VR training, meaning the *core group* received training on the periphery, and the *periphery group* received training on the core (Figure 52). Participants were exposed to VR training games devised in Chapter 5 for 45 minutes on each training day. After the two-week VR training intervention, each participant received a second assessment of the STS movement followed by a second VR assessment using the GPO game. A two-way repeated measure ANOVA with a between-subject factor of group (*core* and *periphery group*), and a within-subject factor of time (pre-training, intermediate, and post-training assessment) was proposed to assess if there were any differences in VR game performance and the STS between the *core* and *periphery group*. It was proposed that the *core group* might improve VR game play when using the core, in response to core-specific training during the first week of the intervention, but not when using the periphery. Core-specific training may lead to improvements in VR performance when using the periphery, and therefore during the second week of VR training the *core group* would be expected to show further improvements in VR game play when using the periphery.

Table 7. Participant information.

Participant Number	Group Allocation	Age (years)	Sex	Diagnosis
01	Periphery	8	Male	CP Asymmetric Quadriplegia
02	Core	6	Female	CP Quadriplegia
04	Core	8	Male	CP Spastic Diplegia
05	Periphery	9	Female	CP Diplegia
06	Core	9	Female	CP Asymmetrical Diplegia
07	Core	5	Female	CP Diplegia
08	Core	9	Female	CP Hemiplegia (left)
09	Core	10	Male	CP Ataxia
10	Periphery	6	Female	CP Hemiplegia (right)
11	Periphery	9	Female	CP Athetosis
12	Periphery	10	Female	CP Hemiplegia (left)

1st Friday: Pre-training assessment of core and lower extremities

Sit-to-Stand
Goblin Post Office
Duration: 60 minutes

↓

1st week, Mon - Thurs:

***Core group*: Core control training**

***Periphery group*: Lower extremity training**

4 days, 45 minutes games training per day

↓

2nd Friday: Intermediate assessment of core and lower extremities

Sit-to-stand
Goblin Post Office
Duration: 60 minutes

↓

2nd week, Mon - Thurs:

***Core group*: Lower extremity training**

***Periphery group*: Core control training**

4 days, 45 minutes games training per day

↓

3rd Friday: Post-training assessment of core and lower extremities

Sit-to-stand
Goblin Post Office
Duration: 60 minutes

Figure 52. A flow diagram detailing the order of testing for each group of participants in the randomised, cross-over study designed to assess the effect of VR training on ADL performance.

6.2.3 Equipment and Software

6.2.3.1 VIRTUAL ENVIRONMENT

A portable version of the CAREN system used in Chapter 3 (Section 3.2.3) provided the VR environment for VR testing and training in schools. The portable CAREN system consisted of one Xsens sensor connected to one Alienware M18x Laptop (Dell, UK) via USB. In addition a virtual scene driven by CAREN D-Flow software was displayed to the participant on a projector screen or television monitor (Figure 53).

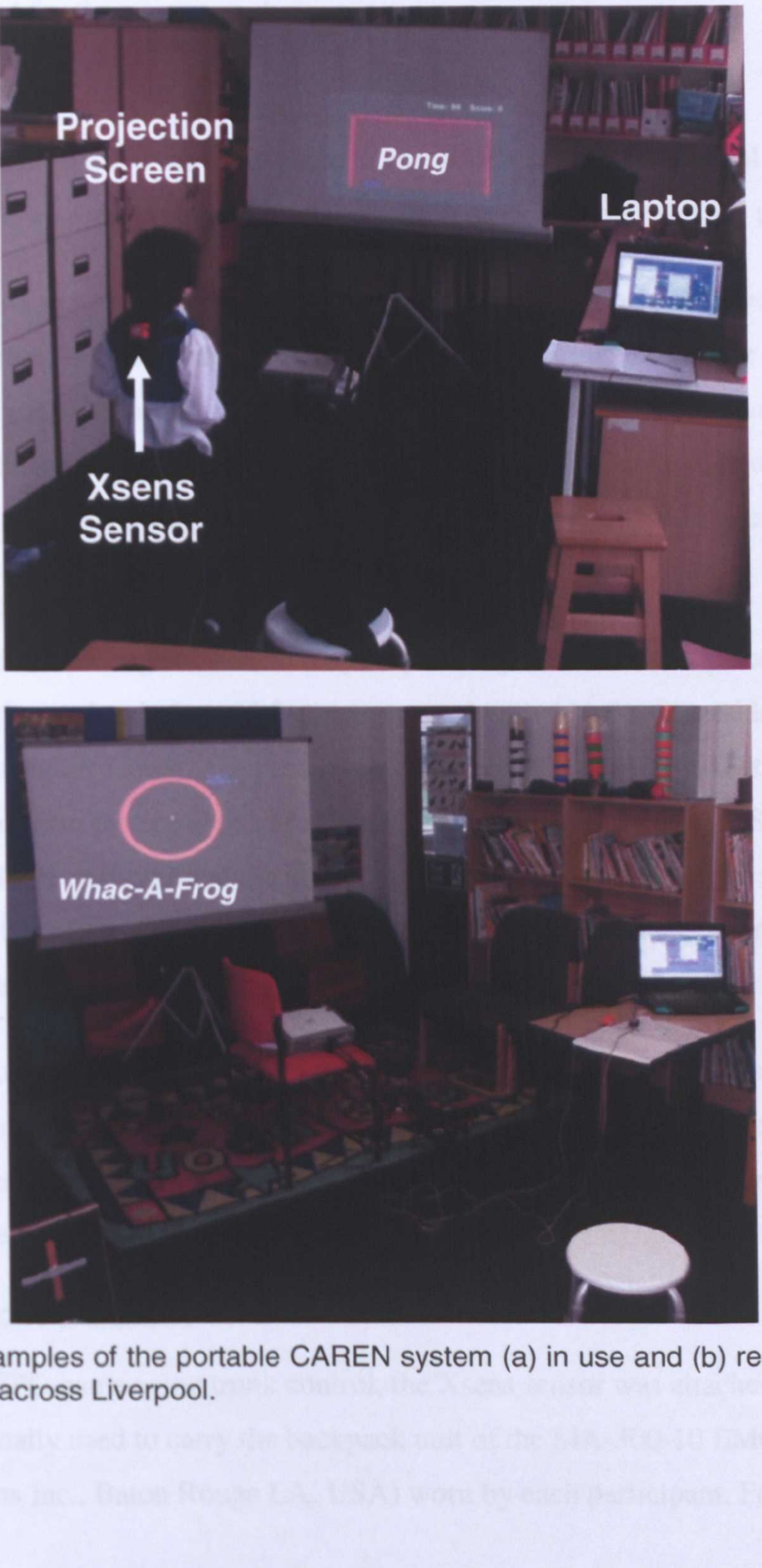


Figure 53. Two examples of the portable CAREN system (a) in use and (b) ready for use, in primary schools across Liverpool.

6.2.3.2 THE GOBLIN POST OFFICE

The GPO game (Section 3.2.3) was used to test VR performance during the pre-training, intermediate, and post-training assessments. Forward speed of the virtual dragon was controlled by the same adaptive speed algorithm (Taylor & Creelman, 1967) described in Chapter 3 (Section 3.2.3), which responds to target hits and misses. All virtual targets were positioned in the same manner as described in Chapter 3 (Figure 9, Section 3.2.3). A number of additional control schemes and body postures used to interact with the GPO game were developed for the current study.

6.2.3.3 CONTROL SCHEMES

Trunk control was used to drive the GPO game to assess selective motor control of the core whilst knee and ankle control were used to assess selective motor control at the periphery.

Trunk: Participants were informed that the trunk could be used to control left to right movement of the virtual dragon using rotation about the longitudinal axis of the trunk in the transverse plane (trunk rotation). Movement of the dragon upward and downward required tilt about the mediolateral axis of the trunk in the sagittal plane (trunk tilt). Combined trunk rotation and trunk tilt was defined as cross plane motion (trunk both).

Knee: Flexion and extension of the knee joint about the mediolateral axis in the sagittal plane was used to steer the dragon down and up respectively. The foot was placed into a 'Street Glider' which consisted of a mid foot support and with wheels either side of the support (similar to a Roller Skate). The participant was then able to roll the foot forwards and backwards to perform the required knee flexion and extension. Using the 'Street Glider' allowed isolated movement at the knee joint without the need to lift the upper leg in the air using hip flexion. Only one foot was placed in the 'Street Glider' at one time, and for safety children had to remain seated while wearing the wheels.

Ankle: Plantarflexion (down) and dorsiflexion (up) of the ankle joint about the mediolateral axis of the tibiotalar joint in the sagittal plane were used to steer the dragon. For participants with limited range of motion at the ankle, the 'Street Glider' device was used as a pivoting device.

6.2.3.4 SENSOR PLACEMENT

When driving the GPO game using trunk control, the Xsens sensor was attached to a Velcro jacket (normally used to carry the backpack unit of the MA-300-10 EMG system by Motion Lab Systems Inc., Baton Rouge LA, USA) worn by each participant. For knee and ankle control, the exact anatomical location and orientation of the sensors are described in Figure 54. The sensors were secured in position using hypoallergenic double-sided tape and cohesive bandage (firstaid4sport.co.uk).

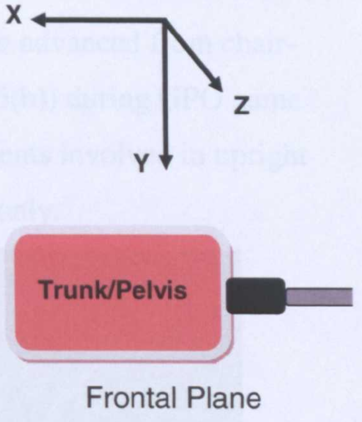
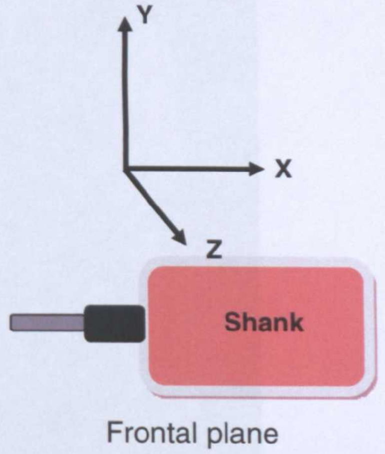
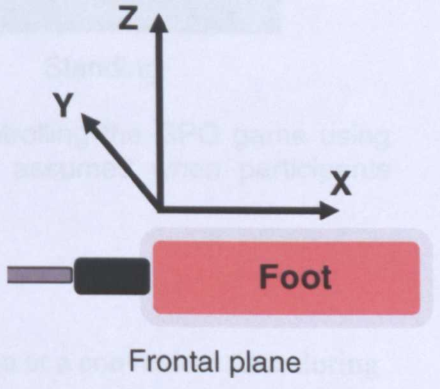
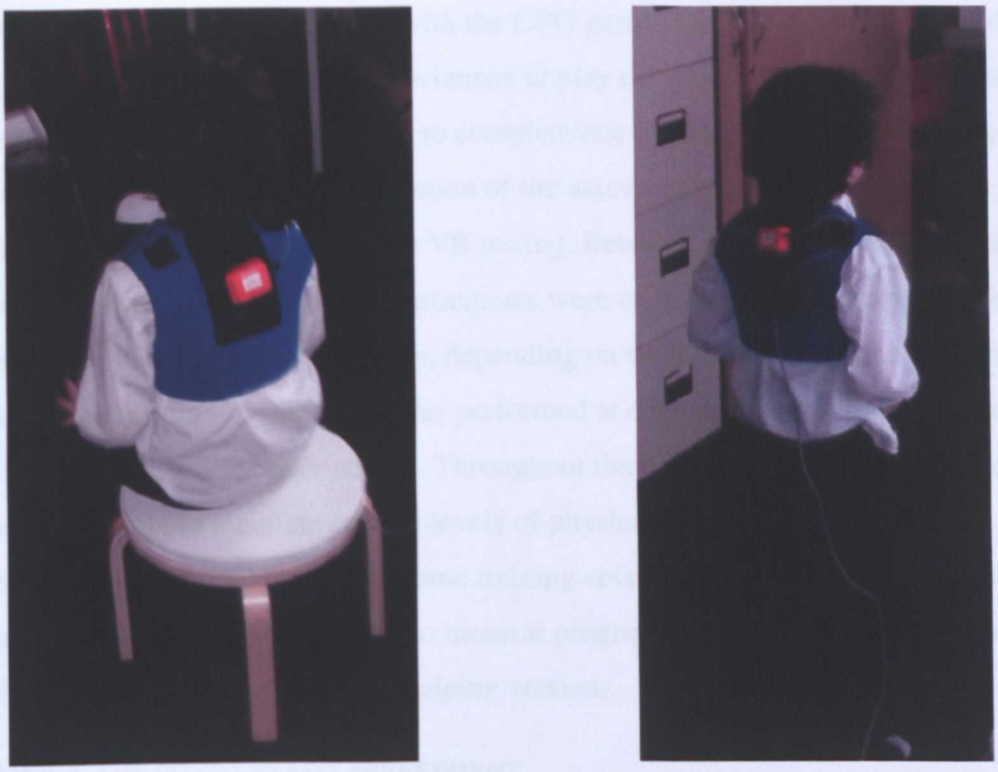
Trunk:	Positioned on posterior surface of upper torso, over the surface of T8	
+X	Running from right to left along horizontal axis through the upper torso	
+Y	Pointing distally	
+Z	Perpendicular to X and Y pointing away from the torso in a posterior direction	
Right/Left Shank:	Positioned on anterior surface of shank, 120 mm below the head of the fibula.	
+X	Pointing medially in parallel with the mediolateral axis of the knee joint	
+Y	Pointing in a superior direction	
+Z	Perpendicular to X and Y pointing away from the shank in an anterior direction	
Right/Left Foot:	Positioned on the superior aspect of the foot, across the metatarsals.	
+X	Pointing medially in parallel with the mediolateral axis of the ankle joint	
+Y	Pointing in a posterior direction	
+Z	Perpendicular to X and Y, pointing in a superior direction	

Figure 54. Position and orientation of the Xsens sensor on each body segment during the GPO game task, along with the local co-ordinate system of the sensor.

6.2.3.5 BODY POSTURES

To ensure the GPO game was playable for all participants with differing levels of functional mobility, two postures designed to increase difficulty gradually were established. In the first posture, chair-sitting (Figure 55(a)) participants sat on a stool whose height was adjusted to lower leg length, measured from the head of the fibula to the most inferior portion of the calcaneus. This provided a base of support under the pelvis, with the aim of reducing activity of the knee and ankle joint when using trunk control during VR game play. The same chair-sitting posture was used for knee and ankle control, with the aim of reducing activity of the trunk. The second posture advanced from chair-sitting by asking participants to maintain free standing (Figure 55(b)) during GPO game play, thereby requiring co-ordinated movement of all body segments involved in upright standing. In the standing posture participants used trunk control only.



Chair-sitting

Standing

Figure 55. a) The chair-sitting posture was used when controlling the GPO game using the trunk, knee, or ankle. b) The standing posture was assumed when participants advanced from chair-sitting using trunk control.

6.2.4 Procedures

Participants carried out the two-week VR training intervention at a convenient time during their school semester. Participants were required to take part for one hour per day, beginning on a Friday, and continuing on week days Monday to Friday for two consecutive weeks. Fridays were labelled as assessment days. Pre-training assessments were performed on all participants on the first Friday of the two-week period, followed by an intermediate assessment one week later, and finally the post-training assessment one week after that (Figure 52). Each assessment day followed the same format with participants carrying out an independent outcome measure related to activities of daily living by completing a STS task at the beginning of the assessment. This lasted no longer than 15 minutes and was followed by an assessment of VR performance using the GPO game (Section 3.2.3.2). *Core group* participants were tested on selective motor control of the periphery followed by the core during each assessment, but the *periphery group* received testing on the core before the periphery. This counterbalanced the order of training to rule out any bias towards the order of testing on assessment days. Prior to the GPO assessment game, each participant carried out a range of motion task. This enabled the investigator to determine whether the participant could move the required body segment through an appropriate range of motion to be able to interact with the GPO game. The task also familiarised each participant with the necessary control schemes to play the game before being exposed to the first GPO level. Participants aimed to complete one *run* in each of the GPO playing postures and control schemes. The duration of the assessment days lasted no longer than one hour, with 45 minutes dedicated to VR testing. Between pre-training and intermediate assessments (Monday to Thursday), participants were exposed to VR training which targeted either the core or the periphery, depending on their group allocation (Figure 52). All testing and training for the study was performed at each participant's current school, either during class-time or after school. Throughout the two-week period parents were told that their child should maintain current levels of physical activity and routine physiotherapy appointments. During some training sessions the community physiotherapist in charge of a participant was present to monitor progress of their patient, but had no formal role during the assessment or training session.

6.2.4.1 THE SIT-TO-STAND ASSESSMENT

An adjustable stool with no back rest or arm supports was used for the STS assessment. The effect of a back rest has not been reported in the STS literature. Using a back rest may limit the amount of trunk extension that can occur during Phase 1 of the STS, where some participants may produce trunk extension before trunk flexion initially to gather momentum. Therefore the lack of back rest eliminates any restriction of trunk motion. Seat height for the participant was adjusted to lower leg length, measured from the head of the fibula to the most inferior portion of the calcaneus (Schenkman *et al.*, 1990). This resulted in a starting knee angle as close as possible to 90° flexion, with the shank positioned perpendicular to the floor (Figure 56). A low seat height can make the STS more demanding for children and adults (Schenkman *et al.*, 1996; McMillan & Scholz, 2000; Hennington *et al.*, 2004), and typically the height of the knee is used to determine the height of the seat (McMillan & Scholz, 2000; Park *et al.*, 2003; Hennington *et al.*, 2004).

The participant was asked to maintain the trunk and head in an upright position at the start, before performing the STS at a self-selected comfortable speed. Typically the STS is performed with constraints on use of the arms (Janssen *et al.*, 2002; Hennington *et al.*, 2004) thus arms were folded or held by the side. Constraining the arms prevented the participant from using their arms or hands to push up off the stool, and from swinging the arms to build up additional momentum. The participant chose a comfortable starting position for both feet in the first session, and this position was kept the same throughout all trials during each of the three assessments. The distance from the base of the heel to the stool leg, and the distance between the feet whilst in the start position were used to standardise foot position across assessments. If participants wore an ankle-foot orthosis as prescribed by their physiotherapist, they were asked to perform the STS movement with the orthosis in position. Upon completion of one STS trial, the participant was instructed to place their feet in the correct starting position, indicated by electrical-tape stuck to the floor. One Xsens sensor was attached to a Velcro jacket worn by the participant on the trunk segment (Figure 56). The sensor was placed as close as possible to the spinous process of the eighth thoracic vertebra (T8), palpated by the experimenter. A second Xsens sensor was placed on the thigh of the affected side for participants diagnosed with CP hemiplegia, and the dominant side of all other participants, and secured in position using hypoallergenic double-sided tape and cohesive bandage (firstaid4sport.co.uk). The exact anatomical location for placement of the sensors and the corresponding co-ordinate systems are shown in Figure 57. Before each trial, both sensors were reset whilst the participant was seated in the start position. After two practice trials, data were collected for five trials of the STS or for as many as the participant was able to perform if they found the movement difficult or fatigued substantially. A custom CAREN application captured the angular displacement and acceleration output from the Xsens sensors during the STS at 300 Hz.

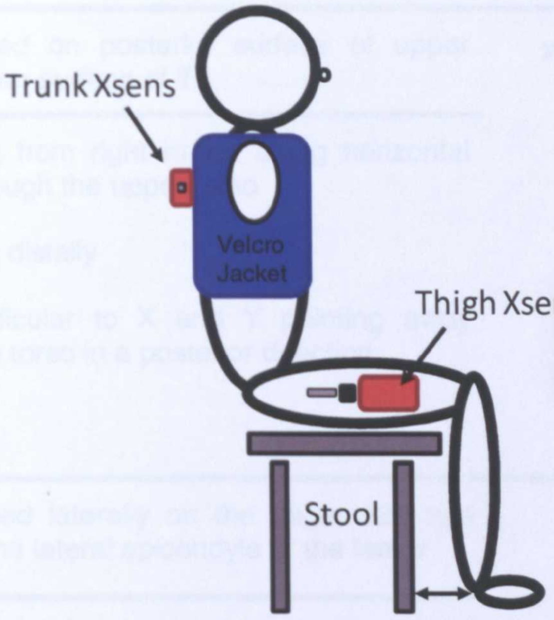


Figure 56. The start position of the STS, with the two Xsens sensors positioned on the trunk and thigh. Note that the trunk and thigh are in the neutral position at the beginning of the STS. The height of the stool and the positioning of the feet were adjusted for each participant.

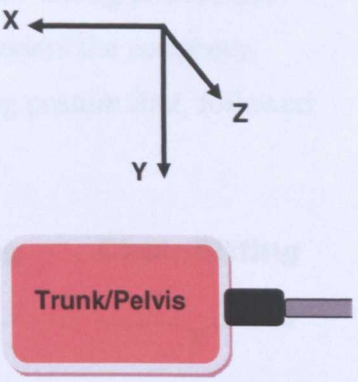
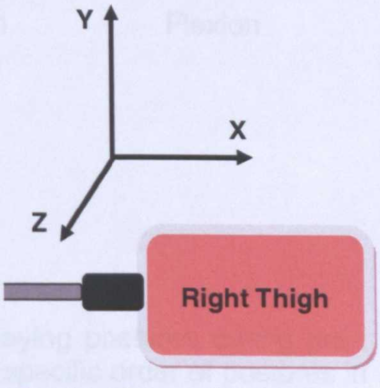
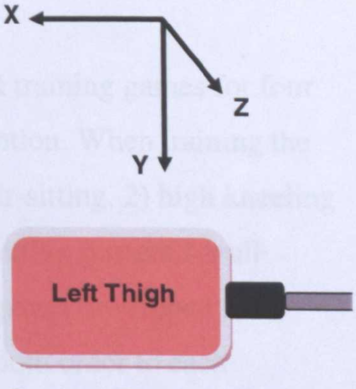
Trunk:	Positioned on posterior surface of upper torso, over surface of T8	 Frontal Plane
+X	Running from right to left along horizontal axis through the upper torso	
+Y	Pointing distally	
+Z	Perpendicular to X and Y pointing away from the torso in a posterior direction	
Right Thigh:	Positioned laterally on the thigh, 120 mm above the lateral epicondyle of the femur	 Sagittal Plane (Right Side)
+X	Aligned with long axis of the thigh, pointing in an anterior direction when seated	
+Y	Pointing away from the thigh in a superior direction	
+Z	Perpendicular to X and Y, pointing laterally in parallel with the mediolateral axis of the knee joint	
Left Thigh:	Positioned laterally on the thigh, 120 mm above the lateral epicondyle of the femur	 Sagittal Plane (Left Side)
+X	Aligned with long axis of the thigh, pointing in anterior direction when seated	
+Y	Pointing away from the thigh in an inferior direction	
+Z	Perpendicular to X and Y, pointing laterally in parallel with the mediolateral axis of the knee joint	

Figure 57. Position and orientation of the Xsens sensor on each body segment during the STS when seated, along with the corresponding co-ordinate systems used by the sensors.

6.2.4.2 THE GOBLIN POST OFFICE ASSESSMENT

During the VR assessment the *periphery group* played the GPO game first in the chair-sitting posture, using the trunk to control single plane motion, followed by cross plane motion (Figure 58). The next posture was standing, requiring single plane motion followed by cross plane motion. When testing the periphery, participants were seated in the chair-sitting posture, and began with knee joint control on the right side, followed by the left side. The ankle joint was the last level of control, starting on the right side and moving to the left side. The *core group* began the VR assessment in the chair-sitting posture but began with knee joint control followed by ankle joint control to assess the periphery. When testing the core, participants were seated in the chair-sitting posture first, followed by the standing posture.

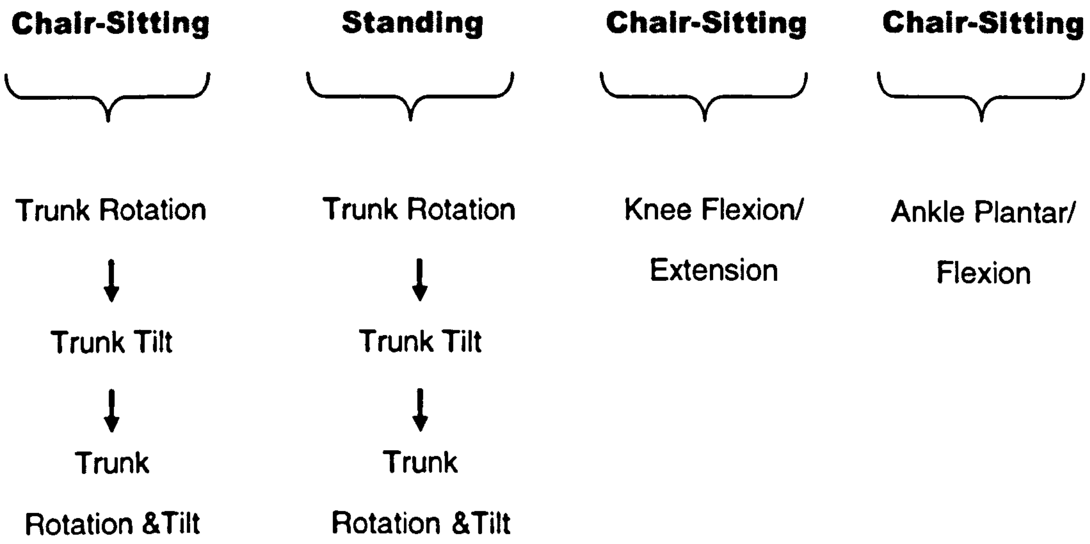


Figure 58. Flow chart representing the *Goblin Post Office* playing postures during pre-, intermediate, and post- training assessments. See text for the specific order of postures in the *core* and *periphery groups*.

6.2.4.3 VIRTUAL REALITY TRAINING

Both the *core* and *periphery group* were exposed to the same VR training games for four days from Monday to Thursday in both weeks of the VR intervention. When training the core, participants were exposed to three playing postures; 1) chair-sitting, 2) high kneeling (Section 3.2.3) and 3) standing. Participants played in the chair-sitting posture for all training on the periphery. Participants were exposed to training games developed in Chapter 5 (Section 5.4). Training games were presented in a random order to each participant, with exposure to two games in each VR training session. The same control schemes described to control the GPO (Section 6.2.3) were used to control the VR training games.

6.2.5 Measures of Performance

6.2.5.1 SIT-TO-STAND

Dependent variables of the STS movement were calculated using the custom MATLAB program (Appendix 13) described in Chapter 4 (Section 4.5). The following dependent variables were calculated: STS duration, peak flexion and peak extension of the trunk segment, peak dorso-ventral and axial accelerations of the trunk, peak positive and negative resultant acceleration of the trunk, peak flexion and extension of the thigh segment, peak positive and negative resultant acceleration of the thigh.

6.2.5.2 VARIATION OF PASS DISTANCE

Variation of pass distance was used as a way of quantifying selective motor control of the trunk, pelvis, knee and ankle. Pass distance was defined as the distance of the dragon's trajectory (as defined by the tip of the horn) from the centre of the target when the dragon passed through the plane containing the centre of the target. The variation of pass distance for each *run* was the standard deviation over all *trials* within a single *run*, which was used to define selective motor control for each body segment. An improvement in selective motor control was achieved if the variation of pass distance reduced. A custom MATLAB program (Appendix 19) was written to extract the pass distance of the virtual dragon from each *trial* performed in each *run* by all participants at every level of difficulty. Pass distance during single-plane control was defined along the X or Y axis depending on the control scheme (horizontal or vertical respectively), whilst pass distance during cross-plane motion was defined as the magnitude of the XY vector (Figure 59).

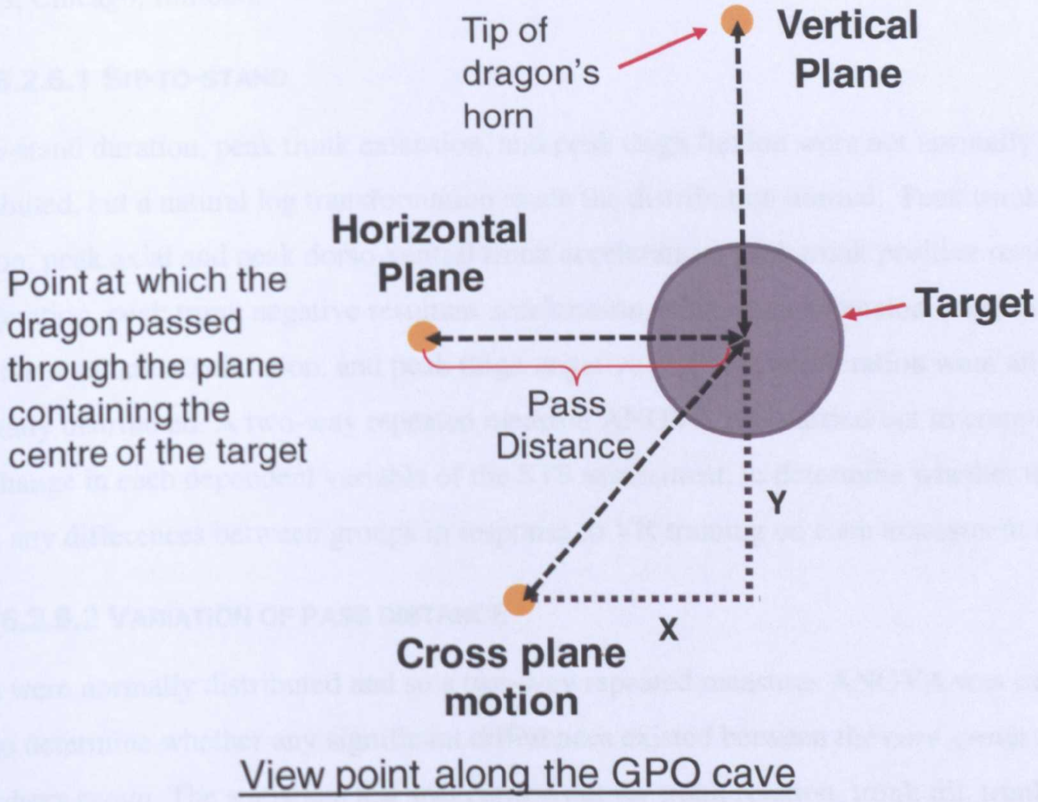


Figure 59. Pass distance was defined as the distance of the dragon's trajectory (tip of the horn) from the centre of the target when the dragon passed through the plane containing the centre of the target. Pass distance was measured along the X or Y axis for single plane control, whilst pass distance during cross-plane motion was defined as the magnitude of the XY vector.

6.2.5.3 MAXIMUM SETTLED SPEED

A custom MATLAB program described in Chapter 3 (Section 3.2.5.1) (Appendix 11) was used to extract the speeds of the virtual dragon (speed profile) from each *run* performed by all participants at every level of difficulty, during each session. The program then determined the maximum (max) settled speed, which was defined as the highest mean speed achieved with the smallest speed variance during one *block* of each *run*. Comparisons of max settled speed were made across all playing postures used by participants to play the GPO game.

6.2.6 Statistical analysis

One participant withdrew from the study due to illness after the pre-training assessment (participant 06). One participant withdrew for unspecified reasons after the pre-training assessment (participant 07), and one participant withdrew for unspecified reasons on the 2nd VR training day in week one (participant 05). The *core group* and *periphery group* had four remaining participants each, who completed the two-week VR training intervention and each assessment. Group statistical tests were carried out using SPSS *version 17.0* (SPSS, Chicago, Illinois).

6.2.6.1 SIT-TO-STAND

Sit-to-stand duration, peak trunk extension, and peak thigh flexion were not normally distributed, but a natural log transformation made the distribution normal. Peak trunk flexion, peak axial and peak dorso-ventral trunk acceleration, peak trunk positive resultant acceleration, peak trunk negative resultant acceleration, peak thigh extension, peak thigh positive resultant acceleration, and peak thigh negative resultant acceleration were all normally distributed. A two-way repeated measure ANOVA was carried out to compare the change in each dependent variable of the STS assessment, to determine whether there were any differences between groups in response to VR training on each assessment day.

6.2.6.2 VARIATION OF PASS DISTANCE

Data were normally distributed and so a two-way repeated measures ANOVA was carried out to determine whether any significant differences existed between the *core group* and *periphery group*. The statistical test was carried out for trunk rotation, trunk tilt, trunk both, the right and left knee, the right and left ankle in the chair-sitting posture. Participants found it difficult to play the GPO game using the core in the standing posture. No statistical analysis was carried out in this posture due to missing data values.

6.2.6.3 MAXIMUM SETTLED SPEED

There was a large amount of missing max settled speed data. This was due to the inability of some participants to reach a settled speed, whilst three participants also withdrew from the study. It was not possible to carry out a two-way repeated measures ANOVA as planned. Descriptive statistics were instead reported that analysed the differences between control schemes within the core (single plane trunk motion (trunk rotation and trunk tilt) versus cross plane trunk motion), differences between control schemes within the periphery (knee control versus ankle control), and the differences between core and peripheral control (trunk single plane and cross plane motion combined versus knee and ankle control combined). Combined scores were based on no fewer than two values of max settled speed for each condition for each group.

6.3 Results

6.3.1 Summary of data obtained

The main findings indicate that there were minimal changes to performance of the STS movement in response to VR training for either the *core group* or the *periphery group*. Game performance improved in both groups after VR training, highlighted by a reduction in variation of pass distance, and an increase in max settled speed for the GPO playing postures. Specifically, single plane movements of the trunk were better controlled than cross plane movements, whilst ankle control was better than knee control in both groups after VR training. Overall, the periphery was better controlled than the core during VR game performance.

6.3.2 Sit-to-stand analysis

Changes in dependent variables of the STS movement are reported in Figure 60 and Figure 61. The *core group* demonstrated a statistically significant increase in peak trunk flexion ($p = 0.037$) from 36.88 ± 20.30° (pre-training) to 48.68 ± 16.37° (intermediate) (Figure 60(b)). Figure 60(d) indicates that there was a large difference between groups when measuring peak axial acceleration of the trunk during the sit-to-stand movement ($p = 0.069$). The *core group* produced larger accelerations than the *periphery group* during the intermediate assessment (3.63 $m.s^2$). Following the second week of training, peak axial trunk accelerations at post-training assessment (6.27 $m.s^2$) matched those measured at pre-training (6.33 $m.s^2$) for the *core group*, indicating a decrease back to baseline. The *core group* took longer to complete the STS when grouped together across assessments

(2.01 ± 0.92s) compared to the *periphery group* (1.76 ± 0.57), but the difference between groups was not significant (Figure 60(a)). There were no significant differences ($p > 0.05$) in all remaining STS dependent variables (Figure 60(b-k)) in response to VR training, and no significant differences were found between groups.

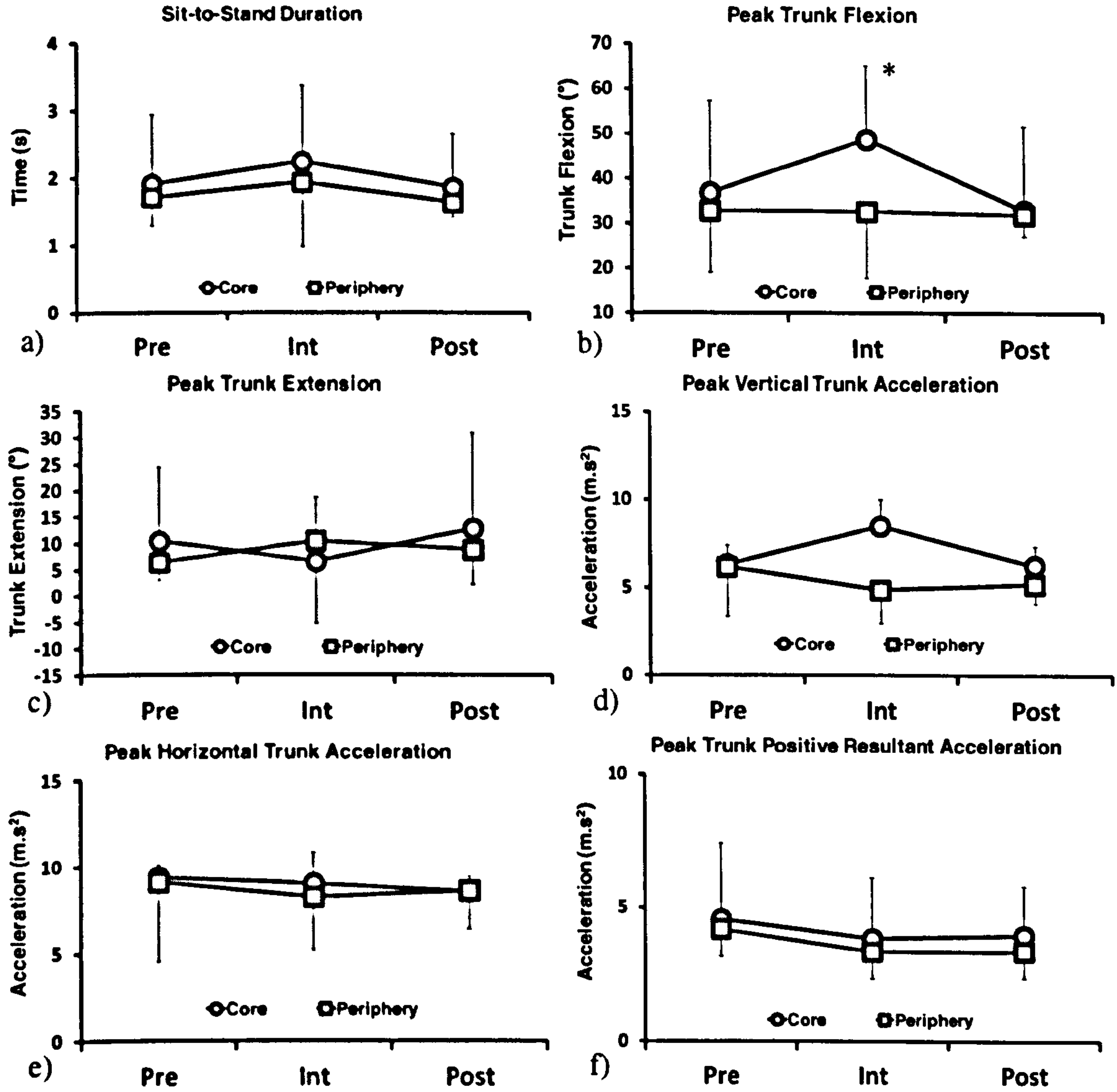


Figure 60. Limited change in STS dependent variables occurred for both the *core* and *periphery group* at each assessment in response to VR training. There was a statistically significant change (*) in trunk peak flexion across assessments (b), with large changes in peak axial trunk acceleration (d).

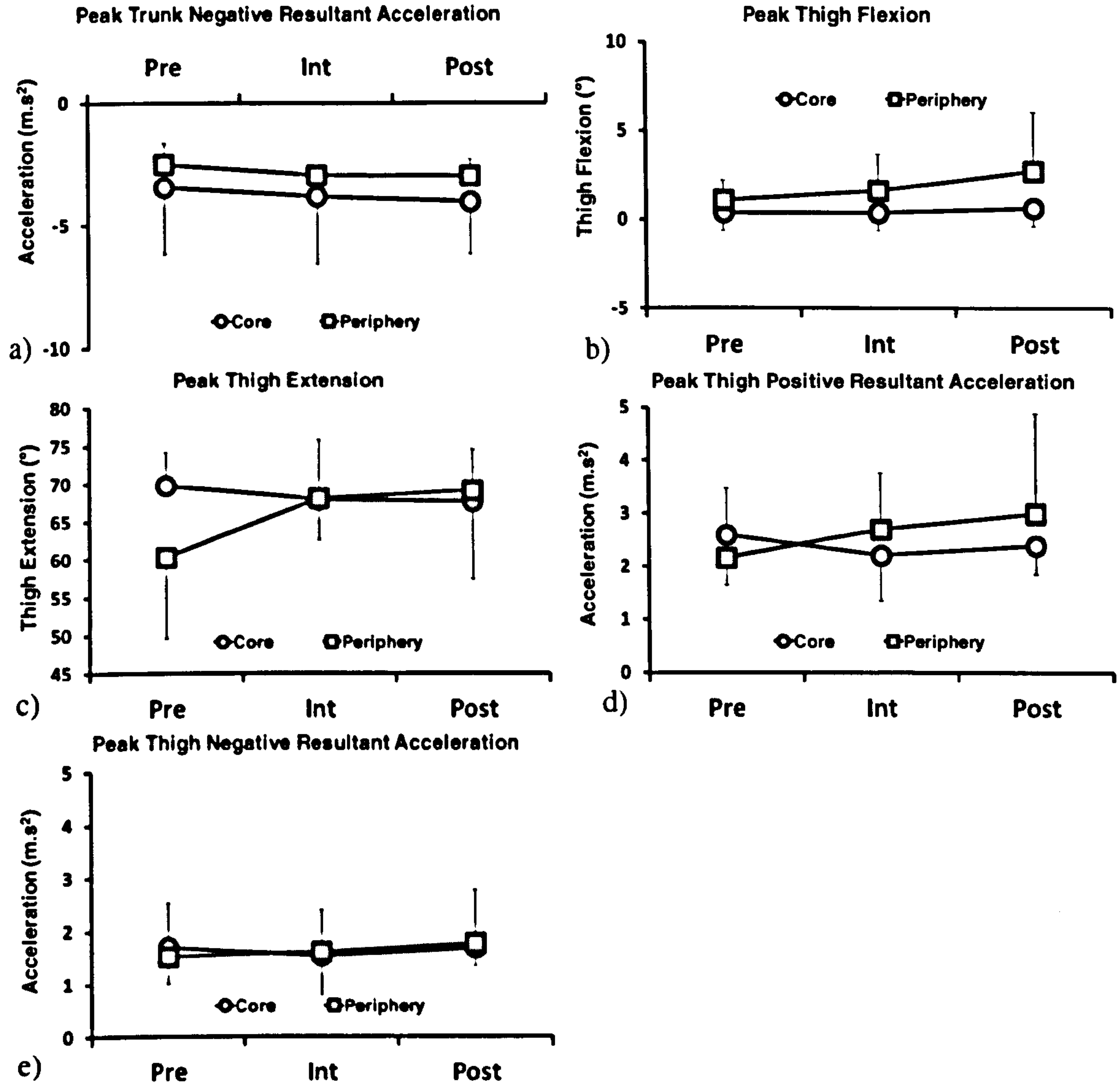


Figure 61. Limited change in STS dependent variables occurred for both the *core* and *periphery group* at each assessment in response to VR training.

6.3.3 Variation of pass distance

6.3.3.1 CHAIR-SITTING TRUNK ROTATION/TRUNK TILT/TRUNK BOTH

In chair-sitting trunk rotation there was a significant reduction in variation of pass distance between pre- and post-training assessments regardless of group allocation ($F_{1,5} = 6.650$, $p = 0.05$). The *core group* showed a reduction from 19.00 ± 16.44 m (pre-training) to 11.37 ± 9.17 m (post-training), whilst variation of pass distance in the *periphery group* decreased from 13.23 ± 9.34 m (pre-training) to 7.71 ± 3.14 m (post-training). There was a large reduction in variation of pass distance between pre- and post-training assessments when playing the game using trunk tilt in chair-sitting (Figure 62(b)), indicated by a mean reduction of 8.94 (95% CI = -0.84, 18.72, p = 0.66). Figure 62(c) illustrates that variation of pass distance for chair-sitting trunk both increased in the *periphery group* after receiving VR training on the periphery, and decreased in response to core training. The changes were not significant though (p > 0.05). There were no main effects of group allocation on variation of pass distance for control schemes used in chair-sitting (p > 0.05).

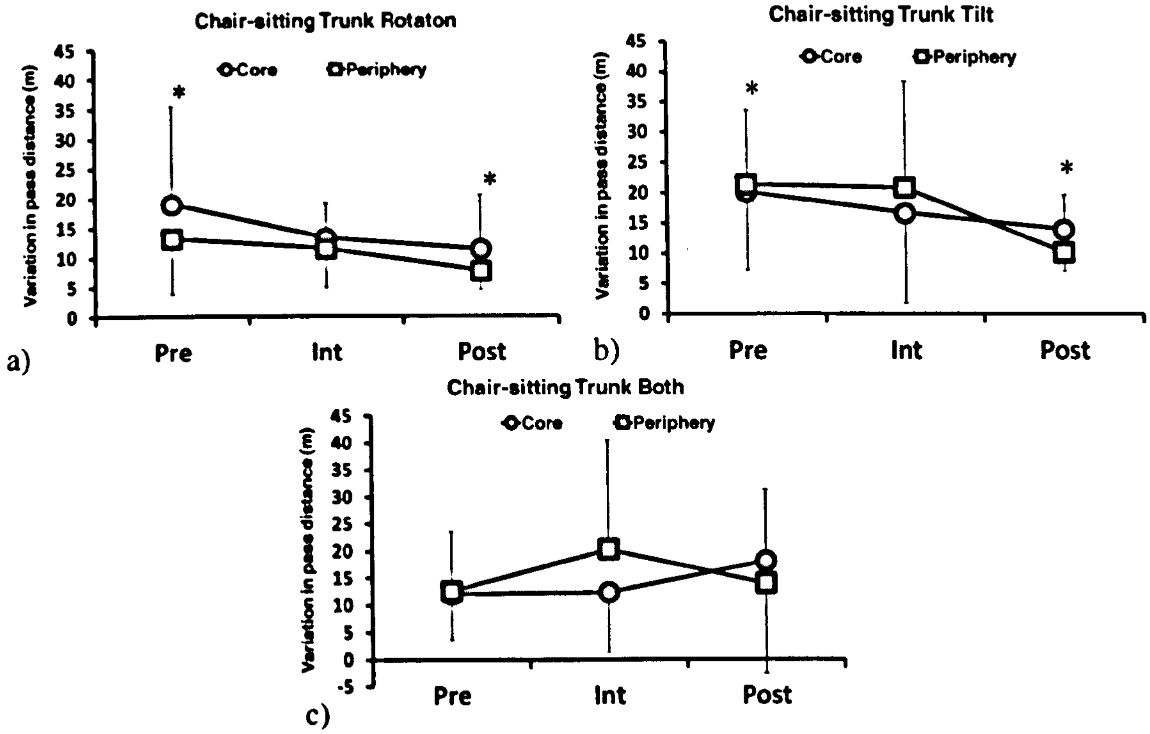


Figure 62. a) There was a significant reduction in variation of pass distance in chair-sitting trunk rotation. b) A large reduction in variation of pass distance existed between pre- and post-training during chair-sitting trunk tilt. c) Variation of pass distance increased in the *periphery group* in response to peripheral training between pre- and intermediate assessments. Asterisks denote where statistically significant changes occurred between assessment days.

6.3.3.2 CHAIR-SITTING RIGHT KNEE/LEFT KNEE

The results suggest that there was a large decrease in variation of pass distance across assessments, when using the right knee to steer the virtual dragon (p = 0.087) (Figure 63(a)). This is highlighted by a significant difference between pre- and post-training assessments regardless of group allocation (p = 0.014), and a mean difference of 6.79 m (95% CI = 1.93, 11.65, p = 0.014). There were no significant changes for variation of pass distance in response to VR training on the left knee. Figure 63(b) shows that on average the variation of pass distance in the *periphery group* remained similar across pre-training, intermediate, and post-training assessments. The *core group* demonstrated a mean increase in variation of pass distance at intermediate assessment of 9.54 m. In response to VR training on the periphery during the second week, *core group* variation of pass distance remained similar at post-training to that recorded at intermediate assessment. There were no significant differences between groups (p > 0.05) for the right or left knee.

6.3.3.3 CHAIR-SITTING RIGHT ANKLE/LEFT ANKLE

There were no significant differences across assessment days for both groups when using ankle joint control in the chair-sitting posture (Figure 63(c & d)). Figure 63(d) indicates that variation of pass distance increased from pre-training (15.77 ± 6.20 m) to intermediate assessment (20.18 ± 17.33 m) in the *core group* in response to core training, but reduced at post-training in response to peripheral training (12.63 ± 9.80 m).

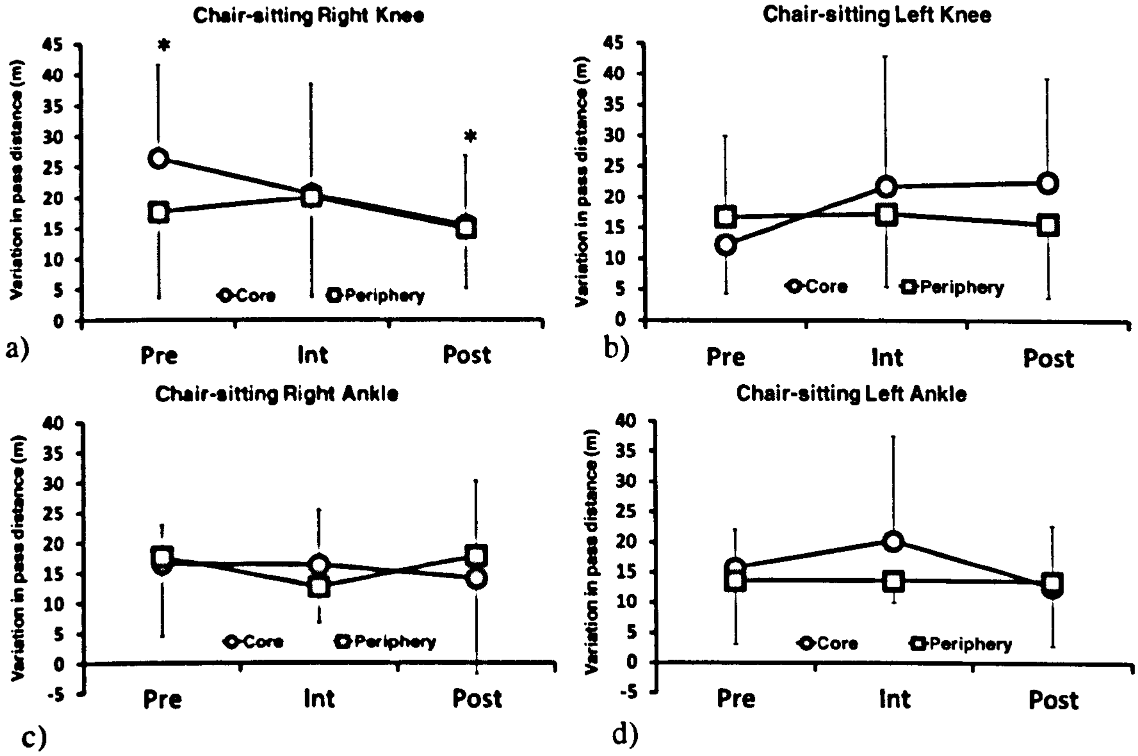


Figure 63. Variation of pass distance is larger across assessments for the knee joint (a-b) in both the core and *periphery group* than variation of pass distance at the ankle joint (c-d). Asterisks denote where statistically significant changes occurred between assessment days.

6.3.3.4 OVERALL COMPARISON

There was a reduction in variation of pass distance for both groups in response to VR training at post-training assessment, with a mean decrease of 2.25 m in the *core group* and 2.42 m in the *periphery group* (Figure 64). The *periphery group* demonstrated greater accuracy across all assessments throughout the two-week intervention.

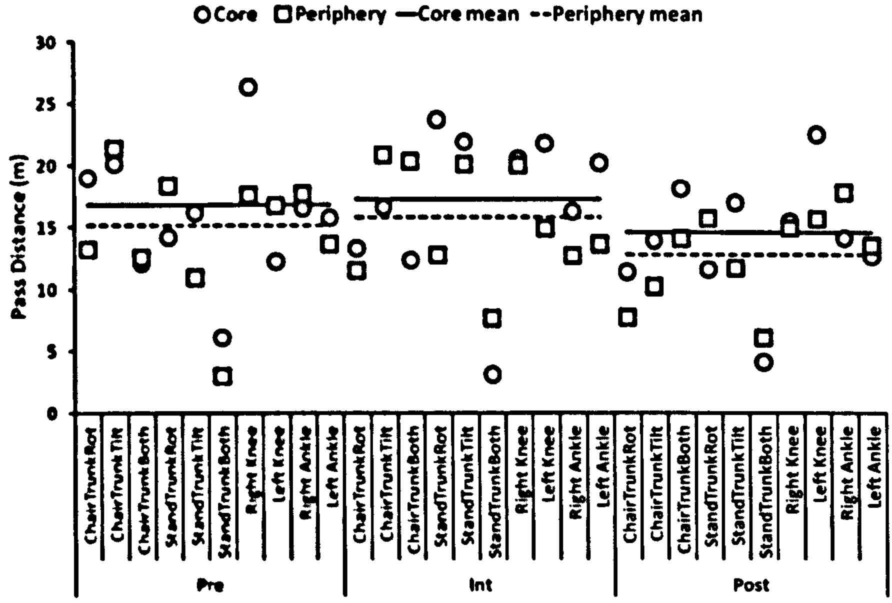


Figure 64. Changes in variation of pass distance across all postures for each assessment session. Mean differences indicate that the *periphery group* were on average closer to the target than the *core group* at each assessment (mean variation of pass distance represented by horizontal black line (core) and dashed line (periphery)).

6.3.4 Maximum Settled Speed

6.3.4.1 SINGLE PLANE MOTION VERSUS CROSS PLANE MOTION OF THE TRUNK IN CHAIR-SITTING

Analysis of control at the core during chair-sitting indicates that single plane motion of the trunk is better controlled than cross plane motion for both the *core* (Figure 65(a)) and *periphery group* (Figure 65(b)). In the *core group* the mean difference between single and cross plane motion across all assessments was 4.22 m.s^{-1}, compared to 12.41 m.s^{-1} for the *periphery group*. The *core group* achieved similar max settled speeds at post training for both single and cross plane motion.

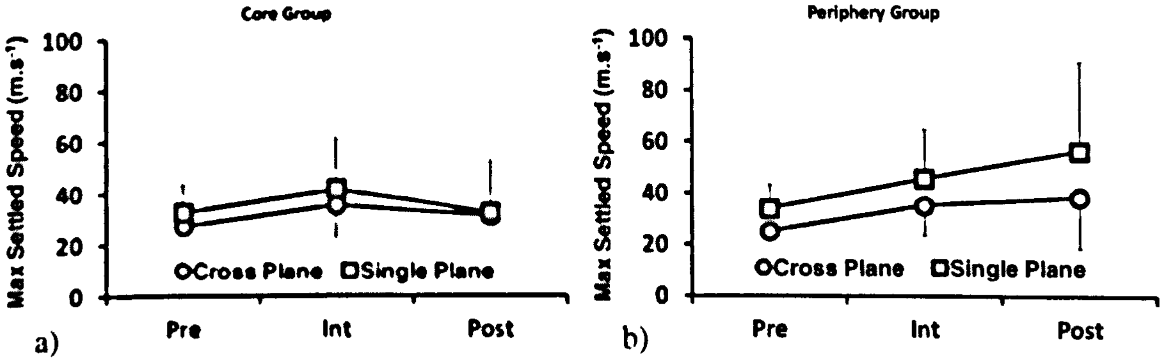


Figure 65. Single plane motion of the trunk achieves greater max settled speed than cross plane motion of the trunk during GPO game play, in both the *core group* (a) and the *periphery group* (b).

6.3.4.2 KNEE VERSUS ANKLE CONTROL

Participants in both training groups achieved greater max settled speed when driving the GPO game using the ankle joint compared to the knee joint. The difference between the knee and ankle in the *core group* at pre-training was 20.51 $m.s^{-1}$ compared to 8.61 $m.s^{-1}$ at post training. In the *periphery group* the difference was again higher at pre-training (34.17 $m.s^{-1}$) compared with post-training (13.44 $m.s^{-1}$) (Figure 66).

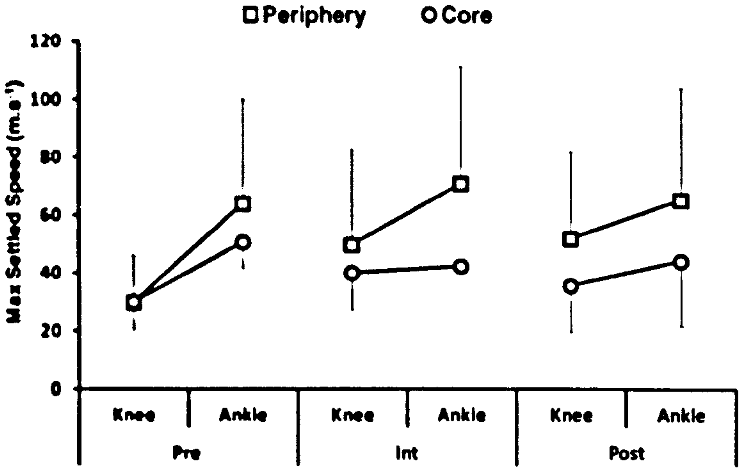


Figure 66. The ankle joint reaches higher max settled speed during GPO game play compared to the knee joint, in both the *core* and *periphery group.*

6.3.4.3 A COMPARISON OF THE CORE AND PERIPHERAL SEGMENTS

Figure 67 indicates that participants belonging to both the *core* and *periphery group* achieved greater max settled speed using the knee and ankle joints (peripheral segments) when compared to the trunk (core segment). This pattern of performance is present at pre-, intermediate, and post-training assessment for all participants. A larger separation between the *core* and *periphery group* at post-training suggests that the *periphery group* responded more to VR training at the trunk, knee and ankle than the *core group.* The highest average max settled speed was registered by the *periphery group* during intermediate-assessment at the knee and ankle (59.38 $m.s^{-1}$) in response to the first week of VR training on the periphery.

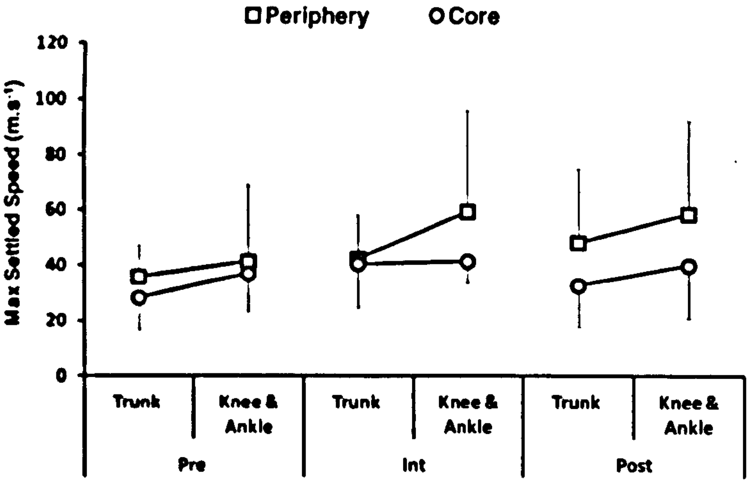


Figure 67. Greater max settled speed was reached using the peripheral segments (knee and ankle) compared to the core segment (trunk) during GPO game play at each assessment for both the *core* and *periphery group*.

6.3.4.4 OVERALL COMPARISON

The *core group* demonstrated an increase in max settled speed from pre- to intermediate-assessment (9.19 $m.s^{-1}$), a decrease in max settled speed from intermediate to post-training (-5.15 $m.s^{-1}$), and an increase overall from pre- to post-training (4.05 $m.s^{-1}$) in response to VR training when averaging across all postures. An increase in max settled speed was also evident for the *periphery group*, represented by a change of 11.62 $m.s^{-1}$ between pre- and intermediate-assessment, 2.60 $m.s^{-1}$ between intermediate and post-training, and an overall change of 14.23 $m.s^{-1}$ between pre- and post-training (Figure 68). The results of both groups show an improvement in GPO game performance as a result of training, but the performance of the *core group* dropped after the second week of VR training indicated by achieving lower max settled speeds. Figure 68 indicates that the *periphery group* reached higher max settled speed than the *core group* for the majority of playing postures.

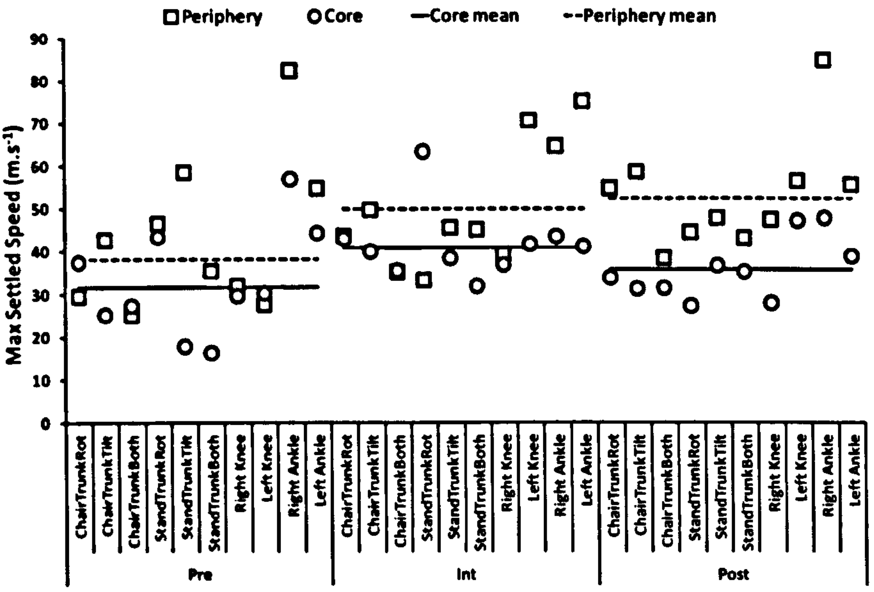


Figure 68. Changes in max settled speed across all postures for each assessment session. Mean differences indicate that the *periphery group* outperformed the *core group* at each assessment (mean max settled speed represented by horizontal black and dashed lines respectively).

6.4 Discussion

The experimental hypothesis stated that VR training of the core followed by VR training of the periphery would improve performance of the STS to a greater degree than VR training of the core only. Increases were found in VR performance at both the core and periphery in each training group, but did not transfer to performance of the STS, with minimal changes occurring in all dependent variables. On this basis, the experimental hypothesis for the study was rejected. The biomechanical mechanisms that may relate to the lack of change in the STS movement, and the positive changes in VR game performance are further discussed.

6.4.1 The sit-to-stand does not improve in response to virtual reality training

Peak flexion of the trunk increased significantly in the *core group* at intermediate-training compared to pre-training, with no significant change in the *periphery group*. During the STS movement peak trunk flexion occurs when rising from the seated position. Forward momentum is generated to make the transition into standing easier (Park *et al.*, 2003; Galli *et al.*, 2008). Flexing the trunk further than at pre-training during the STS could have enabled the *core group* to generate greater forward momentum and thereby require less muscular effort of the lower limbs (Papa & Cappozzo, 2000). The reported significant increase in peak axial trunk accelerations is therefore likely to be a consequence of greater momentum during the flexion-momentum phase. It is possible that VR training led to the increase in trunk flexion in the *core group*, since the training of trunk tilt requires the centre of mass to move close to the edge of the base of support frequently during game play. After a sustained period of training, in this case four days of intense practice, participants' perceived improvement in control of the trunk could have led to participants allowing their centre of mass to move closer to the edge of the base of support. However it could be argued that an increase in peak trunk flexion and therefore greater momentum would also result in a decrease in STS duration, which is not reported in the current results. Although changes could be attributed to core-specific VR training during the first week for the *core group*, the *periphery group* demonstrated no change in response to core-specific VR training after week two, indicating that the results are not generalised across both groups.

The STS durations reported in this study are consistent with previous literature reporting STS duration in children with CP. Hennington *et al.* (2004) reported that CP children took 1.71 ± 0.36 s to complete the STS compared to TD children who completed it in 1.24 ± 0.18 s. The *periphery group* match the findings of Hennington *et al.* (2004) for STS duration (1.76 ± 0.57 s), whilst the *core group* took longer (2.01 ± 0.92 s). Park *et al.* (2003) reported that children with CP diplegia took longer to complete the STS movement (2.44 ± 1.01 s) than children with CP hemiplegia (2.09 ± 0.98 s). Although STS duration in the *core group* was similar to that reported by Park *et al.* (2003) in children with CP hemiplegia, the *core group* consisted of one quadriplegic, one spastic diplegic, one child with ataxia and one hemiplegic. In addition to more consistent pathology, Park *et al.* (2003) had a larger group size (n =12), providing a more reliable indication of performance than the current findings. Interestingly, Hennington *et al.* (2004) report that children with CP take significantly longer during the extension phase of the STS movement, suggesting children with CP have weakness of the lower-extremity extensor muscles. A possible compensation for weakness might be increased trunk flexion to improve momentum during the flexion momentum phase, and evidence of this was found in the current study.

6.4.2 Game performance increased in response to virtual reality training

Both training groups showed a reduction in variation of pass distance suggesting participants improved the consistency of selective motor control during VR game at post-training in response to the VR intervention, regardless of the order of training. The *periphery group* demonstrated greater consistency during each assessment. Descriptively, greater max settled speeds were achieved in response to VR training for both the *core* and *periphery group*, across all playing postures. Importantly, larger increases in max settled speed were demonstrated in the *periphery group* at both intermediate and post-training assessments compared to the *core group*. One explanation for greater improvement in the *periphery group* may be that the participants in that group responded better to the order of training they received. The current findings therefore suggest that max settled speed game performance may improve to a greater extent when training the periphery first followed by the core. Overall, a reduction in variation of pass distance and increase in max settled speed indicate that participants have made an improvement in selective motor control at both the core and the periphery. The possible explanations for improvement are discussed further in the subsequent sections.

6.4.3 Single plane movements of the trunk are better controlled than cross plane movements

Single plane motion of the trunk in either the transverse or sagittal plane resulted in a higher max settled speed in each assessment, compared to cross plane control which required co-ordinated movements in two planes. Although variation of pass distance from the centre of the target was greater using single plane motion compared to cross plane motion during the pre-training assessment, there was a significant reduction in variation of pass distance using trunk rotation or trunk tilt in chair-sitting at post-training (Figure 62(a & b)). In comparison, variation of pass distance during cross plane motion changed little over assessment periods, with no sign of improvement. The relationship between max settled speed and variation of pass distance suggests participants were better at reaching higher game speeds using single plane motion during each assessment, but developed a higher level of control in response to VR training and may have become more precise with their movements. The current findings indicate that it is easier to control the trunk when moving it about one axis of rotation, supporting previous case study results (Section 3.3). It is likely that cross plane movements provide greater task complexity than single plane movements due to the extra degree of freedom of the trunk segment which needs additional control. Combined motion of the trunk is necessary for coping with the demands of many ADL such as gait and STS, hence training cross plane movements in rehabilitation is essential. The use of single plane and cross plane motion to control VR games has not previously been reported due to the novel approach of the current research. Further research on a larger population of children with CP would show whether the findings revealed in this study can be generalised to the wider CP population. If similar findings were found, incorporating cross plane motion training into future rehabilitation programmes could be essential for exposing children to movements that lead to better performance in ADL.

6.4.4 Ankle control is better than knee control

Greater max settled speeds were achieved when using the ankle joint to control GPO game play, as opposed to knee joint control, during each assessment. Variation of pass distance from the targets was less in chair-sitting right ankle and left ankle control compared to right knee and left knee control (Figure 63(a-d)). The discovery that the ankle performs better than the knee contradicts the assumption that loss of selective motor control is more severe in the distal portion of the limb than the proximal portion (Gage *et al.*, 2009), but the effects of pathology on human movement in children with CP can vary. The mechanical properties of these joints could explain the increased performance at the ankle joint during VR game play. In the chair-sitting posture, the knee is a central link between the upper and lower leg, and is controlled by bi-articular muscles that aim to provide enhanced movement to the most distal part of the lower limb. In comparison the ankle joint affects the resulting position of the foot predominantly, and is largely influenced by how the knee joint behaves. Therefore training at the knee joint ultimately led to training at the ankle joint simultaneously, even when the ankle joint is not used to drive the GPO game, which could have led to greater control at the ankle. However, in response to VR training the results show that knee control improved more progressively than ankle control across the assessment days, indicated by a smaller difference between both joints on intermediate and post-training assessment days. This suggests that knee control responded to VR training more than ankle control.

The additional level of control required to drive the GPO game using the 'Street Glider' device could have led to greater task complexity at the knee compared to the ankle, since the movement task required at the knee joint is unfamiliar. Typically flexion and extension at the knee joint during sitting requires the surrounding musculature to perform against gravity using the concentric and then eccentric contraction of extensor muscles. Instead, the 'Street Glider' device essentially provided knee flexion and extension by accelerating the foot forwards and backwards along the floor, excluding the effect of gravity. Hence whilst concentric contraction of extensor muscles occurred in a similar manner when translating the foot forwards, a concentric contraction of the knee flexors was required in order to translate the foot backwards. Therefore an alternative muscle activation pattern may have resulted in lower max settled speed being achieved during VR assessment due to unfamiliarity with the task.

6.4.5 Control of peripheral segments is better than control of core segments

Better game performance was achieved using the periphery to control VR game play in comparison to core control in both training groups, evidenced by larger max settled speeds. Better control at the periphery is expected due to the frequent use and better selective control of the lower limbs during ADL, compared to selectivity of the trunk. Typically the part of the brain that controls the periphery is associated with an increased cortical representation ensuring good selective control of the extremities during ADL such as walking, rising from a chair, and standing. In contrast, the trunk and pelvis have a smaller cortical representation resulting in low selective motor control during ADL (Gage *et al.*, 2009). The current study results support this theory, since control was better at the periphery than the core during baseline measurements at the pre-training assessment, before VR training had commenced. Gage *et al.* (2009) stated that due to larger cortical representation, the periphery is more affected as a result of brain injury. Typically the most notable difficulties experienced by children with CP are related to selective motor control at the upper and lower extremities. You *et al.* (2005) state that hemiparetic CP (weakness on one side of the body) can typically lead to delays in motor development or de-conditioning of the affected limb, with a tendency to compensate by using the intact limb rather than attempts to use the involved limb. This ultimately leads to suppressing development of cortical representation for the affected side whilst increasing representation of the intact side. The same neural mechanism could explain poor control of the core, since evidence from the current study suggests that selective motor control of the trunk and pelvis is outperformed by the periphery during VR game play. Compensations for poor core control may develop through the use of the extremities, such as using the upper extremity to push up from the seated position, or holding on to nearby objects to maintain an upright posture during sitting or standing. As a consequence the cortical representation of the core may be diminished while representation of the periphery is increased.

There is evidence to suggest that lower extremity treadmill training can lead to a greater cortical representation of the ankle joint in the brain in children with CP (Phillips *et al.*, 2007). Furthermore, You *et al.* (2005) reported evidence of neuroplastic changes in response to an upper extremity VR intervention, suggesting that cortical reorganisation can occur. In the current findings it is possible that the periphery had a greater cortical representation than the core prior to intervention, resulting in better performance at the periphery, but that both the core and periphery are likely to increase cortical representation in response to VR training. Functional MRI was not an outcome measure of VR training in the current research project and so suggestions that changes to the brain may have occurred are speculative and based on current findings in the literature (You *et al.*, 2005).

6.4.6 Limitations of the research design

A randomised cross-over design consisting of six participants in the *core group* and five participants in the *periphery group* was devised to address the study aims and objectives. As a result of subject attrition only four participants in each group completed the training study resulting in low statistical power. During the recruitment period for the study, NHS physiotherapists provided the names of 22 children who matched the inclusion criteria for the study. Not all children were able to take part in the study for a number of different reasons including; school commitments, the inability to make contact with parents/guardians, lack of interest in participating. Some participants withdrew after the study began. Within the two groups there was large variation in the classification of children, thus confounding factors could have led to misleading changes in response to VR training. Inconsistent pathology amongst participants in each group makes the findings on selective motor control difficult to generalise to rehabilitation in children with CP.

6.4.7 Training frequency and intensity

The increased frequency and intensity of training in the current study compared to study one (Chapter 3) aimed to provide the maximum amount of exposure to VR training for participants in a small time frame. This ensured there was minimal disruption to the participant's daily routine at school. The study consisted of an intense four-day burst of training on the core or periphery of the body followed by another four days on the alternative body segments. Intense periods of training at a high frequency have resulted in improved ADL. Woollacott *et al.* (2005) reported that five days of intense postural balance training on children with CP can lead to regaining balance faster in response to external perturbations. Shumway-Cook *et al.* (2003) showed that children with CP reduced centre of pressure area and increased their time to stabilisation in response to external perturbations, following five days of intense training. Though positive changes in VR performance occurred following intense periods of VR training in the current study, the positive changes did not transfer to the STS movement and so it must be considered that the training frequency and intensity were inadequate. In contrast to short intense training periods, You *et al.* (2005) reported that 60 minutes of training, five times a week, for four weeks resulted in improvements in upper limb function, due to cortical reorganisation. Sandlund *et al.* (2009) reported that computer game-based training interventions in children with sensorimotor disorders typically last four weeks, although interventions do not always result in a positive effect during that time. In retrospect, the current VR training intervention might have been too short to transfer improvements in VR game play to ADL. Further exposure to VR training over a longer week period might better determine whether improvements in VR performance can transfer to ADL.

The current findings provide an indication of the effect size which leads to a significant difference in selective motor control in response to VR training. For example, variation of pass distance significantly reduced in the *core group* for chair-sitting trunk rotation, indicated by a reduction from 19.00 ± 16.44 m (pre-training) to 11.37 ± 9.17 m (post-training). The effect size (the difference between the means divided by the standard deviation of the pre-training variation of pass distance) is equal to 0.46. This indicates that the VR intervention had a moderate effect (Knudson, 2009) on selective motor control of trunk rotation in the core group. A moderate effect suggests that the current VR training intervention may not have been sufficiently designed to improve selective motor control of trunk rotation. Instead, the large variability reported could explain the change in the variation of pass distance. A reduction in the variability of the group scores, or a greater difference in variation of pass distance between pre- and post-training would result in a larger effect.

6.5 Conclusion

The current study is the first to report the effects of VR training on the STS movement. In addition, it is the first study to consider a VR based cross-over design looking at the effects of training order on VR outcome measures in children with CP. The STS did not improve in response to VR training on the core followed by the periphery, though selective motor control of the trunk, knee and ankle improved in response to VR training when measured using VR specific outcome measures (max settled speed and variation of pass distance). Several outcomes specific to VR game play were reported; single plane movements of the trunk were better controlled than cross plane movements, the ankle produced better control than the knee, and control of peripheral segments were better than control of core segments. Low participant numbers make the findings on selective motor control difficult to generalise to a larger population of children with CP. It is hypothesised that increased participant numbers and longer exposure to VR training might lead to greater benefits in ADL such as the STS.

Chapter 7. General discussion

7.1 Overview

The main aim of this research was to investigate the effect of virtual reality (VR) training on performance of activities of daily living (ADL) in children with cerebral palsy (CP). Training was approached by targeting the core of the body, with evidence to suggest a high demand is placed on the trunk and pelvis during ADL (Butler, 1998; Sartor *et al.*, 1999; Giansanti *et al.*, 2007). Participants were either exposed to VR training using the core (experimental group), or VR training using joystick control (control group) in a feasibility study (Study One). Measures of VR performance and gait analysis before and after a six-week training period assessed firstly whether there were any improvements in VR game play, and secondly whether improvements in VR game play led to benefits in gait. A secondary aim of the research was to develop a portable and more practical method of virtual rehabilitation to make VR training more accessible to children with CP. A portable VR system that uses inertial measurement units (IMU) to control VR game play was used within primary schools across Liverpool to address both aim one and two simultaneously. Training was designed to target the core followed by the periphery of the body using a portable VR system, to assess whether exposure to peripheral training beyond core training led to improvements when completing the sit-to-stand movement (STS) (Study Two). Some aspects of the results have been discussed in preceding chapters, but a number of general questions arose. The following specific questions will be addressed in subsequent sections;

- Why did improvements in VR game performance not lead to improvements in ADL?
- Does selective motor control at the core and periphery improve in response to VR training?
- Is there a preferred order for VR training to maximise the benefits?
- Does a portable VR system solve the overriding issue of access to virtual rehabilitation?

To answer these questions some more fundamental questions must be posed:

- Should ADL be used as an independent outcome measure of performance in response to VR training?
- Why does greater selective motor control exist at the periphery compared to the core?

- Does virtual rehabilitation provide benefits beyond conventional physiotherapy?
- Do existing commercial systems such as the *Nintendo Wii* and *Microsoft Kinect* provide a better alternative for virtual rehabilitation?

7.1.1 Improvements in virtual reality game performance do not translate to improvements in activities of daily living

Features of game performance (max settled speed and variation of pass distance) were used to assess changes in selective motor control in this research project, but existing VR interventions typically use real-world independent outcome measures to monitor changes in performance, such as reaching tasks (You *et al.*, 2005; Chen *et al.*, 2007). Gait and the STS were chosen to assess whether improvements in selective motor control, as defined by game performance, transferred to improvements in ADL. Changes in gait were measured using the Gait Deviation Index (GDI), which quantified how patients moved towards or away from normality. Assuming that a single number can encapsulate even subtle and localised changes of gait, the GDI did not change significantly, suggesting improved game performance did not transfer to gait. Whilst the role of the core is important during gait, Study One failed to measure the intricate details of how the trunk and pelvis interact during gait, considering that the kinematic model outlined by Davis *et al.* (1991) recorded movement of the lower extremities and the pelvis only. Attention to the role of the trunk during gait analysis would have provided an outcome measure that was specific to VR training on the core. Equally, the specificity of VR training could be questioned as a method for improving movement of the lower extremities through core-specific training. Sartor *et al.* (1999) suggest that anti-phase coupling of the trunk and pelvis aids progression of the swing limb, implying a lead role for the core during gait that improves efficiency by increasing step length. The single-subject design nature of Study One due to low participant numbers meant it was difficult to make any conclusions on how VR affects gait in children with CP. Gait is a combination of more hard-wired local control modulated by descending signals and direct control both established by experience during development and maturation. The VR interventions trained movement components which were likely to improve performance of the required motor task during game play, but the improvements are unlikely to cause direct changes to well established gait patterns that have developed over time as a result of maturation. They may lead to reorganisation and adaptation of gait in the long term if VR training continued.

In Study Two the STS was chosen as an independent outcome measure because it requires greater selective motor control of both the core and periphery. The STS relies on selective motor control of the trunk to initiate the movement during the flexion-momentum phase, whilst the lower extremities are crucial in performing the extension phase which ultimately leads to standing. The previous study considered the transfer of improvements at the core to functional performance at the periphery (a distally directed transfer of control). The specificity of the STS as an outcome measure was assumed to be more appropriate in assessing the transfer of core-specific VR training to control of the core during the STS. Findings indicated that trunk flexion increased significantly in the *core group* in response to core training at intermediate-training, but returned to baseline at post-training. Flexing the trunk further than at pre-training could have enabled the *core group* to generate greater forward momentum and thereby require less muscular effort in the lower limbs (Papa & Cappozzo, 2000) throughout the STS. Reduction of STS duration however did not occur as a result of VR training, but was in agreement with previous literature reporting STS duration in children with CP (Park *et al.*, 2003; Hennington *et al.*, 2004).

There is a paucity of research reporting the effects of VR training on gait or the STS due to the limited existence of VR training studies in children with CP. Studies use specially developed motor function measures rather than objective video motion analysis to independently assess the outcome of training interventions. The Gross Motor Function Measure (Russell *et al.*, 2000) is routinely used to assess changes as a result of training interventions involving children with CP. It is scored by observation of a child's performance on tasks such as crawling, kneeling, sitting, standing, and walking. Based on the Gross Motor Function Measure, training interventions have demonstrated positive effects on movement function. For example, Borggraeffe *et al.* (2010) demonstrated that robotic-assisted treadmill therapy led to increased walking distance and duration in children and adolescents with bilateral spastic CP. Schindl *et al.* (2000) reported that treadmill training with partial body weight support led to significant improvements in ambulation for children with CP, ranging from increased walking distances, to being able to independently climb stairs. Use of such measures may have shown improvements in motor control that were not recognised through motion analysis.

7.1.2 Selective motor control at the core and periphery improves in response to training

Study One and Study Two demonstrated that game performance improved in response to VR training, suggesting that virtual rehabilitation had a beneficial effect on selective motor control of the trunk, pelvis, knee, and ankle in children with CP. Study One reported that *core group* participants achieved large improvements in max settled speeds in all playing postures. Similarly, Study Two reported an improvement in max settled speeds and a reduction in variation of pass distance at both the core and periphery in response to VR training in all playing postures. Barton *et al.* (2006) previously demonstrated that different control patterns existed between a typically developing child and an asymmetrical CP diplegic adolescent when driving a VR game using the pelvis. However, evidence of improved selective motor control at the core has yet to be reported in the VR literature and so the results of this research provide a unique insight into how the core responds to specific VR training. Improvements at the periphery are supported by previous research which demonstrated that VR exercises elicit a greater range of motion at the ankle joint in comparison to conventional (selective motor control without VR) exercise in children with CP (Bryanton *et al.*, 2006). Deutsch *et al.* (2001) reported that a stroke patient achieved a 30% increase in accuracy during VR game play when using selective motor control of the ankle joint to drive a virtual aeroplane towards oncoming targets. Improvements in game play transferred to increased ranges of motion being produced during selective plantarflexion (14°), inversion (5°), and eversion (10°) of the ankle joint in a real-world task. Training selective motor control in Study One and Study Two was not explicitly designed to improve the range of motion at specific joints, but there may have been a therapeutic effect as a result of training, such as increased range of motion reported by Deutsch *et al.* (2001). Importantly, VR training was intended to improve control at the specific joints targeted using the existing range of motion, which was evidenced by an ability to reach higher speeds during game play, and move closer to targets.

7.1.2.1 BETTER CONTROL EXISTS AT THE PERIPHERY PRIOR TO AND AFTER VIRTUAL REALITY TRAINING

Study One reported that the trunk performed better than the pelvis during VR game play, suggesting a top-down reduction in control. Conversely, Study Two demonstrated that better control existed at the ankle, then the knee, followed by the trunk. Importantly the results from Study Two imply that children with CP possess greater control at the periphery than the core both before and after VR training. It was suggested that greater control exists at the periphery due to a larger cortical representation in comparison to the core. This is most probably a result of the reliance on the periphery during ADL to carry out functional tasks, interact with the surrounding environment, and the lack of refined selective motor control that exists at the core. Increased exposure to core specific training is likely to increase the cortical representation of the core segments, but is unlikely to improve representation of the periphery.

7.1.2.2 SINGLE PLANE MOTION IS BETTER CONTROLLED THAN CROSS PLANE MOTION

Of particular interest was the finding that single plane movements of the trunk are better controlled than cross plane movements in response to VR training. Movement of the trunk is controlled in multiple degrees of freedom during cross plane motion due to the game requirements, as opposed to single axis control in single plane movements. Hence cross plane movements are likely to increase task complexity in comparison to single plane movements and result in lower performance. It was previously stated that physiotherapy should promote a goal-oriented approach to enhance the child's ability to perform activities in the context of daily life (Østensjø *et al.*, 2004). During ADL adequate control of the trunk in both the transverse and sagittal plane simultaneously is required to maintain equilibrium. Therefore the benefits of training cross plane motion are expected to transfer to ADL to a greater extent than single plane motion.

7.1.3 Implications for future virtual rehabilitation

7.1.3.1 SHOULD VIRTUAL REALITY TRAINING REMAIN ON THE CORE PRIOR TO THE PERIPHERY OF THE BODY?

Study Two does not provide conclusive evidence to suggest that training the core prior to the periphery of the body leads to significant improvements when carrying out ADL. Greater control was reported at the periphery in comparison to the core of the body, yet both responded to VR training with improved control. The important role of the core during gait and the STS emphasize the way in which humans rely on the core to perform ADL, and the need to improve movement control of the core in children with CP. Activation of the core musculature prior to lower extremity movement (Hodges and Richardson, 1997), trunk flexion initiating the STS (Schenkman *et al.*, 1990; Park *et al.*, 2003), and the interaction between the trunk and pelvis to maintain dynamic equilibrium during gait (Sartor *et al.*, 1999) provide justification for training the core. Similarly, there is support for training the periphery to improve ADL (Schindl *et al.*, 2000; Borggraeffe *et al.*, 2010). Training the core prior to the periphery was based on the concept of Targeted Training, with evidence to suggest that gaining adequate control at the core first before training the periphery can lead to better movement function in children with CP (Butler and Major, 1992; Butler, 1998; Farmer *et al.*, 1999; Major *et al.*, 2001). The current VR evidence does not support the sequential ordering to training, but there are several differences between the two processes. Firstly, Targeted Training uses external perturbations to stimulate control at the targeted joint, training the reactive control at a joint in comparison to VR which requires the participant to activate control at the joint independently. The VR training games require a certain amount of existing control to be available at the targeted joint, whereas Targeted Training is typically used to train joints that have little or no control. Secondly, there are a number of segmental levels during the process of Targeted Training, with the trunk separated into seven levels. Compartmentalising the trunk is difficult to achieve without the use of a Targeted Training frame. Ultimately, Targeted Training is used to train control in children who are more affected by CP pathology, who suffer from poor neck and trunk control, to the extent where the child finds it difficult to sit upright independently. In comparison VR training was aimed at children with greater levels of independent control, who have a higher level of existing motor control. The VR training paradigm provides an alternative way to train dynamic components of core control that is not available through existing physiotherapy, but the evidence from this research is unable to justify the training of the core prior to the periphery.

7.1.3.2 DOES VIRTUAL REHABILITATION PROVIDE BENEFITS WITH CONVENTIONAL PHYSIOTHERAPY?

For children with independent control of the body, access to regular physiotherapy is limited. Some children within the current study received physiotherapy on a weekly basis, and others attended sessions once every four to six weeks. The level of physiotherapy being received depended on the level of pathology, with children who had CP diplegia or CP hemiplegia receiving less than those who had CP quadriplegia. The use of VR training on a daily basis exposed all children in both studies to levels of therapy that were probably not experienced before, suggesting virtual rehabilitation provides a convenient way of exposing children to therapy on a regular basis. A key feature of virtual rehabilitation is its ability to motivate the user to physically interact with games using the desired movement components. Previously it was reported that compliance rates improved in response to VR training compared with convention physiotherapy exercises (Bryanton *et al.*, 2006), and compliance in Study One and Study Two support this finding. Aside from compliance and regular exposure, it is difficult to conclude from the evidence provided in this research project whether virtual rehabilitation provides physical benefits beyond those received through conventional physiotherapy. To answer this question, a research design comparing the effects of VR training on one group whilst a second group receives conventional physiotherapy techniques is preferable. Outcome measures for both groups should include VR based performance measures and physiotherapy assessments such as joint range of motion to compare the two types of therapy. Based on previous research it could be hypothesised that children receiving regular VR training would gain greater benefits in VR performance, and improve joint range of motion to a greater extent than children receiving regular physiotherapy.

7.1.3.3 A PORTABLE VIRTUAL REALITY SYSTEM FOR VIRTUAL REHABILITATION

One of the main aims of this research was to develop a portable and practical method of rehabilitation to make VR training more accessible to children with CP. Virtual rehabilitation is often criticised for being expensive, complex, and therefore difficult to access for use in physiotherapy. The portable VR system that was developed provided training to children with CP in their school, making virtual rehabilitation more accessible for children and placing less time demands on parents. Custom training games were developed to train specific movements aimed at improving movement function. One important consideration is whether commercial VR systems such as the *Nintendo Wii* and *Microsoft Kinect* are able to provide the same type of training as the portable VR system devised in this research project. The financial cost and simple user interface make it convenient for physiotherapists to introduce into regular therapy. Support for the use of the *Nintendo Wii* is provided by Deutsch *et al.* (2008), who reported that upper extremity training in the seated and standing position led to a reduction in postural sway, and increased walking distance (from 4.6 m at pre-training to 45.7 m post-training) for a 13 year old adolescent with spastic diplegia CP. The *Nintendo Wii* is predominantly played using the upper extremities, but the findings of Deutsch *et al.* (2008) suggest that in a standing posture interaction with the games develops further control at the lower extremities. Despite this, the research on using the *Nintendo Wii* is scarce, and does not directly train specific movement components. For example, it is quite simple to use cheating mechanisms during game play as position within the virtual onscreen game is defined by acceleration of the handheld controller, rather than segmental position or orientation. Small movements performed at a higher frequency can therefore generate the required accelerations as opposed to the desired movement components which require a larger range of motion. This questions the efficacy and validity of using the handheld controller for rehabilitation. In comparison, there were difficulties experienced using the IMU to control the portable VR system in the current research. As described previously, IMU's are affected by ferromagnetic materials (De Vries *et al.*, 2009), and angular displacement can suffer from drift over time. During the VR training intervention in schools across Liverpool, several areas were deemed unfeasible for VR training due to lack of uniformity in the surrounding magnetic field. Mapping the magnetic field as suggested by De Vries *et al.*, (2009) was essential, but is impractical. There are benefits and limitations to using the portable system devised in this research project, or existing commercial VR systems. The principle objective for rehabilitation has to be training the physical component of movement though, making the portable VR system and IMU unit more desirable for training the correct movements.

New VR training games were developed to increase motivation during intensive training periods for children taking part in the study. Training games were driven by the same body segment control schemes used to drive the GPO assessment game and so the specificity of training was applicable. Although the games that were created might seem fun and enjoyable for children at a young age, the longevity of interest in the games over a continuous period of time would most certainly be reduced due to lack of progression in game play. Gaming systems such as the *Nintendo Wii* and *Microsoft Kinect* benefit from the availability of commercial games which are engaging for children, and could provide a much more motivating VR scenario than the games produced in the current research. Using games consoles, rather than the portable VR systems like the one developed in the current research, may be the solution to increasing the longevity of virtual rehabilitation since games consoles now have software development kits which allows custom programs to be written for them. Advances towards integrating commercial games into the current portable system driven by an IMU would enhance game play for patients whilst still providing the appropriate training to specific body segments.

7.1.4 Limitations

7.1.4.1 LOW PARTICIPANT NUMBERS

Low participant numbers was the overarching limitation of both VR training interventions. In spite of collaborating with the regional NHS centre for CP management (North West Movement Analysis Centre, Alder Hey Children's NHS Foundation trust), only five participants were recruited for the first training intervention (Section 3.3.1) and eight participants for the second intervention (Section 6.2.2). Inevitably, the complex research design devised for Study One was made redundant due to low participant numbers, which resulted in single-subject analysis of findings. The majority of VR interventions for children with CP consist of single-subject designs (You *et al.*, 2005; Barton *et al.*, 2006; Chen *et al.*, 2007; Golomb *et al.*, 2010), so the difficulties in Study One are not uncommon. There were positive inferences to make from the results produced in Study One, leading to a more complex research design for the second VR intervention. In Study Two there was a large variation in the diagnosis of CP between participants within training groups, thus confounding factors may have led to misleading changes in response to VR training. For example, children with CP hemiplegia might produce better control with the non-affected side during peripheral training compared to the affected side. Participant recruitment on a larger scale may have enabled grouping of children based on CP classification within each training group to avoid confounding factors. However this would have required recruitment outside of the North West on a larger scale, which was beyond the scope of this programme of research. In reality CP is a continuous spectrum of a mix of numerous problems at motor, sensory and intellectual levels. This means that recruiting homogenous groups is a major challenge and inevitably leads to low participant numbers. The proposed research designs aimed to address complex questions within the area of VR training, where previously single-subject designs have been used. Nevertheless, findings are of important value for the future development of VR training interventions.

7.1.4.2 TRAINING FREQUENCY AND INTENSITY

The second VR intervention was devised to provide increased exposure of VR training to participants within a two-week period. This was aimed at delivering high intensity VR training beyond that received in the first VR intervention. Greater improvements in trunk control were reported in the first VR intervention of the current research where children received VR training twice a week for six weeks. This would suggest that training over a longer period of time with low intensity leads to greater improvements in selective motor control of the trunk. Existing literature supports the use of intense periods of training at a high frequency leading to improvements in balance and posture (Woollacott *et al.*, 2005; Shumway-Cook *et al.*, 2003). In contrast to short intense training periods, many training studies carry out specific training regimes over a period of weeks or months, aiming to maximise the potential for change. You *et al.* (2005) combined high intensity training over a prolonged period of time and reported that 60 minutes of training, five times a week, for four weeks resulted in improvements in upper limb function, leading to cortical reorganisation in the brain. Sandlund *et al.* (2009) reported that the typical length of interactive computer game play interventions in children with sensorimotor disorders lasted four weeks, stating that the benefits of training were varied. Thus contrasting reports exist in the current literature concerning the most appropriate length of training interventions. A review of studies of different durations and frequencies of therapy on CP children might indicate the optimum training period.

7.1.5 Recommendations for future research

There are a number of recommendations for future VR training in children with CP based on the current evidence provided in this thesis. Importantly, a database that contains information on how TD children play VR games like the GPO would provide a useful indication of the level of performance that is reached by those unaffected by pathology. To a further extent data from TD children of varying age groups would allow comparison of VR performance to stages of maturation. By categorising TD children into separate age groups such as 6-7 yrs, 8-9 yrs, and 10-11 yrs, the performance of children who have CP can be compared across to the relevant age category to monitor improvements. Comparing the first assessment in children with CP to existing TD data would determine the extent to which selective motor control is diminished in CP children before training begins, whilst providing a benchmark for improvements through VR training. There are several findings within this thesis regarding levels of control during GPO game play, specifically participants performed single plane motion better than cross plane motion, trunk rotation was better controlled than trunk tilt, and the periphery achieved higher max settled speeds and lower variation of pass distance than the core. These findings are yet to be determined in TD children to see whether there is agreement regarding task performance and would provide useful information for future training in children with CP. Evaluation of the coupling (or lack of) that exists between the trunk and pelvis segments in TD children at initial assessment and in response to training would provide useful information about selective motor control of the pelvis to compare to findings in Study One (Chapter 3).

The findings from both VR interventions were positive regarding selective motor control during VR game play, but more research is required to determine whether this transfers to ADL. The reported findings were inconclusive regarding the effect of VR training on both gait and the STS. Gait analysis should be considered as a future outcome measure of VR training, but assessment of the way in which the trunk interacts with the lower extremities would be more specific to training. The coupling between the trunk and pelvis has previously been measured to assess co-ordination during gait (Lamoth *et al.*, 2002; Lamoth *et al.*, 2006) indicating that changes occur in response to increased walking speeds. It would be interesting to know whether coupling changes in response to VR training, particularly as a result of the in-phase coupling that developed between the trunk and pelvis in Study One (Chapter 3).

An alternative method to the GDI for processing large amounts of complex gait is the Movement Deviation Profile (MDP) (Barton *et al.*, 2010). The MDP produces a single number which summarises the deviation of gait from normality using a neural network approach, and was shown to correlate well with the GDI. It progresses from the GDI by providing a summary of the deviation from normality across the entire gait cycle, represented by a summary MDP curve. Using the MDP in research and clinical interpretation could provide important information that is not provided by the GDI in this research project.

The development of the segmental assessment of trunk control (SATCo) protocol (Butler *et al.*, 2010) referred to in Chapter 2 (Section 2.9) provides a new method for assessing dynamic trunk control. Validation with the existing Alberta Infant Motor Scale and high inter-rater reliability between clinicians performing the assessment make the SATCo a possible outcome measure for further VR interventions aimed at improving trunk control. Changes in SATCo scores could determine whether control of the trunk improves in response to VR training.

fMRI can be used to determine the changes in neural mechanisms associated with improved global motor function. You *et al.* (2005) provide evidence of this in response to VR training in a child with CP. Future VR training studies which incorporate fMRI as an outcome measure both prior to and after receiving VR training are most likely to provide a greater understanding of whether training improves motor function in children with CP. In addition to assessing changes in neural mechanisms, fMRI during core- and periphery-specific VR assessments would provide additional information on whether cortical representations change in response to VR training.

There are a number of alternative options for progressing VR training in children with CP. Firstly, altering the inclusion criteria so that only children with a specific CP classification take part would lead to a more homogenous group of CP children receiving VR training. Alternatively, recruitment of children with CP on a larger scale than previously recorded in this thesis would enable sub-groups of CP classification within each training group, so that children with CP diplegia in one training group are only compared to children with CP diplegia in the other for example. Changes to the way VR training games are controlled by the body might affect the way in which children with CP transfer improvements in VR performance to ADL. For example, controlling a VR game by using the motion of the thigh or trunk during performing the STS is likely to improve the child's ability to perform ADL due to the specificity of training.

The existing literature in VR highlights the benefit of training the periphery, and there remains a limited amount of research which considers training the core. Further research which distinguishes between the methods of training either the core or periphery is required before being able to determine the most effective form of VR treatment for children with CP.

7.2 General conclusions

Evidence of training the core using VR is scarce in the literature. In fact much of the existing VR research aims to train and test the upper or lower extremities. The findings related to core control during VR game play are therefore novel and provide insight into the level of control that exists in children with CP at the core. Findings from Study One and Study Two suggest that improvements in game performance (max settled speed, variation of pass distance) may not transfer to improvements in ADL, regardless of core-specific VR training or VR training on the core and periphery. The results provide a greater understanding of the control that exists at the core in children with CP, and suggests possible ways to train and test the core using VR games. The results of Study Two build upon existing VR research that reported improvements in peripheral control as a result of a VR training intervention. To the author's knowledge, Study Two was the first VR intervention to report the use of an IMU to control a portable VR game system. Due to low participant numbers, which seems to be a limitation inherent within existing literature on VR training in children with CP, the findings should be generalised with caution. Nevertheless, this thesis has provided an important insight into VR training aimed at improving selective motor control of the core and periphery in children with CP.

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Appendices

other and form a vicious cycle. Further research should look into the intervention strategies for this group of patients with the focus on transferring the treatment effect into the functional tasks.

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doi:10.1016/j.gaitpost.2009.08.219

P101

Are gait patterns in chronic post stroke patients characterised by specific clinical and functional parameters?

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Summary and conclusion

The gait of 46 post stroke patients was classified in three subgroups. Correlations between clinical and functional parameters showed a high correlation between strength and walking speed. The subgroup with only mild deviations was characterised by a higher walking speed and more strength compared to the other subgroups.

Introduction

Different post stroke gait patterns are well described in literature [1,2]. We previously described the kinematics and kinetics of three subgroups (knee extension – knee flexion – mild group with almost normal knee motion) [1]. However, it is still unclear if these three subgroups are characterised by the same clinical and functional parameters.

Patients/materials and methods

46 patients with chronic cerebrovascular accident (CVA) (24L, 22R) with a mean age of 54.4 years (±12.7) were included in this study. All subjects underwent a lower limb 3D gait analysis, including kinematics and kinetics (8 camera VICON system, 2 AMTI forceplates), EMG of 8 lower extremity muscle groups and a full clinical evaluation, including evaluation of spasticity and strength. Total strength score was defined as the sum of the Manual Muscle Testing score of eight lower limb muscle groups (with a maximum score of 40), while the total spasticity score was defined as the sum of the Modified Ashworth Score of 6 lower limb muscle groups (with pathology deviating from the typical score 0). Correlation between strength, spasticity, walking velocity and time since CVA was done by the Spearman correlation coefficient. Kruskal Wallis (post hoc Mann Whitney *U*) was used to evaluate between group differences.

Results

All 46 patients could be classified in three subgroups. There were statistical significant differences between the three subgroups at the level of the pelvis, hip, knee and ankle [1].

The mean data of strength, spasticity, walking velocity and time since stroke can be found in Table 1.

Table 1
Mean data of strength, spasticity, walking velocity and time since stroke of the three subgroups.

	Total strength score	Total spasticity score	Walking velocity (m/s)	Time since CVA (years)
Extension group	22.95	8.19	0.46	4.2
Flexion group	23.06	7.41	0.38	5.0
Mild group	31.29	6.43	0.77	7.8

Data analysis showed a high correlation (0.71) between strength and walking speed ($p<0.001$). The negative correlation between spasticity and walking velocity is significant ($p<0.05$) but low (−0.29). No correlations were found between time since stroke and the other parameters. Within the different subgroups, the differences of strength and walking velocity were significant between both flexion and extension group and the mild group ($p<0.05$). The differences in spasticity and walking velocity between the flexion and the extension group were not significant.

Discussion

Since there is a high correlation between strength and walking speed, strength training is an important part of the rehabilitation, as discussed by other authors [3]. The information on gait analysis data in combination with clinical parameters allows us to make the rehabilitation process more targeted.

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doi:10.1016/j.gaitpost.2009.08.220

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Movement control of the trunk and pelvis in cerebral palsy diplegia

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Summary

Core control was quantified using performance measures derived from a computer game driven by rotation and tilt of the trunk and pelvis. Baseline results showed reduced control of tilt in comparison to rotation, and cephalo-caudal reduction of control. Training of pelvic tilt control may improve pelvic kinematics, reducing the risk of developing low back pain.

Conclusions

Testing of movement control of the core embedded in playing a custom made computer game revealed that children with diplegia have better control over segmental rotation than tilt. Movement of the core is most difficult to control in the sagittal plane, particularly at pelvic level. If training of core control could lead to improved pelvic tilt then that could potentially reduce single and double bump pelvic patterns [1] which are associated with low back pain.

Introduction

Our ongoing pilot study exposes diplegic children to visual and somatosensory stimuli in computer games driven by 3D move-

Appendix 2

THE EFFECTS OF GAME TRAINING ON TRUNK TO PELVIS COUPLING: A CASE STUDY OF A CHILD WITH CEREBRAL PALSY

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INTRODUCTION

Good control of the core (trunk and pelvis) provides the proximal stability for distal mobility (Kibler *et al.,* 2006) which is a fundamental concept in both rehabilitation and prevention of sports injuries.

Children with Cerebral Palsy (CP) often have reduced selectivity of the core as part of their primary abnormalities (Gage & Novacheck, 2001). Our custom made computer game based on real time biofeedback was designed to measure and selectively train movement control of the core. Initial results indicated that the trunk and pelvis have different roles while playing the game (Barton *et al.,* 2009).

The aim of this study was to quantify how the trunk and pelvis are coupled during playing the computer game and how coupling changes in response to training.

METHODS

One child with CP diplegia (10yrs 2mo; 1.30m; 36kg) was exposed to the bespoke computer game twice a week for 6 weeks, and measures of movement control were obtained pre and post training.

Two clusters of three markers placed on the trunk and the pelvis were used to capture the 3D orientation of the segments using a real time VICON 612 system. The child's task was to use pelvic rotation to drive a flying dragon left and right toward 8 different targets appearing repeatedly in a random order in the Goblin Post Office game implemented in a CAREN system (MOTEK, Amsterdam).

Rotation of the trunk and pelvis were used to formulate angle-angle plots for each trial of all targets, normalised to their respective ranges of motion. The areas within convex hulls that contain all data points were used to quantify the coupling between segments.

RESULTS

The angle-angle plots indicated that the pelvis and trunk rotate independent of each other while approaching a target pre-training, but coupling of segments is increased post-training.

Figure 1 suggests tighter coupling between the trunk and pelvis segments for all 8 targets when considering all trials, indicated by a reduction of the area (from median = 0.35, IQR = 0.17 to median = 0.21, IQR = 0.14).

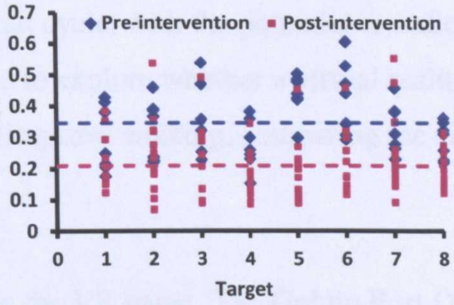

Figure 1: The median area of all trials (dotted lines) reduces in response to training for all 8 targets.

DISCUSSION

Rather than developing more selectivity of the pelvis, the results suggest tighter coupling with the trunk after training.

Previous findings indicate better control at the trunk during computer based game-play when compared to the pelvis (Barton *et al.,* 2009). The tighter coupling of the pelvis to the trunk may be regarded as a strategy to make use of the trunk's better control at the pelvic level. Subsequent research will continue to explore the cause-effect relationship between the pelvis and trunk.

CONCLUSION

Our case study of a child with CP diplegia demonstrated that control was translated from the trunk to the pelvis through tighter coupling, which is likely the most economical way to play the game efficiently.

Overall the improved control of the core is expected to lead to better functioning of the extremities.

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Appendix 3

Training the core in children with Cerebral Palsy using computer games: A sensitivity analysis of its impact on walking

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Reduced selectivity of the core (trunk & pelvis) can lead to difficulties in walking in children with Cerebral Palsy (CP), impacting upon activities of daily living. The Gait Deviation Index (GDI) (Schwartz & Rozumalski, 2008) and Movement Deviation Profile (MDP) (Barton et al., 2010) express the deviation of gait from normality as a single discrete value. In addition, the MDP enables a sensitivity analysis of the entire gait cycle, with the potential to indicate which joints contribute most to the deviations. We aimed to explore whether a virtual reality (VR) game designed to train selectivity of the core can improve walking, comparing the GDI and MDP as outcome measures of walking.

One child with CP diplegia (10yrs) was trained on the VR game 'The Goblin Post Office' twice a week for 6 weeks. Game speed increased as a function of performance, controlled by a psychophysical algorithm (PEST) (Macmillan & Creelman, 2005), used to determine changes in selectivity of the core during the VR game. Nine gait curves of the pelvis, hip, knee and ankle were measured using a motion capture system to calculate GDI and MDP values before and after intervention. To conduct the sensitivity analysis pelvic, hip and knee/ankle variables (3 groups) were systematically eliminated from the MDP calculation to assess the influence each group had on the outcome.

There was a significant increase in game speed in response to training ($t_{10} = -9.836$, $p < 0.0005$), with a mean increase of 32.6±11.0 m/s. There was minimal change in GDI or MDP_{mean} as a result of intervention (GDI: before=75.8; after=75.4, MDP: before=20.8°; after=23.2°). Sensitivity analysis revealed minimal deviation from normality when considering pelvic and knee/ankle angles combined (normal = 6.9°, before = 9.8°, after = 11.3°). Hip and pelvic (normal=5.9°, before=14.4°, after=16.4°) or hip and knee/ankle angles (normal=9.0°, before=19.5°, after=21.0°) combined produced greater deviations from normality for both before and after MDP values.

Improvements in game speed suggest VR game play improves selective control of the trunk and pelvis. No change in GDI and MDP implies that improvement in selectivity does not

Appendix 4

International Conference on Virtual Rehabilitation 2011
Rehab Week Zurich, ETH Zurich Science City, Switzerland, June 27 - 29, 2011

Playing the Goblin Post Office game improves movement control of the core: A case study.

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Abstract— Movement function of the core (trunk and pelvis) can be improved in cerebral palsy, potentially leading to benefits which transfer to activities of daily living. A single child with CP diplegia played our custom made game which runs on the CAREN system. Three playing postures gradually introduced more and more joints in the legs to be controlled. Vicon cameras tracked trunk and pelvis rotations which drove a dragon towards envelope targets. Forward speed of the game was adjusted by an adaptive algorithm leading to a maximum settled speed for the various conditions. Results showed that core control improved after the six week training period. The trunk was better controlled than the pelvis, sideways rotations were better controlled than fore-aft rotations of body segments, and single plane rotations were more efficient than cross-plane rotations of the core. The quantifiable improvements suggest a good potential for our technique to improve core control which is a prerequisite for good movement control of the legs and arms.

Keywords— cerebral palsy; movement training; core control; virtual rehabilitation

I. INTRODUCTION

Traditionally the core of the body (pelvis and trunk) has been regarded as a "passenger unit" carried by the lower extremities which are termed the "locomotor unit" [1] suggesting a passive role for the pelvis and trunk in gait. There is however evidence supporting a more active role for the pelvis and trunk. Responses triggered by balance perturbations involve trunk, neck and thigh muscles which contract at the same time, or even before the activation of muscles around the ankle joint [2-5]. In prospective studies [6,7] reduced strength and impaired proprioception around the core could be associated with increased risk of injuries, specifically around the knee, suggesting that control over the core is a prerequisite for efficient and effective use of the legs.

Cerebral palsy (CP) is a neuro-musculo-skeletal disorder caused by damage to the immature brain around birth. It has an incidence of 1 in 400 live births [8]. The treatment of children with CP focuses mainly on secondary abnormalities (altered bone and muscle growth) and avoids addressing the primary abnormalities characterizing CP which include loss of selective muscle control, muscle imbalance and deficient equilibrium reactions [9]. These abnormalities affecting the pelvis and trunk lead to reduced stability and control of the core, which impairs movement control of distal body segments (arms and legs) leading to inefficient performance of activities of daily living.

In spite of the primary damage to the central nervous system in CP, global motor function can be improved by controlled exercises that take advantage of the brain's capacity to reorganize in targeted areas (neuroplasticity). Reactive balance training of children with CP on a movable platform led to improvement of muscle responses, and the quantifiable benefits were carried over for one month after training [10]. Balance training improved stance and gait leading to a more symmetrical walking pattern in a group of children with hemiplegic CP [11].

The clinical application of virtual reality (VR) is expanding dramatically. It is a promising area for the application of new technologies in movement rehabilitation, underpinned by a growing number of published studies supporting the feasibility and benefits of virtual rehabilitation [12]. Research efforts in the area of movement rehabilitation using VR have focused mainly on training the arms and legs [13-17]. The aim of this study was to evaluate the effects of a six week training programme using a custom made VR game developed to train movement control of the trunk and pelvis. Results from a single child with CP diplegia are presented here.

II. METHODS

A. Participant and training/testing protocol

One boy with CP diplegia (age: 10 years; height: 1.34 m; mass: 36 kg) trained on a custom-made computer game called the "Goblin Post Office" (GPO) for a period of six weeks, twice a week, for 30 minutes in each session. The child had no previous history of surgical intervention and received no

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This project was funded by The WellChild Trust and Alder Hey Children's NHS Foundation Trust.

Appendix 5

The effects of game training on trunk to pelvis coupling in a child with cerebral palsy

Gabor Barton[1], Malcolm Hawken[1], Richard Foster[1], Gill Holmes[2], Penny Butler[3]

[1]Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, Liverpool

[2] North West Movement Analysis Centre, Alder Hey Children's NHS Foundation Trust, Liverpool

[3]The Movement Centre, Robert Jones and Agnes Hunt Hospital, Oswestry

Abstract

Good control of trunk and pelvic movements is necessary for well controlled leg movements required to perform activities of daily living. The nature of movement coupling between the trunk and pelvis varies and depends on the type of activity. Children with cerebral palsy often have reduced ability to modulate coupling between the trunk and pelvis but movement patterns of the pelvis can be improved by training. The aim of this study was to examine how pelvis to trunk coupling changed while playing a computer game driven by pelvic rotations. One boy with cerebral palsy diplegia played the Goblin Post Office game on the CAREN virtual rehabilitation system for six weeks. He navigated a flying dragon in a virtual cave towards randomly appearing targets by rotating the pelvis around a vertical axis. Convex hull areas calculated from angle-angle plots of pelvic and trunk rotations showed that coupling increased over game training ($F_{1,11}=7.482, p=0.019$). Reaching to targets far from the midline required tighter coupling than reaching near targets ($F_{1,12}=10.619, p=0.007$). Increasing coupling appears to be an initial compensation mechanism using the better controlled trunk to drive rotation of the pelvis. Co-contractions causing increased coupling are expected to reduce over longer exposure to training. The control scheme of the training game can be set to facilitate de-coupling of pelvic movements from the trunk. Using large ranges of pelvic rotation required more coupling suggesting that training of selective pelvic movements is likely to be more effective close to a neutral pelvic posture.

Keywords: virtual rehabilitation, cerebral palsy, core control, pelvis and trunk coupling.

Appendix 6

Royal Liverpool Children's NHS Trust,
Eaton Road, Liverpool L12 2AP.
Telephone: 0151 228 4811

Royal Liverpool Children's NHS
NHS Trust

Are games good for you?

Why play games?

People and animals like to play games because they are fun, but games also help us to learn to use our brains, our senses and our muscles. We think that playing games could also do this for people who find it difficult to control their bodies and we need people to help us to find out if this is true. Would you like to help us? You can decide whether you'd like to help or not, it's quite up to you.

What you'll do

If you'd like to help we're going to ask you to play some computer games, surprise surprise! Our games are a bit different because you'll play them by moving your whole body about, not by using your hands and arms. We use video cameras to watch how you move to control the game. For the cameras to see you properly we need to fix several little round markers to you with double sided sticky tape.

Playing the games

To play the games you sit, kneel or stand on a big round platform, and there's a large screen in front of you to show the game. While you're moving about on the platform it moves about a bit too, (just to make it more difficult, we're sneaky that way!). If you lose your balance there's a harness which will catch you and will stop you falling. Everyone plays the game on the platform some of the time, but because we would like to find out whether it makes a difference how you play, you might play the game more times on the platform, or you might play again it on a normal computer.

It's up to you

It's often quite difficult to get people to stop playing the game ☺, but if you want to you can stop playing at any time for any reason - if you get tired for example.

What we need

To see whether the game has helped we'll also need to look at how you walk before and after you've been playing the game. You'll need to go to Alder Hey Hospital for this where we'll ask you to walk up and down a few times while the video cameras film you, and you'll be wearing the round markers again.

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Improving Core Control of Children with Cerebral Palsy Using Virtual Reality Games

Investigators: Mr R Foster, Dr G Barton, Dr M Hawken, Dr P Butler, Mrs G Holmes,

Dear Parent/Guardian,

The aim of this leaflet is to answer any questions that you may have about this research study and to help you to decide whether you and your child would like to take part in the study. We ask that you read the leaflet and then let us know what your decision is over the next 5 days.

What is the study about?

Children with cerebral palsy have difficulty co-ordinating the movements of their arms and legs. One of the causes of this can be poor control of the muscles of the pelvis and trunk (core), which can lead to difficulties carrying out activities of daily life, including walking.

Why do we need to do the study?

It has been shown that balance on walking can be improved by training these core muscles using controlled exercises. This has now become a common treatment in physiotherapy but there is little scientific evidence to support its use.

The core muscles can be trained through conventional physiotherapy and by using a moving mechanical platform similar to a flight simulator, which is controlled by an interactive computer game that the child plays. Liverpool John Moores University has the only system in the UK that can do this.

The aims of the study are to:

- Develop and test computer virtual reality games designed to assess and improve the control of the core muscles in children with cerebral palsy;
- Establish whether using these games can lead to improved core control and walking;
- Compare the benefits of computer based training with those gained from conventional physiotherapy.

What will be involved?

If you agree to take part in the study, then we will inform your physiotherapist (with your permission) and then your child will be randomly allocated to a CORE or to a CONTROL group. (Please also see the Protocol Flow-chart in the Appendix.)

1. All Children

Before treatment begins your child will be assessed in two tests. The first test will take place in the Gait Laboratory at Alder Hey, where the process will be explained in detail to you. This will include a routine gait analysis assessment, which will take about 3 hours.

The second test will take place in the Movement Function Research Laboratory at Liverpool John Moores University, where details of the process will be explained to you. Your child's core control will be measured by playing a computer game driven by the movement of the pelvis and trunk (core). This test will take about 30-60 minutes.

2.a. CORE Group

If your child is in the CORE group he/she will receive core control training by playing a series of virtual reality games. This will take place at Liverpool John Moores University, Henry Cotton Campus (15-21 Webster Street, Liverpool, L3 2ET, see attached map for directions in the Appendix) twice a week for 6 weeks.

At the University your child will be taught how to play the computer games, which involves small markers being put on to your child's pelvis and trunk and then them heel sitting, kneeling or standing on a moving platform. The game is played by movements of your child's pelvis and trunk. Each session will last for approximately 30 - 60 minutes.

2.b. CONTROL Group

If your child is in the CONTROL group he/she will play the same series of virtual reality games as the CORE group but on a PC using a conventional game controller (e.g. joystick or mouse). This will take place at Liverpool John Moores University, Henry Cotton Campus (15-21 Webster Street, Liverpool, L3 2ET, see attached map for directions in the Appendix) twice a week for 6 weeks. Each session will last for approximately 30 - 60 minutes.

3. All Children

After the six week period your child will be re-assessed again both at the University and in the Gait Laboratory at Alder Hey, repeating the tests as outlined in point 1 above.

Duration of the study

The whole study is 18 months long but your child will come to the laboratories only 15 times. The exact dates/times of your appointments will be given to you once you and your child agree to participate.

Travel expenses

£10 for each visit (either to Alder Hey or to the University) will be reimbursed at the end of each week.

What are the risks involved for the children?

If your child is in the CORE group, then he/she will be positioned on a 2 m diameter moving platform which is flush with the floor. The platform is mounted in a 2.5 m diameter pit and is driven by a computer. The movements that your child may feel during the computer game are a gentle rocking of the platform similar to a breeze moving a floating magic carpet or a gentle nudge when colliding with an object in the game.

Being positioned on a moving platform may put your child at risk of losing their balance leading to a fall on the platform, which may cause soft tissue or skeletal injury, or trapping of a limb between the platform and the edge of the pit.

The risk of this happening has been reduced by the following safety measures:

1) Your child will wear a body harness, which will support them in the event of a fall;
2) A helper will always stand at the edge of the platform pit to provide support if needed;
3) While the game is in progress, the operator will continually monitor your child and in the event of loss of balance or any other emergency will be able to stop the platform instantly using an emergency shutdown button;
4) The way the platform moves is based on past research and advice from the physiotherapists taking part in the research who have extensive clinical experience working with children with cerebral palsy;
5) One of the selection criteria for your child to be included in the study was that he/she is able to stand unaided and this helps to make sure that the risk of losing their balance is small.

Will my child feel any discomfort?

Your child will be asked to wear swimming trunks or costume for their gait analysis and for playing the games so that lightweight reflective markers can be taped on their skin over bony points of their feet, legs, pelvis and trunk using double-sided medical tape. Removing these markers may be uncomfortable but this is not as bad as removing a sticking plaster.

To prevent any embarrassment to your child during the gait analysis, complete privacy is ensured in the laboratories.

Playing games by moving the pelvis and/or spine can be tiring at first but your child will be asked regularly whether they need a rest while playing the game.

What are the benefits of taking part?

It is hoped that your child will have improved control of his/her core muscles, which may lead to improved walking. There may also be no benefit, however, it is hoped that children with cerebral palsy will benefit as a result of this research.

Access to the computer games training facility at the University is for the period of the study only and it is not possible to use this facility once the study has ended. Once we have analysed the results, we may be in a position to give advice as to the potential benefits of using commercially available computer games (Sony Playstation EyeToy, Nintendo Wii, etc.) which inevitably lack the specificity of our techniques but may be useful to maintain levels of movement function.

Who will have access to my child's personal details?

1) The clinical and secretarial staff at the Gait Laboratory, Alder Hey Hospital, who would normally have access to patients' health records.
2) The investigators of the research team at Liverpool John Moores University will also have access to your child's gait analysis reports (produced by the Gait Laboratory, Alder Hey) so that they can understand the results of the research project.

Will my child's information be kept confidential?

Yes. Whilst information will be stored and analysed on University and hospital computers these are password protected. Processed information (e.g. graphs) will be electronically transferred between the University and Alder Hey Hospital, but will be accessed only by members of the research team. Personal addresses and telephone numbers will be used by the Gait Laboratory (Alder Hey Children's Hospital) to contact you but will not be used for any other purpose. We will ensure that all information is kept anonymous in order to ensure your child's confidentiality.

Will I be informed of the results of the study?

Yes. When the study has been fully completed and conclusions drawn up, a social event will be held to which you, your child and your child's physiotherapist will be invited. The purpose of this meeting will be for the research team to give feedback to everyone who took part.

What will happen to the results of the study?

The results of the study will be shared with paediatric physiotherapists as part of the annual training course organised by the Gait Laboratory, Alder Hey Children's Hospital. It is also the aim of the research team that the results will be published in scientific journals and presented at scientific conferences.

What if I do not wish to continue?

You can withdraw from the study at any time and it will not in any way affect your child's treatment/support.

What will happen if I do not want to be involved?

The researchers will respect your decision and this will not interfere with your child's treatment/support.

Can further information be obtained?

Yes. The researchers will be pleased to give you any further information that you require.

Contacts:

- Dr Gabor Barton, Senior Lecturer in Biomechanics, Liverpool John Moores University, Tel: 0151 231 4333, Email: G.J.Barton@ljmu.ac.uk
- Mrs Gill Holmes, Physiotherapist, Alder Hey, Tel: 0151 252 5949

Independent advice about participating in the study is available from:

- Mrs Eileen Kinley, Physiotherapist, Gait Laboratory, Alder Hey. Tel: 0151 252 5949.
- Prof. Adrian Lees, Professor of Biomechanics, Liverpool John Moores University, Research Institute for Sport and Exercise Sciences, Henry Cotton Campus, Webster Street, Liverpool, L3 2ET. Tel: 0151 231 4322. Email: A.Lees@ljmu.ac.uk

What do I do next?

when you have made your decision please contact either Jenny Tyson (Secretary Gait Laboratory) or Gill Holmes (Gait Laboratory Manager) on 0151 252 5949.

Thank you for taking the time to read this leaflet.

Appendix 8

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Eaton Road, Liverpool L12 2AP
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CONSENT FORM FOR RESEARCH

For parent/person with parental responsibility

Title of Project: **Training and testing core control in children with spastic cerebral palsy – a feasibility study**

Name of Researcher: ____________________ Job title: ________________________

Please initial box

1. I confirm that I have read and understand the information sheet dated .... (version ....) for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐

2. I understand that my child's participation is voluntary and that I am free to withdraw my child at any time, without giving any reason. If I do withdraw, his/her medical care and legal rights will not be affected in any way. ☐

3. I understand that relevant sections of any of my child's medical notes or data collected during the study may be looked at by responsible individuals. These individuals will be from regulatory authorities and/or the Royal Liverpool Children's NHS Trust. I give permission for these individuals to have access to my child's medical records and study data. ☐

4. I agree to my child's physiotherapist being informed of my child's participation in the study ☐

5. I agree for my child to take part in the above study. ☐

Name of patient :

Name of Parent/Guardian: Date: Signature:

Name of Person taking consent: Date: Signature:
(if different from researcher)

Researcher: Date: Signature:

Appendix 9

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Eaton Road, Liverpool L12 2AP
Telephone: 0151 228 4811

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ASSENT FORM FOR RESEARCH (To be completed by the child with their parent/ guardian)

Title of Project: Training and testing core control in children with spastic cerebral palsy – a feasibility study

	Please tick 1 box	
1. Have you read (or had read to you) the information sheet about this project?	☐ yes	☐ no
2. Has somebody else explained what this project is about?	☐ yes	☐ no
3. Have you been given a chance to ask questions about taking part in this project?	☐ yes	☐ no
4. Have you understood the answers that you have been given to your questions?	☐ yes	☐ no
5. Do you understand that you can stop taking part in this project at any time, even if you agree to take part now?	☐ yes	☐ no
6. Do you agree to take part?	☐ yes	☐ no

If <u>any</u> answers are 'no' or you **don't** want to take part, **don't** sign your name!
If you <u>do</u> want to take part, please write your name and today's date
Your name ______________________
Date ______________________
The person who explained this project to you needs to sign too:
Print Name ______________________
Sign ______________________
Date ______________________

Thank you for your help.

Training and Testing Core Control of Children with Cerebral Palsy Using Virtual Reality Games

Royal Liverpool Children's NHS
NHS Trust

FEEDBACK QUESTIONNAIRE

Thank you for taking time to fill in this questionnaire. Please give as much detail as possible and answer questions honestly. It should only take you 15 minutes to complete.

Section 1 - *To be completed by the child with the help of parent/guardian, if appropriate*

1. What did you think of the computer game?
....
....
......

2. Did you enjoy using the moving platform? ☐ Yes ☐ No
If NO, please give details:
....
....
......

3. Was it easy to learn how to play the computer game? ☐ Yes ☐ No
If NO, please give details:
....
....
....

4. How could the game be improved?
....
....
...

5. How did you feel after using the platform and computer game?
....
....
...

6. Is there anything that you found hard to do before the study that is easier now?
....
...
....

7. Would you like to use a computer game to help you with all your physiotherapy exercises?
☐ Yes ☐ No
If NO, please give details:
....
....
...
Any other comments:
....
....
....
......

Section 2 - *To be completed by the parent/guardian*

1. What are your thoughts on the computer game?

....

....

2. How do you think that the game could be improved?

....

....

....

3. Did you notice any changes in your child after using the platform and computer game?

☐ Yes ☐ No

If **YES**, please give details:

....

....

4. Is there anything that your child found difficult to do before the study that they can do better now?

☐ Yes ☐ No

If **YES**, please give details:

....

....

5. Do you think that a computer game would help your child carry out their physiotherapy programme?

☐ Yes ☐ No

If **NO**, please give details:

....

....

Additional Comments:

....

....

Thank you for taking the time to complete this questionnaire.

Appendix 11

Maximum settled speed MATLAB program

```
clear;

PathName = 'M:\GPO_Analysis_111219\Analysis\'; % type in specific folder
FileName = dir('*.mat');
Showfigures = false;

if strcmp(class(FileName),'char')
    one_file= true;
else one_file= false;
end;

if one_file
    num_of_files = 1;
else num_of_files = size(FileName,1);
end;

for file_counter = 1:num_of_files
    if one_file, load(strcat(PathName, FileName.name)); else
load(strcat(PathName, FileName(file_counter).name)); end;
    speeds(file_counter, 1)= {PathName};
    if one_file, speeds(file_counter, 2)= {FileName.name}; else
speeds(file_counter, 2)= {FileName(file_counter).name}; end;
    speeds(file_counter, 3)= {size(struct_data,1)};
    for k=1:size(struct_data,1)
        speeds(file_counter, k+3)= {getfield(struct_data, {k}, 'speed')};
    end;
end;

% no. of blocks calculated as -->  floor(speeds{file_counter,3}/8)

 for file_counter = 1:num_of_files
    for block = 1: floor(speeds{file_counter,3}/8)
        MSD(file_counter, block, 1) = mean (cell2mat
(speeds(file_counter, 4+(block-1)*8:11+(block-1)*8)));
        MSD(file_counter, block, 2) = std (cell2mat (speeds(file_counter,
4+(block-1)*8:11+(block-1)*8)));

    end;
end;
% calculate mean SD for each block of 8 targets to work out max settled
speed

% place Coefficient of Variation in to m
if Showfigures
    for file_counter = 1:num_of_files
         subplot (2,1,1)
         h2 = area(MSD(file_counter,:,1) + MSD(file_counter,:,2));
% make area under top curve grey
         set(h2,'FaceColor',[0.6 0.6 0.6], 'LineStyle','none')
         hold on;
         h3 = area(MSD(file_counter,:,1) - MSD(file_counter,:,2));
% make area under bottom curve white... provides grey band for SD around
the Mean
         set(h3,'FaceColor',[1 1 1], 'LineStyle','none')
         h = plot (MSD(file_counter,:,1));
         set(h, 'color', 'k', 'LineStyle','-','LineWidth',2)
         hold off;
         subplot (2,1,2)
         h4 = plot(MSD(file_counter,:,2) ./ MSD(file_counter,:,1));
% plots the ratio between the standard deviation and mean to give
coefficient of variation
         set(h4, 'color', 'k', 'LineStyle','-','LineWidth',2)
```

```
        waitforbuttonpress;
    end
end

for file_counter = 1:num_of_files
    Max_Settled_Speed (file_counter, 1) = {speeds(file_counter, 2)};
    CV (file_counter, 2) = {min(MSD(file_counter,:,2) ./
MSD(file_counter,:,1))};
    [CVmin, CVindex]= min(MSD(file_counter,:,2) ./
MSD(file_counter,:,1));
    Max_Settled_Speed (file_counter, 2) = {MSD(file_counter, CVindex)};
end


for file_counter = 1: num_of_files
    MSD_slice_sorted = sortrows(squeeze (MSD(file_counter,:,:)),-1);
    SD_min = MSD_slice_sorted(1,2);
    for block = 2:size(MSD_slice_sorted,1)
        if MSD_slice_sorted(block, 2) < SD_min
            SD_min = MSD_slice_sorted(block, 2);
        else break
        end
    end
    if MSD_slice_sorted(block-1,1) <= 15
        Max_Settled_Speed(file_counter, 3) = {-9999};
    else
        Max_Settled_Speed (file_counter, 3) = {MSD_slice_sorted(block-
1,1)};
    end
end

% Min - index value that matches MSS value
for file_counter = 1:num_of_files
    struct_info =
gpofGetRunInfoStructure(cell2mat(Max_Settled_Speed{file_counter,1}));

    Output(file_counter, 1) = {struct_info.subject};
    Output(file_counter, 2) = {struct_info.group};
    Output(file_counter, 3) = {struct_info.session};
    Output(file_counter, 4) = {struct_info.assessment};
    Output(file_counter, 5) = {struct_info.posture};
    Output(file_counter, 6) = {struct_info.controltype};
    Output(file_counter, 7) = {struct_info.controlaxis};
    Output(file_counter, 8) = {struct_info.task};
    Output(file_counter, 9) = {struct_info.trick};
    Output(file_counter, 10) = {struct_info.runnum};
    Output(file_counter, 11) = {struct_info.extn};
    Output(file_counter, 12) = {struct_info.comment};
    if (Max_Settled_Speed{file_counter,2} <= 15) &&
(Max_Settled_Speed{file_counter,2} > 0)
        Output(file_counter, 13) = {'15'};
    elseif Max_Settled_Speed{file_counter,2} < 0
        Output(file_counter, 13) = {'-9999'};
    else
        Output(file_counter, 13) = {Max_Settled_Speed{file_counter,2}};
    end
    Output(file_counter, 14) = {Max_Settled_Speed{file_counter,3}};
end

xlswrite ('test1.xls', Output)
% xlswrite ('MSS_RunData_AllParticipants_v2.xls', Output)

    xlswrite('PT01_heelsit.xls', {struct_info.filename},
'Sheet1',strcat('A', num2str(file_counter)));
```

```
    xlswrite('PT01_heelsit.xls', {struct_info.subject},
'Sheet1',strcat('B', num2str(file_counter)));
    xlswrite('PT01_heelsit.xls', {struct_info.group},
'Sheet1',strcat('C', num2str(file_counter)));
    xlswrite('PT01_heelsit.xls', {struct_info.session},
'Sheet1',strcat('D', num2str(file_counter)));
    xlswrite('PT01_heelsit.xls', {struct_info.assessment},
'Sheet1',strcat('E', num2str(file_counter)));
    xlswrite('PT01_heelsit.xls', {struct_info.posture},
'Sheet1',strcat('F', num2str(file_counter)));
    xlswrite('PT01_heelsit.xls', {struct_info.controltype},
'Sheet1',strcat('G', num2str(file_counter)));
    xlswrite('PT01_heelsit.xls', {struct_info.controlaxis},
'Sheet1',strcat('H', num2str(file_counter)));
    xlswrite('PT01_heelsit.xls', {struct_info.task}, 'Sheet1',strcat('I',
num2str(file_counter)));
    xlswrite('PT01_heelsit.xls', {struct_info.trick},
'Sheet1',strcat('J', num2str(file_counter)));
    xlswrite('PT01_heelsit.xls', {struct_info.runnum},
'Sheet1',strcat('K', num2str(file_counter)));
    xlswrite('PT01_heelsit.xls', {struct_info.extn}, 'Sheet1',strcat('L',
num2str(file_counter)));
    xlswrite('PT01_heelsit.xls', {struct_info.comment},
'Sheet1',strcat('M', num2str(file_counter)));

    xlswrite('PT01_heelsit.xls', Max_Settled_Speed{file_counter,2},
'Sheet1',strcat('N', num2str(file_counter)));
```

Appendix 12
Trunk-Pelvis Coupling MATLAB program

```
clear all

% Define columns of interest to run code on...
TrajCol= 6;
TrunkAngCol= 21;
PelvisAngCol= 24;
TimeCol = 1;
Response = 15;

%% Trunk
Trunk_Rot= zeros(20, 10, 8);
Pelvic_Rot= zeros(20, 10, 8);
TrCounter= zeros(8, 1);

data1= xlsread('PT01_kneel_PELVIS_horizontal_0001_A02_Trunk_Pelvic
Rotation.xlsx');

%place zeros at top of data and concatenate with columns of actual data
i.e zeros are placed in row one, column one & two
%data1= vertcat(zeros(1, 23), data1);

% for row 2 to max size of data in first dimension...
for CurrentRow= 2:size(data1,1)
  %if data is anything above zero then continue in loop...
  if data1(CurrentRow, TrajCol)
   %if CurrentRow-1 in traj column is not equal to data1 current row, i.e
   %there is a change in trajectories...
    if ~(data1(CurrentRow-1, TrajCol)== data1(CurrentRow, TrajCol))
  % then traj is equal to current row in traj column, i.e, new
  % trajectory has started...
       Traj= data1(CurrentRow, TrajCol);
       Time= data1(CurrentRow, TimeCol);
  % Trajectory counter moves up one according to traj variable
       TrCounter(Traj)= TrCounter(Traj)+ 1;
  % start of each trajectory begins with the current row
       TrStartRow= CurrentRow;
    end
    Trunk_Rot(CurrentRow-TrStartRow+1, TrCounter(Traj), Traj)=
data1(CurrentRow, TrunkAngCol);
    Pelvic_Rot(CurrentRow-TrStartRow+1, TrCounter(Traj), Traj)=
data1(CurrentRow, PelvisAngCol);
    Time_change(CurrentRow-TrStartRow+1, TrCounter(Traj), Traj)=
data1(CurrentRow, TimeCol);
    Hit_Response(CurrentRow-TrStartRow+1, TrCounter(Traj), Traj)=
data1(CurrentRow, Response);
  end
end

%% Normalise all data whilst ignoring zero values in each array
%Trunk
%The counter will continue to increase until it reaches a cell that
%contains a zero, at which point the loop will keep all the values before
%the zero, and normalise these values to 101 data points. The final
counter
%value for each vector is used in the calculation to normalise data. It
%provides the length of the vector to divide by 101 data points.
Normalised
%values are placed into a new matrix.

% for trajectories 1 to 8 (3rd dimension)
for dimension=1:8
```

```
% traj_occurence is equal to how ever many of each trajectory there are
in
% each dimension (2nd dimension)
    for traj_occurence= 1:TrCounter(dimension)
        % counter is equal to one
        counter=1;
        % whilst counter is equal to one in each column of the 3rd
        % dimension, AND counter is less than the size of the column,
then
        % add one to the counter each time.
        while Trunk_Rot(counter,traj_occurence,dimension) && (counter<
size(Trunk_Rot,1))
            counter=counter+1;
        % using the 2nd and 3rd dimensions that were specified at the
        % beginning of the loop (dimension, traj_occurence), interpolate
        % the values upto the maximum counter
        end
        Trunk_Rot_Norm(: ,traj_occurence ,dimension )=
interp1(1:size(Trunk_Rot,1),...
            Trunk_Rot(:,traj_occurence,dimension), 1: (counter-2)/100:
counter-1)';
        % "Trunk_Rot_Norm(: ,traj_occurence ,dimension )" - The beginning
of the statement specifies the matrix to transfer
        % the normalised data into. "interp1(1:size(Trunk_Rot,1),
Trunk_Rot(:,traj_occurence,dimension),1:(counter-2)/100:counter-1)'" -
specifies what is needed for the interp1 function -
        %"interp1(x,Y,xi)", x = from 1 to size of Trunk_Rot, Y =
Trunk_Rot
        %data, xi = stepwidth, 101 data points in this case
    end
end

%Pelvis
for dimension=1:8
    for traj_occurence= 1:TrCounter(dimension)
        counter=1;
        while Pelvic_Rot(counter,traj_occurence,dimension) && (counter<
size(Pelvic_Rot,1))
            counter=counter+1;
        end
        Pelvic_Rot_Norm(: ,traj_occurence ,dimension )=
interp1(1:size(Pelvic_Rot,1),...
            Pelvic_Rot(:,traj_occurence,dimension), 1: (counter-2)/100:
counter-1)';
    end
end

%% Mean Trunk
% creates a 2-D matrix of the mean for each trajectory
for ii = 1:size(Trunk_Rot_Norm,1)
    for jj = 1:size(Trunk_Rot_Norm,3)
        meanTrunk(ii,jj)= mean(Trunk_Rot_Norm(ii,:,jj));
    end
end

for ii = 1:size(Pelvic_Rot_Norm,1)
    for jj = 1:size(Pelvic_Rot_Norm,3)
        meanPelvic(ii,jj)= mean(Pelvic_Rot_Norm(ii,:,jj));
    end
end

%% SD Trunk
% creates a 2-D matrix of the SD for each trajectory
for ii = 1:size(Trunk_Rot_Norm,1)
```

```
    for jj = 1:size(Trunk_Rot_Norm,3)
        stdTrunk(ii,jj)= std(Trunk_Rot_Norm(ii,:,jj));
    end
end

for ii = 1:size(Pelvic_Rot_Norm,1)
    for jj = 1:size(Pelvic_Rot_Norm,3)
        stdPelvic(ii,jj)= std(Pelvic_Rot_Norm(ii,:,jj));
    end
end

%creates an upper and lower SD bandwidth for the mean
stdTrunkPlus = (meanTrunk + stdTrunk);
stdTrunkMinus = (meanTrunk  - stdTrunk);
stdPelvicPlus = (meanPelvic + stdPelvic);
stdPelvicMinus = (meanPelvic  - stdPelvic);

%% Subplot of mean and SD values for trunk
figure
for Trajectory_ID = 1:8
    subplot(2,4,Trajectory_ID), plot(meanTrunk(:,Trajectory_ID), 'r')
    hold on;
    plot(stdTrunkMinus(:,Trajectory_ID))
    plot(stdTrunkPlus(:,Trajectory_ID))
    axis([0 101 -30 30])
    title ('Trunk')
end

% Subplot of mean and SD values for pelvis
figure
for Trajectory_ID = 1:8
    subplot(2,4,Trajectory_ID), plot(meanPelvic(:,Trajectory_ID), 'r')
    hold on;
    plot(stdPelvicMinus(:,Trajectory_ID))
    plot(stdPelvicPlus(:,Trajectory_ID))
    axis([0 101 -30 30])
    title ('Pelvis')
end

%% Angle-angle plots
% Flag hits to monitor which trajectories are succesful/unsuccessful
Sum_HitResponse =sum(Hit_Response==1);
Hit = Sum_HitResponse >1;

% open txt file to write area values to...
str_filename='test_file2.txt';
fid = fopen (str_filename, 'a+');
if fid == -1
    fprintf (1,'could not open file %s\n', str_filename)
    return
end

% Trunk amplitude normalised
dd = size(Trunk_Rot_Norm);
Trunk_Rot_AMPnorm = zeros (dd);
Range_of_Data_trunk = range(Trunk_Rot_Norm,1);

for pp = 1:size(Trunk_Rot_Norm,2)
    for qq = 1:size(Trunk_Rot_Norm,3)
        Trunk_Rot_AMPnorm(:,pp,qq) =
Trunk_Rot_Norm(:,pp,qq)/Range_of_Data_trunk(1,pp,qq);
    end
end
```

Appendix 12

```
% Pelvis amplitude normalised
ee = size(Pelvic_Rot_Norm);
Pelvic_Rot_AMPnorm = zeros (dd);
Range_of_Data_pelvic = range(Pelvic_Rot_Norm,1);

for pp = 1:size(Pelvic_Rot_Norm,2)
    for qq = 1:size(Pelvic_Rot_Norm,3)
        Pelvic_Rot_AMPnorm(:,pp,qq) =
Pelvic_Rot_Norm(:,pp,qq)/Range_of_Data_pelvic(1,pp,qq);
    end
end

% create a header in the txt file that corresponds to each column...
fprintf(fid,'trajectory area hit\r\n')

% Calculation of area inside convex hull, plot trunk against pelvis, plot
% raw data...

for Column = 1:size(Pelvic_Rot_Norm,2)
    for dim = 1:8
    figure (dim);
    subplot(6,2,Column)
    plot(Trunk_Rot_AMPnorm(:,Column,dim),
(Pelvic_Rot_AMPnorm(:,Column,dim)));
    hold on
    plot(Trunk_Rot_AMPnorm(1,Column,dim),
(Pelvic_Rot_AMPnorm(1,Column,dim)),'g*');
    plot(Trunk_Rot_AMPnorm(end,Column,dim),
(Pelvic_Rot_AMPnorm(end,Column,dim)),'r*');
    xlabel('Trunk Rotation','FontSize',8)
    ylabel('Pelvic Rotation','FontSize',8)
    hold off
    axis ([-2 2 -0.8 0.8])
    axis equal
    axis square
    [kk,aa]=convhull(Trunk_Rot_AMPnorm(:,Column,dim),
(Pelvic_Rot_AMPnorm(:,Column,dim)));
    hold on
    plot(Trunk_Rot_AMPnorm(kk,Column,dim),
(Pelvic_Rot_AMPnorm(kk,Column,dim)),'r-')
    fprintf(fid,'%3.0f %6.3f %3.0f\r\n', dim, aa, Hit(1,Column,dim))
    legend('Coupling','Start','End', 'Convex Hull', 4);
    end
end

status = fclose(fid);
```

Appendix 13
Sit to stand movement MATLAB program

```
clear all
% name text file for output
textfile = 'Pt01_STS_analysis2.txt';
% set constants
f_sample = 300;
f_cutoff = 6;
UPPER_VEL_THRESHOLD = 30;
LOWER_VEL_THRESHOLD = 5;

[Filename, Pathname] = uigetfile('.txt');
data = struct(uiimport);

% interp data
n = data.Time(end)*f_sample + 1;
data.TimeEven = (0:n)/f_sample;
 interp_time = interp1(data.Time, data.Time, data.TimeEven');
time_wrong_data_length = (interp_time(~isnan(interp_time)));
data.NEW_TIME= time_wrong_data_length(1:length(data.Time));

% filter trunk data
data.TrunkRotX_filt = jvfButterSecondTwopass(data.TrunkRotX, f_cutoff,
f_sample);
data.TrunkRotY_filt = jvfButterSecondTwopass(data.TrunkRotY, f_cutoff,
f_sample);
data.TrunkRotZ_filt = jvfButterSecondTwopass(data.TrunkRotZ, f_cutoff,
f_sample);
data.TrunkAccX_filt = jvfButterSecondTwopass(data.TrunkAccX, f_cutoff,
f_sample);
data.TrunkAccY_filt = jvfButterSecondTwopass(data.TrunkAccY, f_cutoff,
f_sample);
data.TrunkAccZ_filt = jvfButterSecondTwopass(data.TrunkAccZ, f_cutoff,
f_sample);
% filter L_Thigh data
data.L_ThighRotX_filt = jvfButterSecondTwopass(data.L_ThighRotX,
f_cutoff, f_sample);
data.L_ThighRotY_filt = jvfButterSecondTwopass(data.L_ThighRotY,
f_cutoff, f_sample);
data.L_ThighRotZ_filt = jvfButterSecondTwopass(data.L_ThighRotZ,
f_cutoff, f_sample);
data.L_ThighAccX_filt = jvfButterSecondTwopass(data.L_ThighAccX,
f_cutoff, f_sample);
data.L_ThighAccY_filt = jvfButterSecondTwopass(data.L_ThighAccY,
f_cutoff, f_sample);
data.L_ThighAccZ_filt = jvfButterSecondTwopass(data.L_ThighAccZ,
f_cutoff, f_sample);

% filter R_Thigh data
%{
data.R_ThighRotX_filt = jvfButterSecondTwopass(data.R_ThighRotX,
f_cutoff, f_sample);
data.R_ThighRotY_filt = jvfButterSecondTwopass(data.R_ThighRotY,
f_cutoff, f_sample);
data.R_ThighRotZ_filt = jvfButterSecondTwopass(data.R_ThighRotZ,
f_cutoff, f_sample);

data.R_ThighAccX_filt = jvfButterSecondTwopass(data.R_ThighAccX,
f_cutoff, f_sample);
data.R_ThighAccY_filt = jvfButterSecondTwopass(data.R_ThighAccY,
f_cutoff, f_sample);
data.R_ThighAccZ_filt = jvfButterSecondTwopass(data.R_ThighAccZ,
f_cutoff, f_sample);
%}
```

Appendix 13

```
% calculate angular velocity
data.TrunkRotX_AngVel = diff(data.TrunkRotX_filt)./diff(data.NEW_TIME);

data.L_ThighRotZ_AngVel =
diff(data.L_ThighRotZ_filt)./diff(data.NEW_TIME);

%data.R_ThighRotZ_AngVel = diff(data.R_ThighRotZ_filt)./diff(data.Time);

%create time vector for velocity vector
data.TimeVel = data.NEW_TIME(1:end-1);

%calculate start point for STS movement from Trunk Velocity
i_movement_start_point = find(data.TrunkRotX_AngVel >
UPPER_VEL_THRESHOLD, 1);

%if trunk velocity at the point of 'i_movement_start_point' is less than
%LOWER_VEL_THRESHOLD, break from loop, and take that start point as
%beginning of STS movement. If it is not less than threshold, 'end', and
%move to previous time point 'i_movement_start_point =
%i_movement_start_point-1;'

while data.TrunkRotX_AngVel
     if data.TrunkRotX_AngVel (i_movement_start_point)<
LOWER_VEL_THRESHOLD
         break
    end
    i_movement_start_point = i_movement_start_point-1;
end

%calculate end point for STS movement from Thigh Velocity
i_movement_end_point = find(data.L_ThighRotZ_AngVel >
UPPER_VEL_THRESHOLD, 1);

while data.L_ThighRotZ_AngVel
    if data.L_ThighRotZ_AngVel (i_movement_end_point)<
LOWER_VEL_THRESHOLD
        break
    end
    i_movement_end_point = i_movement_end_point+1;
end

% calculate start and end point for STS duration
STS_start = data.NEW_TIME (i_movement_start_point);
STS_end = data.NEW_TIME (i_movement_end_point);
STS_duration = STS_end-STS_start;

% Calculate descriptive measures - peak amplitudes
% Trunk Flexion
trunk_peak_flx_x = max(data.TrunkRotX_filt);

% Trunk Extension
trunk_peak_ext_x = min(data.TrunkRotX_filt);

% Thigh Flexion
l_thigh_peak_flx_z = min(data.L_ThighRotZ_filt);

% Thigh Extension
l_thigh_peak_ext_z = max(data.L_ThighRotZ_filt);

% Trunk Peak accelerations
%trunk_peak_acc_x = max(data.TrunkAccX);
trunk_peak_acc_y = max(data.TrunkAccY);
trunk_peak_acc_z = max(data.TrunkAccZ);
```

```
% Thigh Peak accelerations
l_thigh_peak_acc_x = max(data.L_ThighAccX_filt);
l_thigh_peak_acc_y = max(data.L_ThighAccY_filt);
l_thigh_peak_acc_z = max(data.L_ThighAccZ_filt);

subplot(3,1,1)
plot(data.NEW_TIME, data.TrunkRotX_filt, 'r.-')
hold on;
plot(data.NEW_TIME, data.L_ThighRotZ_filt, 'b.-')
plot(data.TimeVel, data.TrunkRotX_AngVel, 'g.-')
plot(data.TimeVel, data.L_ThighRotZ_AngVel, 'c.-')
y = get(gca, 'ylim');
plot([STS_start STS_start], y, 'g','LineWidth', 1)
plot([STS_end STS_end], y, 'r','LineWidth', 1)
hleg1 = legend('data.TrunkRotX_filt','data.L_ThighRotZ_filt',
'data.TrunkRotX_AngVel', 'data.L_ThighRotZ_AngVel');
set(hleg1,'Location','East')
set(hleg1,'Interpreter','none')

subplot(3,1,2)
plot(data.NEW_TIME, data.TrunkRotX_filt, 'r')
hold on;
plot(data.NEW_TIME, data.TrunkRotY_filt, 'b')
plot(data.NEW_TIME, data.TrunkRotZ_filt, 'g')
y = get(gca, 'ylim');
plot([STS_start STS_start], y, 'g','LineWidth', 1)
plot([STS_end STS_end], y, 'r','LineWidth', 1)
hleg2 = legend('data.TrunkRotX','data.TrunkRotY', 'data.TrunkRotZ');
set(hleg2,'Location','East')
set(hleg2,'Interpreter','none')

subplot(3,1,3)
plot(data.NEW_TIME, data.L_ThighAccX_filt, 'r')
hold on;
plot(data.NEW_TIME, data.L_ThighAccY_filt, 'b')
plot(data.NEW_TIME, data.L_ThighAccZ_filt, 'g')
y = get(gca, 'ylim');
plot([STS_start STS_start], y, 'g','LineWidth', 1)
plot([STS_end STS_end], y, 'r','LineWidth', 1)
hleg3 = legend('data.L_ThighAccX','data.L_ThighAccY',
'data.L_ThighAccZ');
set(hleg3,'Location','East')
set(hleg3,'Interpreter','none')

%write out figures to text file
%
fid = fopen(textfile, 'a');
fprintf(fid,
'%6s\t%6s\t%6s\t%6s\t%6s\t%6s\t%6s\t%6s\t%6s\t%6s\t%6s\t%6s\t%6s\t\n',...
        'trial',...
        'STS_Start',...
        'STS_End',...
       'STS_Duration',...
       'TrunkPeakFlxX',...
       'TrunkPeakExtX',...
       'L_ThighPeakFlxZ',...
       'L_ThighPeakExtZ',...
       'TrunkPeakAccY',...
       'TrunkPeakAccZ',...
       'L_ThighPeakAccX',...
       'L_ThighPeakAccY',...
       'L_ThighPeakAccZ');
```

```
fprintf(fid,
'%6s\t%.3f\t%.3f\t%.3f\t%.2f\t%.2f\t%.2f\t%.2f\t%.2f\t%.2f\t%.2f\t%.2f\t%
.2f\t\n',...
    Filename,...
    STS_start,...
    STS_end,...
    STS_duration,...
    trunk_peak_flx_x,...
    trunk_peak_ext_x,...
    l_thigh_peak_flx_z,...
    l_thigh_peak_ext_z,...
    trunk_peak_acc_y,...
    trunk_peak_acc_z,...
    l_thigh_peak_acc_x,...
    l_thigh_peak_acc_y,...
    l_thigh_peak_acc_z);
fclose(fid);

%
```

Appendix 14

Square wave data

To test the Xsens sensor for larger accelerations, the CAREN platform was driven by a square wave with ±5mm displacement in the three separate directions individually; X, Y, and Z, producing a change in amplitude of 10mm at a frequency of 2Hz. Each trial lasted 30 seconds. The square wave input was chosen to produce accelerations that typically occur during activities of daily living (10-12 $m.s^{-2}$).

Low RMS error values ($\varepsilon <= 0.32 m.s^{-2}$) and strong correlations ($r >= 0.9808$) exist between the Vicon and Xsens sensor when comparing acceleration output for all three axes. When considering each axis separately, the RMS error for accelerations along the Y and Z axis ($0.29 m.s^{-2}$ and $0.32 m.s^{-2}$ respectively) are greater than that reported for the X axis ($0.15 m.s^{-2}$). RMS errors between Vicon and the Xsens sensor accounted for less than 4% of the peak accelerations recorded during square wave trials. However, large error values exist throughout the 30 second trial period for both the Y and Z axis (peak RMS error = $3.1 m.s^{-2}$), as demonstrated in Figure 1, suggesting the low RMS error values reported are misleading when interpreting square wave accelerations.

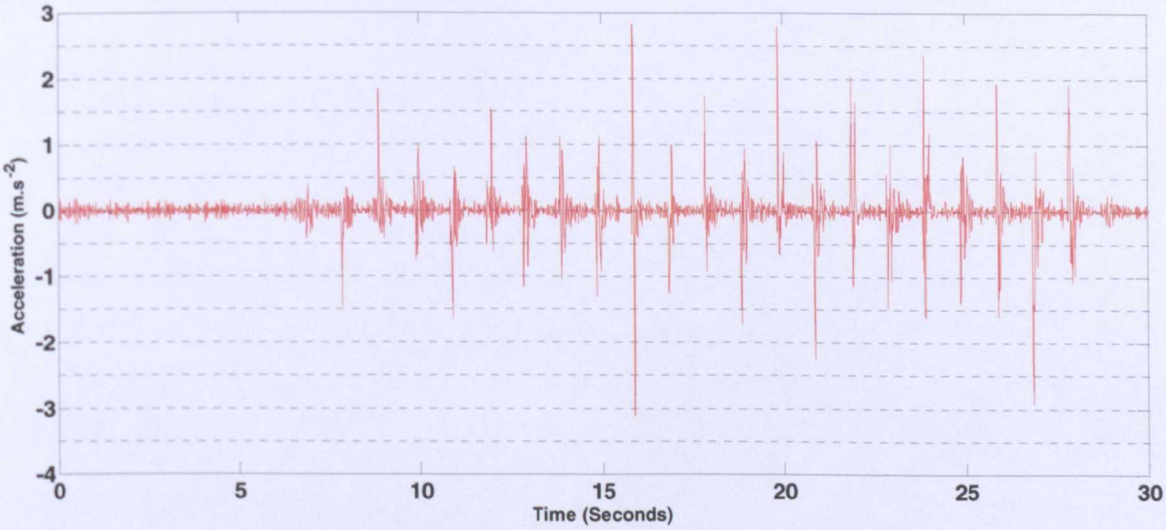


Figure 1. An illustration of the error produced between the Vicon system and Xsens sensor during square wave movement trials, taken from accelerations calculated along the Y axis in CAREN. The maximum peak error reported across all trials was $3.1 m.s^{-2}$.

The RMS error values ($\varepsilon <= 0.53 m.s^{-2}$) and high correlations ($r >= 0.9215$) suggest there is a good match between the Xsens sensor and Vicon system during square wave trials. The RMS error between both devices accounted for less than 4% of peak accelerations. Since the square wave accelerations match those typically reported in ADL (Thies et al., 2007; Janssen et al., 2005; Janssen et al., 2008), the current results provide improved levels of accuracy for the Xsens sensor when measuring acceleration. However, a detailed look at the error across the whole trial between the two systems (Figure 1) showed that errors as high as 3.1m.s^{-2} exist during peak accelerations. An error of 3.1m.s^{-2} equates to 26% of the peak acceleration (11.86m.s^{-2}). This implies that there is inconsistency throughout the trial regarding the amount of error between the two signals, which is masked by the low RMS error and strong correlations. Therefore to accept the RMS error values reported here would be misleading, and falsely give the impression that there is a close match throughout the square wave trials.

JOHN MOORES UNIVERSITY
ANT *INFORMA*TION SHEET

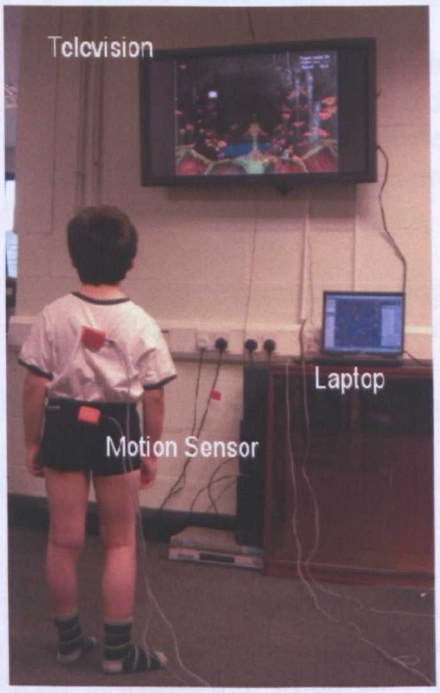
Title of Project: Training and testing selective core and peripheral control in children with movement difficulties
Name of Researcher: Richard Foster
School/Faculty: Research Institute for Sport and Exercise Sciences

Do computer games help you move better?

People like to play games because they are fun, but games also help us to learn to use our brains, our senses and our muscles. We think that playing games could also do this for people who find it difficult to control their bodies and we need people to help us to find out if this is true. Would you like to help us?

What you will do

If you'd like to help we're going to ask you to play some computer games. Our games are similar to the Nintendo Wii or PlayStation Move, you'll play them by moving your whole body, not just by using your hands and arms. We use small movement sensors to monitor how you move to control the game.



Playing the games

- To play the games you sit, kneel or stand on a comfortable mat, with a large screen in front of you to show the game.
- Motion sensors are fastened to you to let you play the game using fun movements of your body.
- You will play on the games at school for 30 minutes a day over 10 days.

It's up to you

It's often quite difficult to get people to stop playing the game ☺, but if you want to you can stop playing at any time for any reason - if you get tired for example.

What we need

To see whether the game has helped you we will need to look at how you play the computer games before, in the middle, and after you've been training. You will also need to do a short standing up test, just like getting up out of a chair, like the one you sit on at school.

Thank you for reading this leaflet,
Rich ☺

Appendix 16

Title of Project: Training and testing selective core and peripheral control in children with movement difficulties
Name of Researcher: Richard Foster
School/Faculty: Research Institute for Sport and Exercise Sciences

Your child is being invited to take part in a research study. Before you decide whether to take part it is important that you understand why the research is being done and what it involves. Please take time to read the following information. Ask us if there is anything that is not clear or if you would like more information before making your decision.

1. What is the purpose of the study?

Children with cerebral palsy have difficulty co-ordinating movements of their body segments, such as their trunk and pelvis (core), arms and legs (extremities). One of the causes of this can be poor control of the muscles, which can lead to difficulties carrying out activities of daily living, such as moving from sitting to standing, and walking.

Although physiotherapy engages these areas of the body, sometime this cannot be enough to help improve activities of daily living. *Further to this, children* can become disenchanted with routine rehabilitation techniques over a prolonged period of time. Custom-made computer games designed at Liverpool John Moores University can now be used in addition to physiotherapy to train specific movements and encourage children to take part.

The aims of the study are to:

- Provide evidence that training movement of the core and extremities using interactive computer games are an effective treatment in children with Cerebral Palsy.
- Establish whether using these games can lead to improved control of the body during activities of daily living.
- Use the study findings to inform future developments in virtual rehabilitation for the benefit of children with Cerebral Palsy.

2. Does your child have to take part?

No. It is up to you and your child to decide whether or not to take part in this study. You will be asked to sign a consent form agreeing to take part if you choose to do so. You are free to withdraw at any time and do not need to give a reason. A decision to withdraw will not affect your rights, or any future treatment or service you may be entitled to or may receive.

3. What will happen if I take part?

Your child will be randomly allocated to one of two possible groups. Both groups will receive training on both the core and extremities, but the order of testing will be different. Your child will be asked to play interactive computer games at their school for 45 minutes every day from Monday to Thursday for two consecutive weeks. On the Friday prior to the first week of training, the Friday of the first week, and Friday of the second week, your child will also be tested on how well they play a computer game and how well they perform a sit to stand test. One month after the intervention, a follow up test of how well your child performs the same computer game and sit to stand test will be assessed. The game and tests are summarised below and in the flow diagram in appendix 1.

Performance test

- The interactive computer game used to test your child's performance is called "The Goblin Post Office". The objective is to steer a virtual dragon through a virtual cave towards oncoming targets that are designed to test your child's ability to move the core and extremities. There are three separate postures used to play the game (kneel-sitting, high-kneeling, and standing) which make the game more difficult to play as your child progresses.

- Movement sensors will be attached to your child's core and extremities to be able to interact with the computer games. These are placed on the child using Velcro and elastic strapping, which are harmless to the child.
- The performance test will take place on each testing day ($1^{st}/2^{nd}/3^{rd}$ Friday), and will last no longer than 60 minutes. The test will aim to work through a series of levels to determine how well your child plays the game.

Sit and stand test

- Your child will take a seat in an adjustable chair that is able to position the child with feet on the floor and knees at ~90°.
- Movement sensors will be positioned on the core and extremities to measure movement of the body segments.
- Your child will be asked to move from sitting to standing, without the use of their arms if possible. This will determine the effect the core and extremities have on the movement. Once the child is standing upright, the trial is completed.
- Each child will be asked to perform 5 trials prior to their performance test on the testing days, to monitor changes in performance as a result of training.

Video camera observation

- The sit-to-stand test will be recorded on video. This is so that any movement compensations can be monitored over the duration of testing to assess changes in response to training that are not possible to measure using the movement sensors.

Training: Interactive computer games

- Interactive computer games designed to be played using movements of the core and extremities will be used on training days. There are a number of games used for training which will provide variation for your child and maintain high levels of motivation.
- Movement sensors will be attached to your child's core or extremities, depending on the training session, to be able to interact with the computer games. These are placed on the child using Velcro and elastic strapping, which are harmless to the child.
- Rotations of the core and extremities are then used to steer a virtual object within the games right and left, or up and down, which are designed to replicate movements that your child would perform during activities of daily living.
- A 'Street Glider' device (similar to the roller-skate) will be used to play the computer games with the lower extremities in a seated position. To use the device your child places their foot into the device, and moves the foot forward or backwards to create movement at the knee joint. This is then used to steer a virtual object within games up and down. Your child will remain seated until the device is removed. The device is fun and enjoyable to use for children and will not provide any discomfort to the foot.

Testing and game playing will be incorporated in your child's daily timetable, either during periods of physical education, at lunch or after school depending on your preference and in consultation with the school. Throughout the process, the principal researcher, Richard Foster, will be present for all sessions in order to help train and test movement of the core and extremities.

4. Are there any risks / benefits involved?

Playing games by moving the core or extremities can be tiring at first, but your child will be asked regularly whether they need a rest during testing and training while playing the game.

Games training may improve core and peripheral control leading to improved strength, posture and mobility in general. Engaging in an enjoyable series of computer games can improve self-esteem and improve the compliance of participants with novel physiotherapy treatments.

5. Will my details and test results be kept confidential?

Yes, each child will be allocated a unique numerical code which shall be used on all forms of data collected for the project so that they cannot be identified. All laptops/computers which have data stored on them will be encrypted, and will only be accessed by members of the research team. We will ensure that all information is kept anonymous in order to ensure your child's confidentiality. The unique numerical code, diagnostic information, and videos/photos regarding your child will be kept on paper or digital format, and locked away in a secure filing cabinet which is only accessible to the research team involved.

Contact Details of Researcher

Primary contact: Richard Foster, Research Student in Virtual Rehabilitation
Email: R.J.Foster@2009.ljmu.ac.uk
Tel: 0151 904 6278
Secondary contact: Dr Gabor Barton, Reader in Biomechanics
Email: G.J.Barton@ljmu.ac.uk
Tel: 0151 904 6263

Thank you for taking the time to read this leaflet.

Appendix 17

Title of Project: **Training and testing selective core and peripheral control in children with movement difficulties**
School/Faculty: Research Institute for Sport and Exercise Sciences
(Please tick each box if you are in agreement)

1. I confirm that I have read and understand the information provided for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily ☐
2. I understand that my child's participation is voluntary and that I am free to withdraw my child at any time, without giving a reason and that this will not affect my legal rights. ☐
3. I understand that any personal information collected during the study will be anonymised and remain confidential. ☐
4. I agree to my child taking part in the above study. ☐
5. I understand that the testing procedure will be video recorded and I am happy to proceed ☐
6. I understand that the videos / photos taken during the assessment will be used to illustrate the study at conferences, in research publications, in teaching and on websites. The images will never contain any personal identifiers and the face will be covered. ☐
7. I agree to allow a summary of my child's medical history be provided to the researcher by my child's current physiotherapist. All information will remain confidential between these parties. ☐

Name of Participant: Date: Signature:

Name of Researcher: Date: Signature:

Richard Foster

Name of Person taking consent: Date: Signature:
(if different from researcher)

Appendix 18

)

Title of Project: **Training and testing selective core and peripheral control in children with movement difficulties**

School/Faculty: Research Institute for Sport and Exercise Sciences

Child (or parent/guardian on their behalf) / young person to circle all they agree with:

Have you read (or had read to you) information about this project?	Yes/No
Has somebody else explained this project to you?	Yes/No
Do you understand what this project is about?	Yes/No
Have you been given a chance to ask questions about taking part in this project?	Yes/No
Have you understood the answers that you have been given to your questions?	Yes/No
Do you understand it's OK to stop taking part at any time?	Yes/No
Are you happy to take part?	Yes/No

If **any** answers are 'no' or you **don't** want to take part, don't sign your name!

If you **do** want to take part, you can **write your name below**

Your name: ....

Date: ....

Your **parent or guardian must write their name here** if they are happy for you to do the project.

Print Name: ....

Sign: ....

Date: ....

The researcher who explained this project to you needs to sign too.

Print Name: ....

Sign: ....

Date: ....

Appendix 19

Variation of pass distance MATLAB program

```
clear;
clc;
PathName = 'M:\GPO_Analysis_111219\Analysis\'; % type in specific folder
FileName = dir('*.mat');
Showfigures = false;


%is FileName a string? if yes, one_file = true, else one_file = false
if strcmp(class(FileName),'char')
    one_file= true;
else one_file= false;
end;

%if one_file is true,num_of_file = 1, else num_of_files = size of
FileName
if one_file
    num_of_files = 1;
else num_of_files = size(FileName,1);
end;

% struct_data contains information regarding a single run
% struct_runinfo contains control scheme and posture info
for file_counter = 1:num_of_files
    %pass_distance_xy contains pathname in 1st column
    if one_file, load(strcat(PathName, FileName.name)); else
load(strcat(PathName, FileName(file_counter).name)); end;
    pass_distance_xy(file_counter, 1)= {PathName};
    pass_distance_x(file_counter, 1)= {PathName};
    pass_distance_y(file_counter, 1)= {PathName};
    %pass_distance_xy contains filename in 2nd column
    if one_file,
        pass_distance_xy(file_counter, 2)= {FileName.name};
        pass_distance_x(file_counter, 2)= {FileName.name};
        pass_distance_y(file_counter, 2)= {FileName.name};
    else
        pass_distance_xy(file_counter, 2)= {FileName(file_counter).name};
        pass_distance_x(file_counter, 2)= {FileName(file_counter).name};
        pass_distance_y(file_counter, 2)= {FileName(file_counter).name};
    end;
    %pass_distance_xy contains no. of trials in 3rd column
    pass_distance_xy(file_counter, 3)= {size(struct_data,1)};
    pass_distance_x(file_counter, 3)= {size(struct_data,1)};
    pass_distance_y(file_counter, 3)= {size(struct_data,1)};

    [num_rows, num_columns]= size(struct_data);
    if isempty(struct_data(num_rows,1).passdist)
        num_rows = num_rows-1;
    end
    % take passxy value from struct_data
    for k=1:num_rows
        pass_distance_xy(file_counter, k+3)= {getfield(struct_data, {k},
'passxy')};
        pass_distance_x(file_counter, k+3)= {getfield(struct_data, {k},
'passdist', {1})};
        pass_distance_y(file_counter, k+3)= {getfield(struct_data, {k},
'passdist', {2})};
    end
end;

 for ii = 1: num_rows
        hit_col(ii,1) = {getfield(struct_data, {ii}, 'hit')};
```

```
 end

%no. of blocks calculated as -->
floor(pass_distance_xy{file_counter,3}/8)
%calculates mean pass_distance_xy and std of pass_distance_xy for each
block within each run

for file_counter = 1:num_of_files
    for run = 1:pass_distance_xy{file_counter,3}
        run_mean_sd_pass_distance_xy(file_counter,1) = mean (cell2mat
(pass_distance_xy(file_counter, 4:run(end)+3)));
        run_mean_sd_pass_distance_xy(file_counter,2) = std (cell2mat
(pass_distance_xy(file_counter, 4:run(end)+3)));
        run_mean_sd_pass_distance_x(file_counter,1) = mean (cell2mat
(pass_distance_x(file_counter, 4:run(end)+3)));
        run_mean_sd_pass_distance_x(file_counter,2) = std (cell2mat
(pass_distance_x(file_counter, 4:run(end)+3)));
        run_mean_sd_pass_distance_y(file_counter,1) = mean (cell2mat
(pass_distance_y(file_counter, 4:run(end)+3)));
        run_mean_sd_pass_distance_y(file_counter,2) = std (cell2mat
(pass_distance_y(file_counter, 4:run(end)+3)));
    end
end

%write Mean and SD pass distance to xls file, with filename broken up
into
%strings using gpofGetRunInfoStructure function
for file_counter = 1:num_of_files
    struct_info =
gpofGetRunInfoStructure(pass_distance_xy{file_counter,2});

    Output(file_counter, 1) = {struct_info.subject};
    Output(file_counter, 2) = {struct_info.group};
    Output(file_counter, 3) = {struct_info.session};
    Output(file_counter, 4) = {struct_info.assessment};
    Output(file_counter, 5) = {struct_info.posture};
    Output(file_counter, 6) = {struct_info.controltype};
    Output(file_counter, 7) = {struct_info.controlaxis};
    Output(file_counter, 8) = {struct_info.runnum};
    Output(file_counter, 9) = {struct_info.extn};
    Output(file_counter, 10) = {struct_info.comment};
    Output(file_counter, 11) =
{run_mean_sd_pass_distance_xy(file_counter, 1)}; % pass distance for
'both' files
    Output(file_counter, 12) =
{run_mean_sd_pass_distance_xy(file_counter, 2)};
    Output(file_counter, 13) = {run_mean_sd_pass_distance_x(file_counter,
1)}; % pass distance for 'horiz' files
    Output(file_counter, 14) = {run_mean_sd_pass_distance_x(file_counter,
2)};
    Output(file_counter, 15) = {run_mean_sd_pass_distance_y(file_counter,
1)}; % pass distance for 'vert' files
    Output(file_counter, 16) = {run_mean_sd_pass_distance_y(file_counter,
2)};
end

xlswrite ('testPassXY.xls', Output)

% xlswrite ('MSS_RunData_AllParticipants_v2.xls', Output)
```